

UNIVERSITY OF SOUTHAMPTON
FACULTY OF PHYSICAL SCIENCES AND ENGINEERING
Electronics and Computer Science

A Stereoscopic Vision Robot

by

Henry S. Lovett

A project progress report submitted for the award of
MEng Electronic Engineering

Supervisor: Prof. Steve Gunn
Examiner: Prof. Mark Zwolinski

4th April, 2013

Turn off iNotes!

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF PHYSICAL SCIENCES AND ENGINEERING
Electronics and Computer Science

A project report submitted for the award of MEng Electronic Engineering

A STEREOSCOPIC VISION ROBOT

by **Henry S. Lovett**

This report describes the research, design, build and test of a stereoscopic robot using two OV7670 Omnivision cameras and an Atmel AT32UC3C0512C. A custom PCB was designed to fit a wheeled base. The report is in two main parts, hardware design and vision algorithms. The hardware design section describes the prototypes and design of the subsystems. The PCB that was designed is also tested.

The vision algorithms section discusses range finding from stereo images, comparison algorithms between stereo pairs and the implementation and test of a two dimensional fast Fourier transform on an AVR.

The final product is a small mobile robot equipped with cameras and capability of image processing. The device has the ability to roam unintelligently and capture photos or be used as a command line terminal to control by a user.

Contents

List of Symbols	xv
Acknowledgements	xvii
1 Introduction	1
1.1 Project Management	2
2 Research	5
2.1 Hardware Research	5
2.1.1 Microcontrollers	5
2.2 Firmware	6
2.2.1 Camera	6
2.2.2 Atmel Software Framework	7
3 Hardware and Firmware Development	9
3.1 Camera	9
3.1.1 Single Camera Operation	10
3.1.2 Dual Camera Operation	12
3.2 SD Card	13
3.2.1 Storing Images	13
3.2.2 User Interface	14
3.3 Motor Driver Development	16
3.3.1 Hardware	16
3.3.2 Firmware Development	16
3.3.3 Testing	21
3.3.4 Conclusion	22
3.4 PCB Development	23
3.4.1 Circuit Design	23
3.4.2 PCB Design	23
3.4.3 PCB Testing	27
3.4.3.1 UART Test	27
3.4.3.2 SD Card Test	28
3.4.3.3 LED Test	29
3.4.3.4 SDRAM Test	29
3.4.3.5 I^2C Test	31

3.4.3.6	Camera Test	32
3.4.3.7	Motor Driver Test	33
3.4.4	PCB Faults	33
3.4.4.1	TCRT1010 Footprint	33
3.4.4.2	SDRAM Footprint	34
3.4.4.3	SDRAM Chip Select	34
3.4.4.4	SDRAM Data Line Resistors	35
3.4.4.5	Camera Interrupt Line	36
3.4.4.6	Motor Driver Pinout	36
3.4.5	PCB Conclusions	36
3.5	Conclusions	39
4	Investigation into Vision Algorithms	41
4.1	Matching Algorithms	41
4.1.1	Sum of Absolute Differences	42
4.1.2	Sum of Squared Differences	42
4.1.3	NCC	42
4.1.4	Comparison	43
4.1.5	Conclusion	45
4.2	Range Finding	45
4.2.1	Derivations	45
4.2.2	Summary	45
4.2.3	Field of View	46
4.2.4	Example	47
4.2.5	Conclusions	47
4.3	Fourier Transform	48
4.3.1	Background Research and the FFT	48
4.3.2	Two Dimensional Fast Fourier Transform	51
4.3.3	Implementing the FFT	52
4.3.4	Testing of the FFT on AVR	55
4.3.4.1	1D FFT Test	55
4.3.4.2	2D FFT Test	58
5	Conclusions and Further Work	61
A	Gantt Chart	63
B	Circuit Diagrams	65
B.1	OV7670 Breakout Board Schematic	65
B.2	Il Matto and Dual Camera Schematic	65
B.3	The Columbus Circuit Diagram	65
C	PCB Design	75
C.1	PCB Top Side	75
C.2	PCB Bottom Side	75

D Costings and Components	79
E Contents of Files	81
F Bitmap File Format	83
F.1 Bitmap File Format	83
G Range Finding Derivations	87
G.1 Object is between the Cameras	87
G.2 Object is to the same side in each camera	89
G.3 Object is in front of a camera	90
H Source Code	93
H.1 C Code for AVR	93
H.1.1 The Columbus Source Code	93
H.1.1.1 main.c	93
H.1.1.2 Bitmap.c	101
H.1.1.3 CustomDevices.h	101
H.1.1.4 ImageProcessor.h	102
H.1.1.5 ImageProcessor.c	103
H.1.1.6 MotorDriver.h	109
H.1.1.7 MotorDriver.c	110
H.1.1.8 OV7670.h	119
H.1.1.9 OV7670.c	125
H.1.1.10 OV7670.c	136
H.1.1.11 PCA9542A.h	139
H.1.1.12 PCA9542A.c	140
H.1.1.13 SD_Card.h	140
H.1.1.14 SD_Card.c	141
H.1.1.15 TWI.c	151
References	153

List of Figures

1.1	The base of the robot	2
3.1	RGB565 pixel format	10
3.2	Signals generated to control the OV7670 capture and read	11
3.3	An Example Image taken using the OV7670 and stored as a Bitmap on the SD Card	14
3.4	Prototype of Dual Camera operation.	15
3.5	Circuit diagram of Optosensor	17
3.6	Graph of Wheel Angle against the Voltage read by the AVR	17
3.7	A State Machine showing the operation of the <i>Motor_Execute</i> method	19
3.8	Dimensions of Interest for Robot Movement	20
3.9	A plot of Expected Distance against the measured data. Line indicates the average of the data at each point.	22
3.10	A hierarchical diagram of the robot	25
3.11	PCB with no components. Left: Top View. Right: Bottom View . .	26
3.12	SDRAM Chip shown against its footprint.	34
3.13	Motor Driver error. Outputs incorrectly connected	37
3.14	Pictures of the built PCB.	38
4.1	Stereoscopic Test Images from MATLAB Examples	41
4.2	Result Graphs of Comparison Algorithms	44
4.3	Stereo pair of images of a rubber duck on a reel of solder	47
4.4	NCC results from matching using the ducks head from the right image as the template to the left image	48
4.5	A Dirac signal and the phase and magnitude of its Fourier Transform	49
4.6	A 2D Rectangular pulse and the phase and magnitude of its Fourier Transform	50
4.7	A 2D Dirac signal and the phase and magnitude of its Fourier Transform	53
4.8	A 2D Rectangular Pulse signal and the phase and magnitude of its Fourier transform	54
4.9	Input Dirac Signal for AVR fast Fourier transform	56
4.10	Output phase and magnitude of the complex output from AVR fast Fourier transform of a Dirac function	56
4.11	Magnitude calculated by the AVR of the Fourier transform of a Dirac function	56

4.12	Input Rectangular Pulse for AVR fast Fourier transform	57
4.13	Output phase and magnitude of the complex output from AVR fast Fourier transform of a Rectangular Pulse	57
4.14	Magitude calculated by the AVR of the Fourier transform of a Rectangular Pulse	57
4.15	3D Plots of the phase and magnitude of the Complex Data returned from the 2D FFT on the AVR of a 2D Dirac Function	59
4.16	3D Plots of the phase and magnitude of the Complex Data returned from the 2D FFT on the AVR of a 2D Square Function	60
A.1	Gantt Chart of how time will be spent in the areas of the project .	64
B.1	The circuit diagram for the OV7670 breakout board	66
B.2	The circuit diagram for Dual Cameras using the Il Matto Board .	67
B.3	The Columbus Circuit Diagram Page 1	68
B.4	The Columbus Circuit Diagram Page 2	69
B.5	The Columbus Circuit Diagram Page 3	70
B.6	The Columbus Circuit Diagram Page 4	71
B.7	The Columbus Circuit Diagram Page 5	72
B.8	The Columbus Circuit Diagram Page 6	73
C.1	The Top side of the CAD Design of the PCB	76
C.2	The Bottom side of the CAD Design of the PCB	77
G.1	Problem 1 - Object is between the Cameras	88
G.2	Problem 2 - Object is to the same side in both cameras	90
G.3	Problem 3 - Object is directly in front of a camera	91

List of Tables

1.1	A list of risks and the prevention steps taken to reduce their impact	3
2.1	Comparison Table of some common microcontrollers. Data of microcontrollers taken from Atmel Corporation (2012a), Atmel Corporation (2012b), Atmel Corporation (2012d) and Texas Instruments (2012). Costings from Farnell (2012)	7
3.1	A table comparing different image formats available (Fulton, 2010)	13
3.2	Pin Connections of the ATMega644P for Dual Camera Operation.	15
3.3	Results of Motor Distance Test	21
3.4	Results of motor speed test	22
3.5	The Pinout of the AVR for the circuit. ‘-’ means unavailable and blank means unused	24
3.6	A table showing examples of the incorrect data returned from the SDRAM	35
4.1	Table of results to calculate the field of view of the camera	46
4.2	Number of clock cycles taken to calculate the Transform of 64 or 256 long data set	58
D.1	A table of all components used and their costs.	79
D.2	All components and their values (if applicable)	80
F.1	Format of a Bitmap file with values used, to write an image from the camera to an SD Card	83

Listings

3.1	UART Test Code	27
3.2	UART Test Code	28
3.3	SDRAM Test Code	30
3.4	I^2C Test Code	31
3.5	Result of I^2C bus scan with Channel 0 of the I^2C MUX selected	32
3.6	Camera Test Code	32
3.7	Motor Test Code	33

List of Symbols

Abbreviations

I^2C	Inter-Integrated Circuit
TWI	Two Wire Interface
SCCB	Serial Camera Control Bus
SPI	Serial Peripheral Interface
kB	KiloBytes
ISR	Interrupt Service Routine
PCB	Printed Circuit Board
FIFO	First In - First Out
ADC	Analogue to Digital Converter
DAC	Digital to Analogue Converter
PWM	Pulse Width Modulation

Images

φ_0	Field of view of the camera
φ_1, φ_2	Angle from camera to the object
B	Separation distance of two cameras
D	Distance from camera to the object
i, j	Pixel index of an Image
x_0	Horizontal resolution of the image
x_1, x_2	Distance of object from the normal of the camera

Motors

δ	Distance to move
γ	Number of tabs on the wheel
A	Angle of rotation
C_w	Circumference of the wheel
r_b	Distance from centre of the robot to the wheel
C_b	$2\pi r_b$

Acknowledgements

I would like to thank Professor Steve Gunn whose help throughout the year was invaluable and for the weekly meetings no matter where he was in the world. I would also like to thank my friends and family for their support and help throughout my degree and with proof reading, to Tom for our years of being lab partners during our time here, and finally to Alice for asking the two golden questions that solved 90% of my problems whenever I had one; “Is it connected?” and “Is it switched on?”.

Chapter 1

Introduction

The original idea for the project was a stereoscopic mapping robot, similar to [Goebel \(2012\)](#). This would autonomously searched an area and return an occupancy map ([Thrun, 2003](#)). However, due to time constraints, the vision part of the project was not implemented. The end robot is able to capture stereo image pairs, move with reasonable accuracy and do some image processing. The theory for distance measuring is discussed and prototyped in MATLAB but is not implemented on the AVR.

Stereoscopy in computer vision is the ability to calculate the locations and depths using images from two or more cameras, which are used to triangulate and estimate distances ([Saxena et al., 2007](#)). By using two cameras on the same plane, separated by a set horizontal distance, the depth of the observed scene can be perceived by the system.

Stereovision is a small section of computer vision which is widely used in many applications, including Microsoft's Xbox Kinect ([Microsoft, 2012](#)), where stereo vision is used to locate a game player in order to use their movements to control the game. [Mrovlje and Vrančić \(2008\)](#) uses stereovision to be able to locate the distance to a marker.

The stereovision robot discussed in this report is a low cost alternative to other robots which use laser range finders or high quality cameras ([Se et al., 2002](#)). The robot will use the base seen in figure [1.1](#) and use two OmniVision OV7670 cameras delivering QVGA format images.

The final robot designed could be used for a variety of applications. As a mapping robot, the device could be used by estate agents to measure room sizes. The robot



Figure 1.1: The base of the robot

could also be adapted to stream the camera data to a remote computer and be controlled by a user to explore unknown and potentially hostile areas safely.

1.1 Project Management

In order to reduce the risk within the project, all aspects of potential issues are looked at and are summarised in table 1.1. A Gantt chart of how time should be spent can be seen in figure A.1.

The project will be designed in stages - first, gaining operation of all the basic sections; movement, image capturing, image detection algorithms etc. These will then be brought together once tested to create the final product.

Risk	Severity	Prevention
Parts not arriving on time	High	Order parts as early as possible
Project not fulfilling specification	High	Develop in stages to obtain functionality in parts. Ensure enough time is allocated to the project.
PCB Design is incorrect	Medium	Check the design carefully and get second opinion
Failure of personal computer causing data loss	Low	Keep back ups of all work on Devtrack Git repository and Dropbox.

Table 1.1: A list of risks and the prevention steps taken to reduce their impact

Chapter 2

Research

The research for this project was split into three sections:

1. Hardware
2. Software, broken down into:
 - (a) Firmware, and
 - (b) Algorithms

Hardware and firmware research will be discussed in this section. Vision algorithms are looked at in detail in chapter [4](#).

2.1 Hardware Research

2.1.1 Microcontrollers

The robot is to be designed with a budget of £80 (not including P.C.B.). The choice of microcontroller will be an important one, as a compromise between cost, power and usability must be made. There are two main brands of microcontrollers present in the consumer market: ARM and Atmel AVRs.

ARM is an architecture which is developed by ARM Holdings. ARM devices come in a many varieties: ARM9, ARM7, Strong ARM, ARM Cortex etc. Whilst ARM Holdings do not fabricate and sell the devices themselves, many companies, such as Texas Instruments, use the architecture and manufacture their own devices.

ARM cores are based on a RISC Harvard architecture and tend to be 32-bit with a high clock speed. ARM microcontrollers have onboard support for SPI, I^2C , PWM, ADCs and can have Flash, SRAM and EEPROM memory built-in. For this comparison, the Stellaris by Texas Instruments will be examined.

Atmel have a variety of products in the microcontroller market. They range from 8-bit, low clock speed devices for the hobbyist (ATMega and ATTiny series), to an improved 8-bit variant (XMega), and a 32-bit design (AT32UC3). XMegas and AVR32s tend to have higher clock speeds than the ATMegas. The AVR core also has a Harvard RISC architecture, and is mainly 8-bit. Atmel devices often have on board peripherals such as I^2C (called TWI on AVRs), SPI and ADCs, as well as a number of different memories: Flash, EEPROM and SRAM. An AT32UC3C0512C, ATXmega256A3BU and ATMega644P will be compared in this section.

Table 2.1 shows a brief summary of some common ARM and AVR microcontrollers. The Stellaris offers the most power with the largest DMIPS performance. However, due to the necessity of floating point operations, the AT32 clearly has a distinct advantage by having a built-in floating point unit. The XMega and ATMega do not offer enough power and are restricted by a small amount of SRAM and Flash. All devices looked at use 3.3V supply and have basic communication protocols (SPI, I^2C and USART). Overall, the AT32UC3C0512C is the best choice with a high throughput, a floating point unit and a vast amount of GPIO and communications. There is no EEPROM which may be desirable, but these can be added onto an SPI or I^2C bus. This device, although slightly more costly, is best suited to this application out of the selection researched.

2.2 Firmware

2.2.1 Camera

The camera used is the OV7670 camera by OmniVision. Steve Gunn provided source code for use on the Il Matto development board which uses an ATMega644P and also has an onboard SD Card reader. The original code streamed video from the camera to a colour TFT screen. The camera is supplied on a small breakout board with a FIFO buffer. The camera operation is discussed in section 3.1. Many implementations of firmware for this camera exist.

	ARM Stelllaris	AT32UC3C0512C	XmegaA3BU	ATmega644P
Clock Speed (MHz)	80	33 or 66	32	12
DMIPS	100	91	-	20 MIPS
Package	100 LQFP or 108 BGA	64, 100, 144TQFP	64 QFP or QFN	40 DIP, 44 TQFP, 44 QFN
Cost of 1 unit(£)	10.30	15.39	6.65	6.86
Flash Size(kB)	256	512	256	64
SRAM Size (kB)	32	64	16	4
EEPROM Size(kB)	2	None internal	4	2
GPIO	64	45, 81 or 123	47	32
Operating Voltage (V)	3.3	5 or 3.3	1.6- 3.6 ¹	2.7-5.5
Communication Interfaces	SPI, I ² C , SSI, MAC, CAN, EPI, USB, US- ART, I2S	SPI, TWI, EBI, USB, Ethernet, CAN, USART, I2S	USART, TWI, USB, SPI	SPI, TWI, USART
Floating Point	None	Built in FPU	None	None
ADCs	16	16	16	8
Timers	4	3 16-bit	7 16-bit, 8 8-bit	2 8-bit, 1 16-bit

Table 2.1: Comparison Table of some common microcontrollers. Data of microcontrollers taken from [Atmel Corporation \(2012a\)](#), [Atmel Corporation \(2012b\)](#), [Atmel Corporation \(2012d\)](#) and [Texas Instruments \(2012\)](#). Costings from [Farnell \(2012\)](#)

2.2.2 Atmel Software Framework

Atmel offer a software framework which contains basic code and device drivers for many of their Xmega and AT32 devices ([Atmel Corporation, 2009](#)). There are also many AVR application notes which provide explanations and example code for protocols like TWI, SPI and timers. These application notes are aimed at older devices like the ATTiny and ATMega and are generally written for IAR Embedded Workbench compiler, as opposed to the AVRGCC compiler used within Atmel Studio.

Chapter 3

Hardware and Firmware Development

For initial development, the *Il Matto* board, designed by Steve Gunn, was used. The system has an ATMega644P clocked at 12MHz and has an on-board SD card socket. This provided the ability to prototype circuits which were then used to create a PCB.

The following section is broken down into the following parts:

- [3.1 Camera Code](#)
- [3.2 SD Card](#)
- [3.3 Motor Development](#)
- [3.4 PCB Development](#)

3.1 Camera

The camera used is an OV7670 by OmniVision. It is mounted onto a break out board and connected to a AL422B FIFO Buffer. The breakout board has all passive components needed and a 24MHz clock mounted. The schematic for the device can be seen in appendix B.

Original code for the camera operation was given by Steve Gunn, which was used to gain the operation required. This code streamed continuous video to a TFT

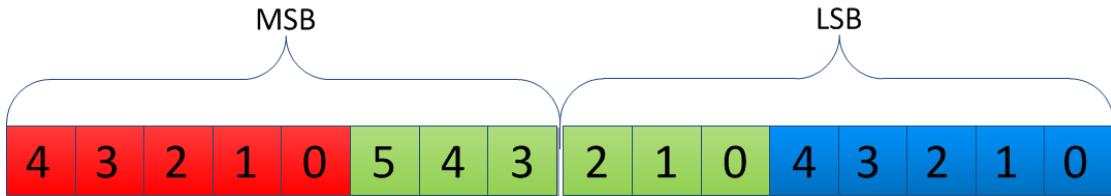


Figure 3.1: RGB565 pixel format

screen. The operation required was to take a single photo from the camera and store the data.

3.1.1 Single Camera Operation

The camera uses a SCCB Interface ([OmniVision, 2007](#)) created by OmniVision. This is almost identical to the I^2C Interface by Phillips and the two protocols are compatible. The original code used a software driven SCCB interface which was very slow and used up processing time. This was changed to make use of the built-in interrupt-driven I^2C interface (named TWI in Atmel AVR s)¹. This communication bus is used to set up the control registers of the OV7670 to enable operation in the correct format.

RGB565 is a 16 bit pixel representation where bits 0:4 represent the blue intensity, 5:10 is the green intensity and 11:15 represent the red intensity (see figure 3.1). This is a compact way of storing data but only allows 65536 colours. Greys can also appear to be slightly green due to the inconsistent colour ratio of the green field. This representation was used as it is a compact format to store images in. It is easily converted to grey scale and is a widely used format.

The camera must use a high speed clock in order to ensure the pixels obtained are from the same time. This makes it difficult for an AVR to be able to respond to the camera quick enough (ATMegas typically clocked at 8-12MHz). This highlights the necessity for a FIFO Buffer.

The OV7670 is set up so that the VSYNC pin goes low at the beginning of every full frame of data, and HREF is high when the data being output is valid. The pixel data is then clocked out on every rising edge of PCLK. To control the buffer, WEN (write enable) is NAND with the HREF signal. When both are high, the write enable to the buffer will be active and the data will be clocked in by PCLK.

¹ I^2C , SCCB and TWI are all the same but are called differently due to Phillips owning the right to the name “ I^2C ”

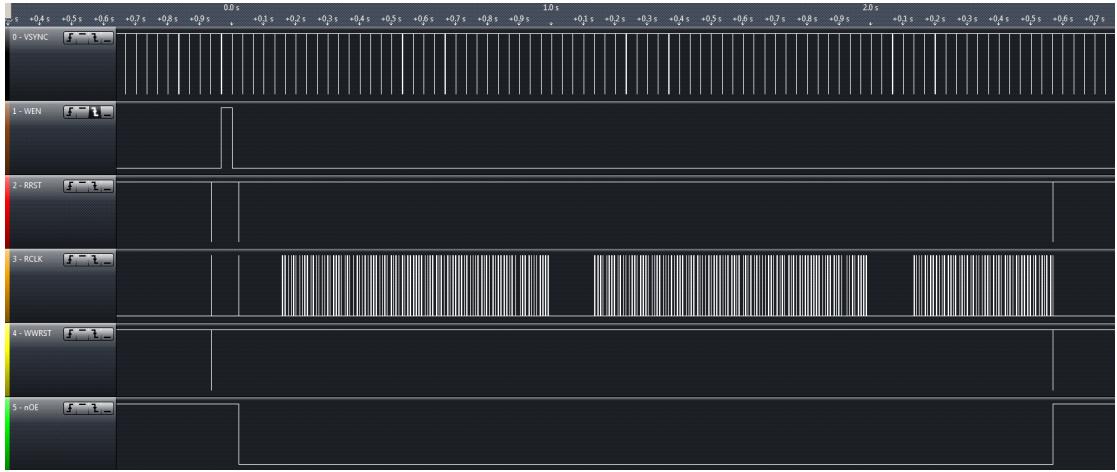


Figure 3.2: Signals generated to control the OV7670 capture and read

In order to acquire a full frame, the first VSYNC pin is set up to interrupt the AVR to enable WEN. The camera will output an entire frame of pixel data and store it into the buffer. When the second VSYNC is received, the WEN signal is disabled, stopping any more data being stored. At this point, the FIFO buffer contains all the image data.

To obtain the data from the buffer, the AVR sets output enable and pulses the read clock. Valid data is available on the input port while RCLK is high. All the data is then read in half a pixel at a time. The entire operation can be seen in figure 3.2.

Difficulties arose at this point with the storage of the data. The ATMega644P has 4kB of internal SRAM, but 153.6kB of memory is needed to store a single image at QVGA (320 by 240 pixels, 2 bytes per pixel) quality.

Firstly, data was sent straight to a desktop computer via a COM Port using USART. A simple desktop program was written in C# to receive and store all the data, and to make a Bitmap image from the data. This method was slow, taking around 30 seconds to transmit one uncompressed image.

The second option was to use extra memory connected to the microcontroller. An SD card is used as FAT file system so that data can be looked at by a user on a computer. Text log files are also written to aid debugging. This is discussed in section 3.2.

3.1.2 Dual Camera Operation

In order for stereovision to be successful, two cameras separated by a horizontal distance (B) will need to be driven at the same time to obtain photos within a small time frame of one another.

A major problem occurred with using the I^2C interface to set up both cameras. The camera has an I^2C address of 21_{16} , which cannot be changed. Multiple I^2C devices with exactly the same address cannot be used on the same bus. Two solutions to this are possible: driving one from I^2C and one from SCCB, or using an I^2C multiplexer. By using two different buses the cameras will be individually addressable. However, SCCB is slow and processor-hungry as it deals with the protocol bit by bit in software. This takes up memory and is not reusable for other operations.

An I^2C multiplexer sits on the bus and has multiple output buses. The master can then address the multiplexer and select whether to pass the bus to bus 0, bus 1 or not allow the data to be transferred. This saves processor time, but means a write operation has to be done to select the camera bus before being able to write to the camera. This slows down the operation, but not as much as using SCCB. The main disadvantage to the I^2C MUX is the extra hardware needed; firstly the MUX itself, but also 7 extra resistors to pull up the two extra buses and the three interrupt lines must be added.

Overall, the disadvantages posed by using a MUX are small, so a multiplexer will be used as opposed to the SCCB interface. A suitable multiplexer is the Phillips PCA9542A ([Phillips, 2009](#)).

The buffers have an output enable pin so the data bus can be shared by both cameras to the AVR. The ATMega644P offers three interrupt pins, two of which are used by the two VSYNC pins for the cameras.

Two ISRs are used to control the relevant WEN signal when VSYNC is triggered. When taking a photo, both frames are taken at a time period close together to capture the same scenario. The data for both images are read back individually by the AVR.

Operation to read an image is identical to using one camera. However, an ID number is passed through the functions to make a decision on the pins to use to read the buffer and to enable the output. Care was taken to avoid bus contention,

	Bitmap	JPEG	PNG	GIF
Extension	*.bmp	*.jpg /*.jpeg	*.png	*.gif
Compression	No	Lossless and Lossy	Lossless ZIP	Lossy
File Size of 320 by 240 pixel Image (kB)	225	20	23	24
Bits per Pixel	8, 16, 24 or 32	24	24, 32 or 48	24, but only 256 Colours

Table 3.1: A table comparing different image formats available ([Fulton, 2010](#))

but no checking procedure is explicitly in place. Both images are then read back from the buffers and stored to memory.

3.2 SD Card

To use the SD card, the FATFS library ([Electronic Lives Manufacturing, 2012](#)) was used. The library supplies all the functions for writing a FAT File System in the files *ff.c*, *ff.h*, *ffconf.h*, *diskio.c*, *diskio.h* and *integer.h*. The *diskio.h* functions control what device is being used - SD/MMC Card, USB drive etc. The *ff.h* header contains all the functions to write to in a FAT File system.

An SD card was chosen due to its small size, low cost and a large data storage. The cards work using an SPI bus which can be used for other devices within the system as well.

3.2.1 Storing Images

Many image formats are common, such as Joint Photographic Expert Group (JPEG), Portable Network Graphics (PNG), Bitmap (BMP) and Graphics Interchange Format (GIF). Table 3.1 shows a summary of some common image formats.

It is clear that the best choice for images would be either PNG or JPEG. However, these require more computational time to compress the image into the correct format. To avoid compression, and thereby save processing time, bitmap was



Figure 3.3: An Example Image taken using the OV7670 and stored as a Bitmap on the SD Card

chosen at the expense of using more memory. The data in a bitmap image is also stored in RGB format so can be read back easily when processing the image. Appendix F shows the make up of a Bitmap File that was used.

By writing the image in this format, they are then able to be opened on any operating system. This aids debugging and allows the prototyping of image algorithms in a more powerful environment. Figure 3.3 shows a photo taken by the OV7670 and stored on a SD card. The quality is not professional, but all features can be seen. The colour is accurate and large text can be read at a small distance.

3.2.2 User Interface

The ATMega 664P pinout for the dual camera operation can be seen in table 3.2. Due to a lack of available GPIO pins, an ATMega168 was added on the I^2C bus to act as a port extender. The ATMega168 accepts a read or write command. A write places the written data on Port D and a read returns any button pressed that occurred on Port C. When a button is pressed, this is stored in the ATMega168 until a read has been done. This is so the master (644P) does not miss any button presses while busy doing lengthy operations such as writing an image. The code is based on Application Note AVVR311 ([Atmel Corporation, 2007](#)), written for

	Port A	Port B	Port C	Port D
0	Data 0	SD Write Protect	I^2C - SCL	No Connection
1	Data 1	SD Card Detect	I^2C - SDA	No Connection
2	Data 2	USB Data Plus	Read Clock 1	VSync 0
3	Data 3	USB Data Minus	Read Reset 1	VSync 1
4	Data 4	SPI Chip Select	Write Enable 1	Read Clock 0
5	Data 5	SPI MOSI	Write Reset 1	Read Reset 0
6	Data 6	SPI MISO	Output Enable 0	Write Enable 0
7	Data 7	SPI Clock	Output Enable 1	Write Reset 0

Table 3.2: Pin Connections of the ATMega644P for Dual Camera Operation.

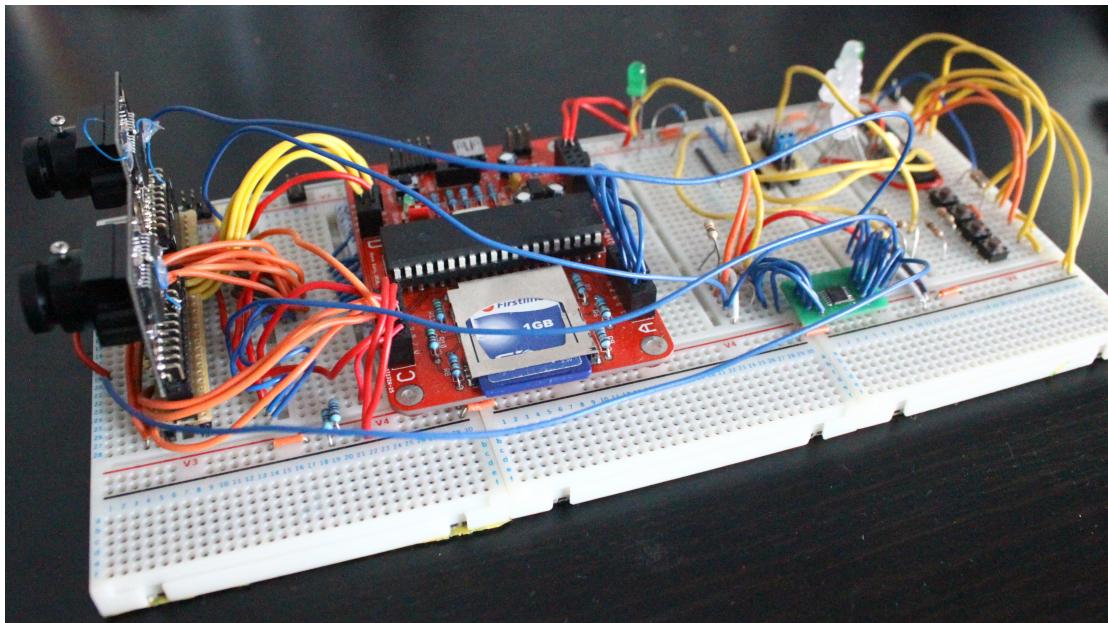


Figure 3.4: Prototype of Dual Camera operation.

IAR Compiler. This code was altered to compile with GCC under Atmel Studio. AVRs contain a hardware based I^2C protocol that is interrupt driven. The ISR of the TWI vector is a state machine which loads the data to send, stores received data, responds to acknowledges and address calls and deals with bus errors that can occur.

The entire prototype for the dual camera operation can be seen in figure 3.4. This circuit was developed to test the cameras and is used to develop the PCB in section 3.4.

3.3 Motor Driver Development

3.3.1 Hardware

Tachometers are devices used to measure rotational speed of a shaft. Tachometers are commonly found in bicycles where a small magnet is attached to the wheel and a sensor is attached to the frame. The elapsed time between every rotation detected by the sensor is measured and, by knowing the size of the wheel, speed can be calculated.

Here an optosensor, the TCRT1010 made by [Vishay Semiconductors \(2012\)](#), is used to measure rotations of the wheel and used to be able to move a distance determined by the microcontroller. The TCRT1010 package contains an IR LED and a phototransistor. The schematic of a simple transistor amplifier used can be seen in figure 3.5 which was reproduced from [Gunn \(2012\)](#).

A similar method to the way a bike measures speed was used. The wheel's rubber absorbed the IR from the LED, so a high voltage was always seen at the collector of the phototransistor when near the wheel. White tippex marks, "tabs", were applied to the wheels at regular intervals. These tabs reflected IR, resulting in a lower collector voltage and thereby giving a way to detect wheel rotation, but not direction. Figure 3.6 shows the voltage at the collector (read by the ADC on the AVR) against the angle of the wheel. Ten tabs were marked on the wheel, and ten dips in the voltage can be seen in figure 3.6. There is a lot of noise that exists on this line due to the non-uniform white tabs applied. However, the dips are prominent and can be detected with the correct threshold voltage.

3.3.2 Firmware Development

The basic outline of the firmware is a set up to calculate how many counts are needed to move the distance, set the inputs to the motor drivers and use PWM to control the speed. The number of times the tabs pass the sensor are counted and when the count reaches the correct number, the motors are stopped. The robot can move in either a straight line or rotate on the spot. More complex movements, for example arcs, would require more accurate tachometers and are not discussed here.

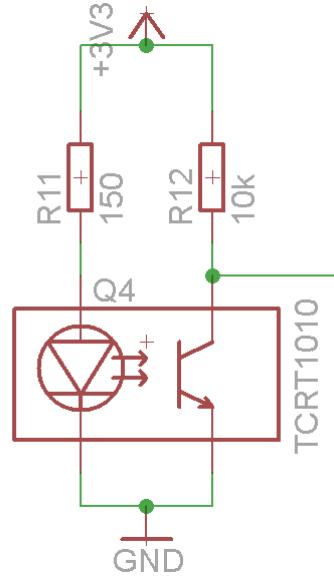


Figure 3.5: Circuit diagram of Optosensor

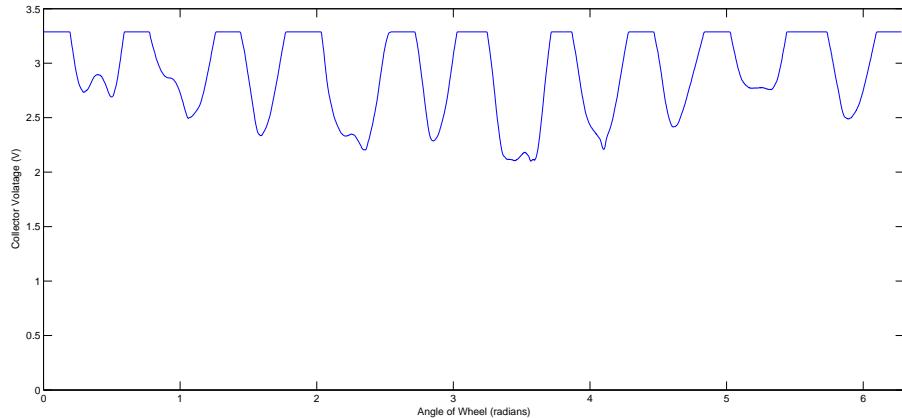


Figure 3.6: Graph of Wheel Angle against the Voltage read by the AVR

Moving in a straight line takes a parameter of how far to move as a signed integer and calculates the total number of counts that need to occur. This can be calculated using equation (3.1). This value is put in a global variable so that other methods have scope to it.

$$\text{Counts} = \delta \times \frac{\gamma}{C_w} \quad (3.1)$$

For rotation, the radius from the centre of the robot to the wheels needs to be known, see figure 3.8(a). The circumference through the wheels is then easily calculated and the angle of rotation is then a ratio. The distance to move is calculated by equation (3.2) and the total number of interrupts can be calculated

using equation (3.1). To rotate clockwise, the left motor is driven forward and the right is driven backwards. To rotate anti-clockwise, the directions are reversed.

$$\delta_R = A \times \frac{C_b}{360} \quad (3.2)$$

Combining equations (3.1) and (3.2) gives:

$$\text{Interrupts} = A \times \frac{\gamma}{C_w} \times \frac{C_b}{360} \quad (3.3)$$

Where A is the angle to rotate in degrees, γ is the counts per revolution of the wheel, C_w is the circumference of the wheel and $C_b = 2\pi \times r_b$ and r_b is the distance from the centre of the robot to the centre of the wheel (see figure 3.8).

As the voltage swing on the collector of the phototransistor does not reach near 0V, the AVR cannot detect this as a logical 0. An external amplifier could be used to generate a full swing voltage. However, the AVR has ADCs and analogue comparators.

The ADC could be used to continually sample the collector voltage and detect dips in the signal. This method has the advantage of a variable threshold and the ability to filter noise. The operation, however, would be complex to implement in code.

An alternative is to use an analogue comparator. The UC3C has two on chip comparator interfaces, each with two comparators. They are a high gain operational amplifier with added options of hysteresis and the ability to interrupt amongst other attributes. The comparators can use two analogue inputs or use the internal DACs as inputs. Potentiometers were used to set the reference voltage externally. This method has the advantage of returning a boolean value of if the collector voltage is higher or lower than the threshold voltage. The detection is easier to detect than reading ADC values and the code will be simpler to implement. This method was decided on for an easier implementation.

The first method implemented was to use the analogue comparators to interrupt when the collector voltage crossed the threshold. Both wheels used the same comparator interface and therefore ran the same ISR when triggered. The ISR then had to read the output of the comparators and decrement the relevant counter for the correct wheel. This method had many downfalls. First, it was not possible to

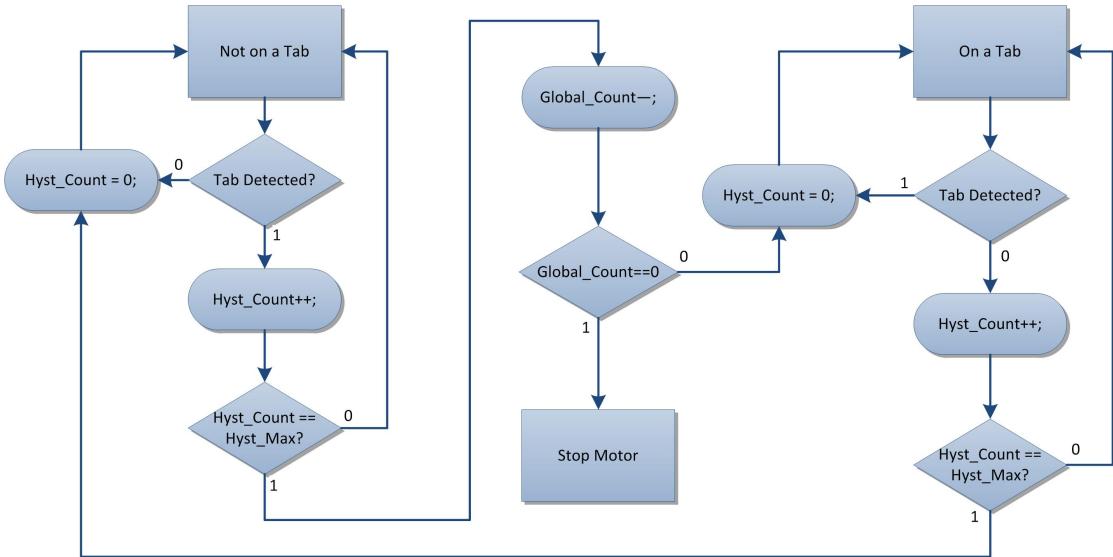
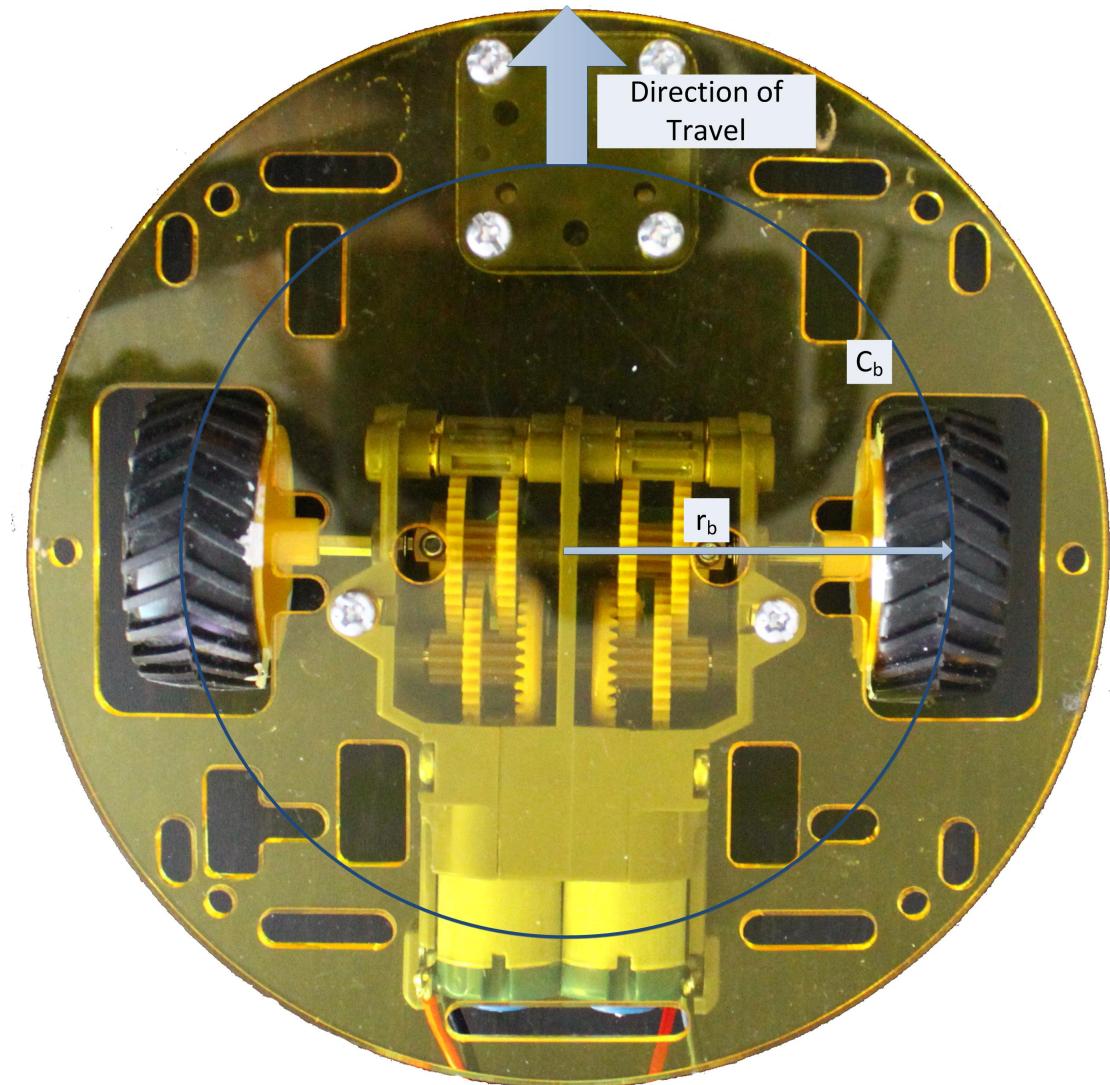


Figure 3.7: A State Machine showing the operation of the *Motor_Execute* method

know which comparator caused the interrupt. If the left wheel triggered the interrupt while the right was below the threshold, both left and right counters would be decremented. This caused a large error each time it occurred. Another problem was noise; occasionally, the lowering voltage would cause multiple interrupts each time. This problem was reduced by setting the hysteresis on the comparators but did not solve the problem completely.

A second approach utilised a simple state machine and software based hysteresis to solve the problems. After the set up is complete, the method *Motors_Execute* is run, containing the state machine to control the motors. The state machine has two states ‘On a Tab’ and ‘Not on a Tab’. When the method enters, the initial state is read from the comparators. If the wheel is already on a tab, it won’t be counted. The code then runs in a loop until the motors stop. A graphic representation of the code can be seen in figure 3.7. Starting in ‘Not on a Tab’ state, a tab must be detected for *Hyst_Max* cycles in succession for the state to change. This is the same for going from ‘On a Tab’ to ‘Not on a Tab’. This is to reduce noise in the form of false readings and increase the certainty that a tab is in detect. The *Global_Count* is only reduced on the transition to ‘On a Tab’ so it is difficult for this to decrement multiple times in normal operation. To increase the certainty, *Hyst_Max* can be increased at the expense of response time.

The motor speed was controlled by PWM. The code sets up a low duty cycle PWM signal to drive the motors slowly. This causes any overshoot that could happen to be low and removes the need for a speed controller.



(a) Top View of robot base showing dimensions of interest



(b) Side View of robot base showing dimensions of interest

Figure 3.8: Dimensions of Interest for Robot Movement

Table 3.3: Results of Motor Distance Test

Distance Specified (mm)	Number of Counts Returned	Counts × Resolution (mm)	Average Measured Distance Moved (mm)	Error (%)
50	4	46.4	47.25	1.83
75	6	69.6	70.75	1.65
100	8	92.8	97.0	4.52
120	10	116.0	113.25	2.37
150	12	139.2	141.0	1.29
170	14	162.4	161.5	0.55
200	17	197.2	201.5	2.18
250	21	243.6	244.5	0.37
300	25	290.0	290.75	0.26

The final code can be seen in appendix H. *Motor_Init* method must be called before operation can occur. This sets up the PWM and analogue comparators. Methods *Motors_Move* and *Motors_Rotate* are the methods that can be called to move in a straight line or rotate on the spot. They both take an input which is a signed integer of either the distance to move (in millimetres) or the angle to rotate (in degrees, and positive is a clockwise movement). They both return the actual movement distances, due to the low resolution of the system.

3.3.3 Testing

Test Rotation

To test the motor system, different distances were given to the movement method. The method prints how many counts will be moved. The actual distance moved was then measured and repeated four times. Table 3.3 shows the results of this test and figure 3.9. The results show that the maximum error observed is 4.52%, which related to 4.5mm. This error is acceptable as a half centimetre error over 10 will not impact the performance of the robot. The error is calculated from the actual distance predicted to move.

A problem was seen that the robot moved in a slight arc. Speed tests were done on the wheel by measuring the total time taken to complete eight full revolutions, the equivalent of moving 928mm. The results and the calculated wheel speeds can be seen in table 3.4. It shows that the left motor runs slightly faster than the right, even though the PWM duty cycle is the same. A controller could be implemented

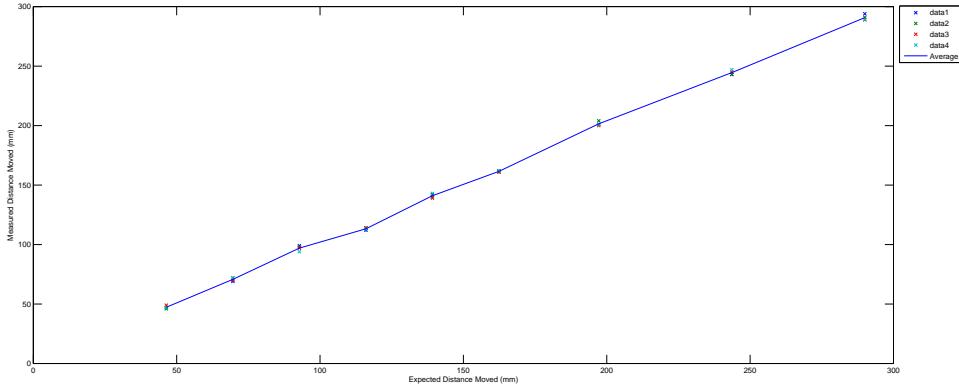


Figure 3.9: A plot of Expected Distance against the measured data. Line indicates the average of the data at each point.

Table 3.4: Results of motor speed test

Wheel	Total Time Elapsed (s)	Calculated Speed ($mm.s^{-1}$)
Left	44.6	20.8
Right	49.6	18.7

to correct this error during operation. However, over the distances covered, the error introduced by this is small enough to neglect.

3.3.4 Conclusion

Due to the low resolution of the sensor (10 counts per revolution), there is a minimum distance that can be moved and a minimum angle of rotation, shown in equations (3.4) and (3.5) respectively. These show that greater distance resolution can be obtained by decreasing the wheel size or increasing γ and a greater rotational resolution can be obtained by the same as distance, or by increasing the distance the wheels are from the centre of the robot. The ratio $C_w : \gamma$ should be as large as possible to obtain the best resolution for movement.

$$\Delta_\delta = \frac{C_w}{\gamma} = 12mm \quad (3.4)$$

$$\Delta_\theta = \frac{360 \times C_w}{\gamma \times C_b} \approx 15^\circ \quad (3.5)$$

This method lacks on two points - lack of speed control and accuracy. A better controller could be implemented to help move at different speeds. This could use the remaining number of counts to gradually slow the speed of the motors

down proportionally as well as correct the speed mismatch between the wheels. A PID controller could be implemented if greater accuracy is needed quicker, at the expense of computation time and potential overshoot.

Rotary encoders could be used to detect the direction of wheels as well. A good, but more costly, alternative would be the HUB-ee wheel by [Creative Robotics Ltd \(2013\)](#), which includes a 120 point quadrature encoder and sensor, motor driver and a geared motor all within the wheel. These wheels have 12 times the accuracy as the method described here and a similar interface.

Given that the robot does not need to move any more accurately than to 1cm, this method has proved to be cheap and successful. The robot is able to move a distance with reasonable accuracy, but to a fairly low resolution.

3.4 PCB Development

3.4.1 Circuit Design

Figure 3.10 shows a basic hierarchy of the robot. Each pin on the AT32UC3C0512C can have one of up to six special functions, as well as being a GPIO pin. Table 3.5 shows the pinout for the microcontroller used.

The circuit diagram for Revision A can be seen in section B.3. The schematic for the SDRAM and values and locations of decoupling capacitors were used from the schematic of the UC3C-EK development board ([Atmel Corporation, 2012c](#)).

3.4.2 PCB Design

The PCB was designed using EAGLE CAD Software. A four layer board was decided to be used to reduce the number of tracks and more easily supply power and ground to the devices. Layer two is a 3V3 plane and layer three is a ground plane. A ground plane is also on the top and bottom layers to help eliminate any ground bounce that could occur.

The SDRAM uses the EBI protocol. In high speed systems, care is often taken to equalise track lengths ([Liu and Lin, 2004](#)). The UC3C maximum clock frequency is 33MHz (with no wait states), which is not fast enough to cause any track

Table 3.5: The Pinout of the AVR for the circuit. ‘-’ means unavailable and blank means unused

Pin	Port			
	A	B	C	D
0	TCK	CAMERA_0		EBI-DATA13
1	TDI	CAMERA_1		EBI-DATA14
2	TDO	CAMERA_2	SDA	EBI-DATA15
3	TMS	CAMERA_3	SCL	EBI-ADDR0
4	USB ID	CAMERA_4	USART TXD	EBI-ADDR1
5		CAMERA_5	USART RXD	EBI-ADDR2
6	AC R	CAMERA_6		EBI-ADDR3
7	AC R	CAMERA_7	EBI NCS3	EBI-ADDR4
8	AC L	STBY1	EBI NCS0	EBI-ADDR5
9	AC L	IN11	EBI-ADDR23	EBI-ADDR6
10	VSYNC0	IN12	EBI-ADDR22	EBI-ADDR7
11	ADCREF	PWM1	EBI-ADDR21	EBI-ADDR8
12			EBI-ADDR20	EBI-ADDR9
13		PWM2		EBI-SDCK
14		IN22	EBI-SDCKE	EBI-ADDR10
15	RRST0	IN21	EBI-SDWE	EBI-ADDR11
16	ADCREF	STBY2	EBI-CAS	EBI-ADDR12
17	-		EBI-RAS	EBI-ADDR13
18	-		EBI-SDA10	EBI-ADDR14
19	RCLK0	SPI-MOSI	EBI-DATA0	EBI-ADDR15
20	WEN0	SPI-MISO	EBI-DATA1	EBI-ADDR16
21	WRST0	SPI-SCK	EBI-DATA2	EBI-ADDR17
22	RRST1	SPI-CS3	EBI-DATA3	EBI-ADDR18
23	RCLK1	SPI-CS2	EBI-DATA4	EBI-ADDR19
24	WEN1	SPI-CS1	EBI-DATA5	EBI-NWE1
25	WRST1	SPI-CS0	EBI-DATA6	EBI-NWE0
26	VSYNC1	SD- DETECT	EBI-DATA7	EBI-NRD
27	NOE1		EBI-DATA8	EBI NCS1
28	NOE0		EBI-DATA9	EBI NCS2
29			EBI-DATA10	
30	-	CLK	EBI-DATA11	EBI-NWAIT
31	-	CLK	EBI-DATA12	-

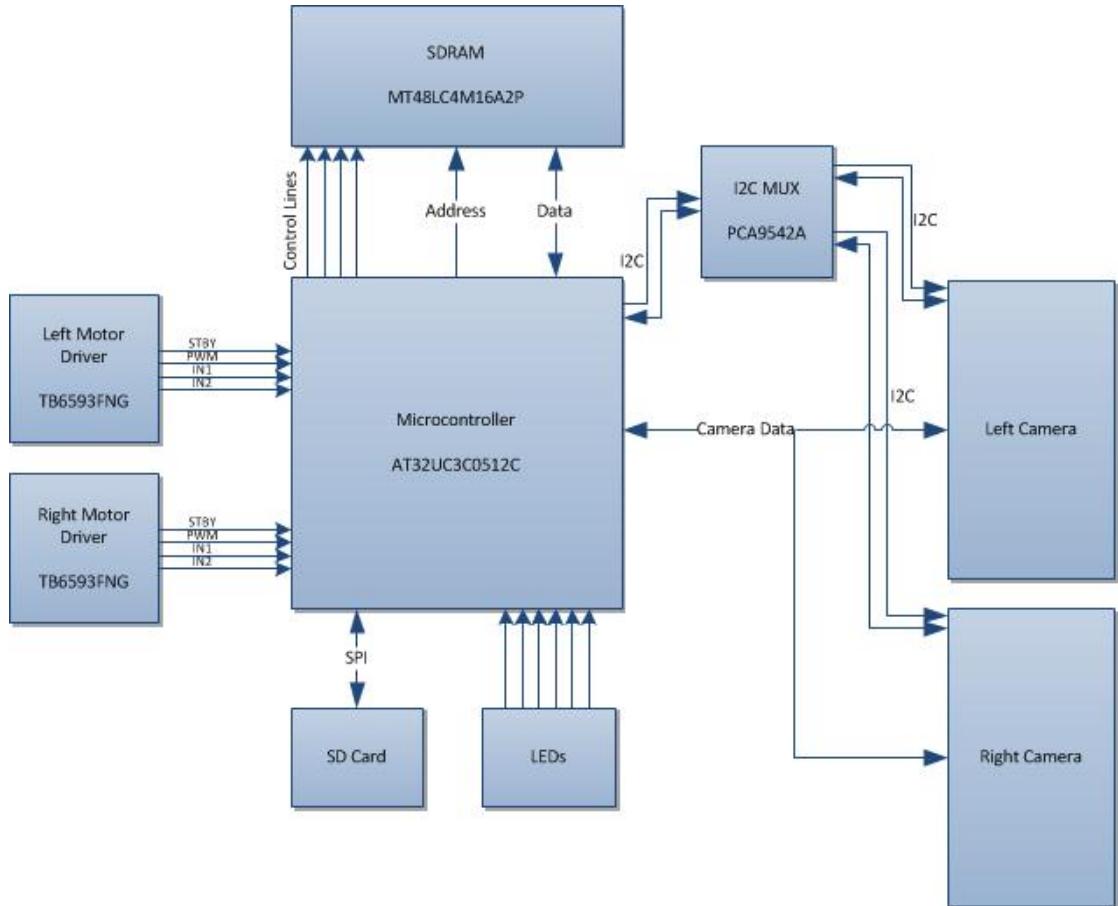


Figure 3.10: A hierarchical diagram of the robot

equalisation problems. Care, however, was taken on the USB lines to ensure correct impedance and the tracks lengths matched to each other.

Tracks were routed in order of priority, starting with the UC3C, SDRAM and cameras. All other devices were then routed (I^2C MUX, SD card, motor drivers etc). As a precaution, spare pins from the UC3C were routed to a header (J8 and J9) so that additions could be done if a pinout or connection was found to be incorrect. UART, I^2C and SPI connections were routed to headers J7, J4 and J5 respectively so logic analysers and COM Port could be attached easily for debugging, or so that extra devices could be added onto the respective protocols for future developments.

Passives used were all surface mount of either 0603 or 1206 size to save space on the board. All headers used were 0.1" spaced for easy connections and a mini B USB socket was added for either power or so that the robot can act as a USB device.

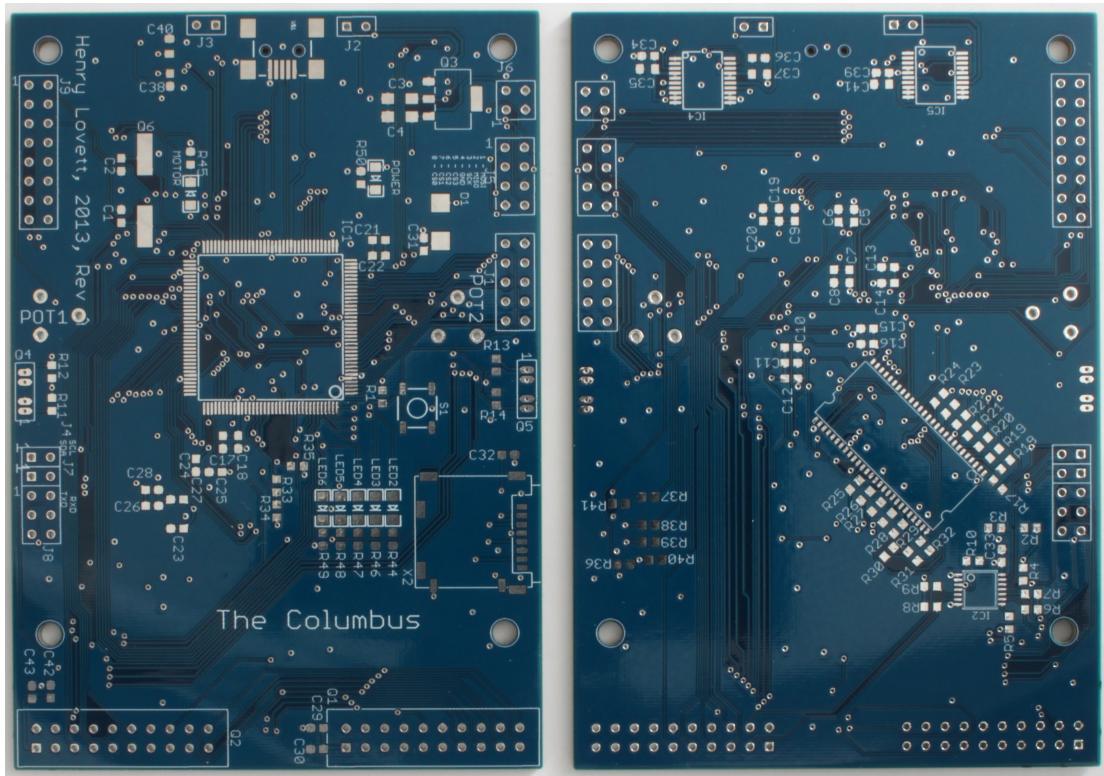


Figure 3.11: PCB with no components. Left: Top View. Right: Bottom View

The layout of components was important. The cameras needed to be as far apart as possible and at the front of the PCB. The motor drivers were situated toward the back of the PCB and headers were added to connect the motors to. The optosensors were positioned such that they could be mounted directly on the PCB and be in the correct position to sense the wheels. Mounting holes were also added onto the board so the PCB could be mounted on to the robot base easily. The overall dimensions of the PCB were $100\text{mm} \times 70\text{mm}$. A full list of components and cost of each is documented in Appendix D

Finally, the name “The Columbus” was decided on as the original application for the project was a mapping robot that would search out an unknown area, so the robot was named after Christopher Columbus who explored and navigated parts of the American continents which were unknown at the time. The Eagle CAD Diagram of the PCB can be seen in Appendix C. The PCB was manufactured by [Cart \(2013\)](#). The PCB cost £205 to manufacture and ship. A photo of the PCB can be seen in figure 3.11.

Considerations - Power consumption of devices not exceeding VReg

3.4.3 PCB Testing

A program was written to test all the devices on the PCB. The following tests are done and are explained in the subsequent sections:

[3.4.3.1](#) UART Send and Receive

[3.4.3.2](#) SD Card

[3.4.3.3](#) LEDs

[3.4.3.4](#) SDRAM

[3.4.3.5](#) I^2C

[3.4.3.6](#) Camera

[3.4.3.7](#) Motor

3.4.3.1 UART Test

When the test program begins, the microcontroller waits for a character input. All characters are echoed back. This enables the user to check the communications work. Once a carriage return key is received (D_{16}), the test program continues. Listing 3.1 shows the test code for the UART protocol.

Listing 3.1: UART Test Code

```
1 ///////////////////////////////////////////////////////////////////
2 // UART Test ///////////////////////////////////////////////////////////////////
3 ///////////////////////////////////////////////////////////////////
4 uint8_t ch;
5 while (true) {
6     ch = usart_getchar(DBG_USART); // get one input character
7     if (ch) {
8         print_dbg(ch); // echo to output
9     }
10    if(ch == 13)
11        break;
12 }
```

3.4.3.2 SD Card Test

The Atmel Software Framework ([Atmel Corporation, 2009](#)) provided drivers and code for SPI communications and use of a FAT32 File System. The code was configured to use the correct Chip Select pin for the SD Card and the correct SPI Bus. The test consists of initialising the memory, reading the capacity of the card and printing it to the user.

The AVR then proceeds to delete any previous log file, create a new log file and writes “*Columbus Tester*” to it. The first 8 characters, which should be “*Columbus*” are read back and checked.

Listing 3.2: UART Test Code

```

1 ///////////////////////////////////////////////////////////////////
2 // SD Card Test ///////////////////////////////////////////////////////////////////
3 ///////////////////////////////////////////////////////////////////
4 print_dbg("\n\n\rSD Card Memory Test:\n\r");
5 // Test if the memory is ready - using the control access memory abstraction
6 // layer (/SERVICES/MEMORY/CTRL_ACCESS/)
7 if (mem_test_unit_ready(LUN_ID_SD_MMC_SPI_MEM) == CTRL_GOOD)
8 {
9     // Get and display the capacity
10    mem_read_capacity(LUN_ID_SD_MMC_SPI_MEM, &VarTemp);
11    print_dbg("OK:\t");
12    //printf_ulong((VarTemp + 1) >> (20 - FS_SHIFT_B_TO_SECTOR));
13    i = ((VarTemp + 1) >> (20 - FS_SHIFT_B_TO_SECTOR));
14    print_dbg_ulong(i);
15    print_dbg("MB\r\n");
16    print_dbg("SD Card Okay.\n\r");
17 }
18 else
19 {
20     // Display an error message
21     print_dbg("Not initialized: Check if memory is ready... \r\n");
22 }
23 nav_reset();
24 // Use the last drive available as default.
25 nav_drive_set(nav_drive_nb() - 1);
26 // Mount it.
27 nav_partition_mount();
28 nav_filelist_reset();
29 if(nav_filelist_findname((FS_STRING)LOG_FILE, false))
30 {
31     print_dbg("\n\rLog File Already Exists\n\rAttempting to delete...");
32     nav_setcwd((FS_STRING)LOG_FILE, true, false);
33     nav_file_del(false);
34
35     if(nav_filelist_findname((FS_STRING)LOG_FILE, false))
36         print_dbg("\n\rLog File Still Exists...");
37     else
38         print_dbg("\n\rLog File Deleted!");
39 }
```

```

39     print_dbg("\n\rCreating Log File.");
40
41     if(nav_file_create((FS_STRING)LOG_FILE) == true)
42         print_dbg("\n\rSuccess!");
43     else
44         print_dbg("\n\rNot worked...");
45     print_dbg("\n\rWriting to log file.");
46     Log_Write("Columbus Tester:\n\r", 18);
47     nav_filelist_reset();
48     nav_setcwd((FS_STRING)LOG_FILE, true, false);
49     file_open(FOPEN_MODE_R); //Open File
50     file_read_buf(Buffer, 8);
51     noErrors = 0;
52     if(Buffer[0] != 'C')
53         noErrors++;
54     if(Buffer[1] != 'o')
55         noErrors++;
56     if(Buffer[2] != 'l')
57         noErrors++;
58     if(Buffer[3] != 'u')
59         noErrors++;
60     if(Buffer[4] != 'm')
61         noErrors++;
62     if(Buffer[5] != 'b')
63         noErrors++;
64     if(Buffer[6] != 'u')
65         noErrors++;
66     if(Buffer[7] != 's')
67         noErrors++;
68     file_close();
69     if(noErrors == 0)
70         print_dbg("\n\rSD Card Read Successful\n\r");
71     else
72         print_dbg("\n\rSD Card Read Fail\n\r");
73     noErrors = 0;

```

This exercises all basic File I/O functions, creating, reading and writing and checks them on the device.

3.4.3.3 LED Test

All LEDs are turned on for 1 second, and then turned off. The user should check this occurs. It verifies that all the LEDs are functional and correctly mounted. The Power LED should be on when power is supplied to the PCB.

3.4.3.4 SDRAM Test

The SDRAM test consists of initialising the SDRAM, calculating the SDRAM size, writing a unique test pattern to the whole memory, and then reading it back

and checking it. The total number of errors are reported.

The test was adapted from an example application from the ASF (Atmel Corporation, 2009). The code can be seen in listing 3.3. It consists of two *for* loops. In the first, the iteration number is assigned to the memory location. The second loop reads back the data and checks it is correct. An int, *noErrors*, is used to count errors.

Listing 3.3: SDRAM Test Code

```

1 ///////////////////////////////////////////////////////////////////
2 // SDRAM Test ///////////////////////////////////////////////////////////////////
3 ///////////////////////////////////////////////////////////////////
4 print_dbg("\n\n\rSDRAM Test:");
5 sdram_size = SDRAM_SIZE >> 2;
6 print_dbg("\n\rSDRAM size: ");
7 print_dbg_ulong(SDRAM_SIZE >> 20);
8 print_dbg(" MB\r\n");
9 // Determine the increment of SDRAM word address requiring an update of the
10 // printed progression status.
11 progress_inc = (sdram_size + 50) / 100;
12 // Fill the SDRAM with the test pattern.
13 for (i = 0, j = 0; i < sdram_size; i++)
14 {
15     if (i == j * progress_inc)
16     {
17         print_dbg("\rFilling SDRAM with test pattern:");
18         print_dbg_ulong(j++);
19         print_dbg("%");
20     }
21     sdram[i] = i;
22 }
23 print_dbg("\rSDRAM filled with test pattern      \r\n");
24 // Recover the test pattern from the SDRAM and verify it.
25 for (i = 0, j = 0; i < sdram_size; i++)
26 {
27     if (i == j * progress_inc)
28     {
29         print_dbg("\rRecovering test pattern from SDRAM: ");
30         print_dbg_ulong(j++);
31         print_dbg("%");
32     }
33     tmp = sdram[i];
34     if (tmp != i)//failed
35     {
36         noErrors++;
37     }
38 }
39 print_dbg("\rSDRAM tested: ");
40 print_dbg_ulong(noErrors);
41 print_dbg(" corrupted word(s)      \r\n");

```

3.4.3.5 I^2C Test

The I^2C test checks the bus for devices. It prints out a table showing the address of any devices that acknowledge a probe. A probe is a set up to write to the address. If a device exists on the line, it should acknowledge (Phillips, 2012). The test is done three times, with no channel selected on the I^2C MUX, with channel 0 selected and with channel 1 selected. The two addresses expected at 21_{16} for the OV7670 Camera and 74_{16} for the I^2C MUX. The camera should only acknowledge when the I^2C MUX has the relevant channel selected. Listing 3.4 shows the test code for the I^2C bus and listing 3.5 shows the result from the full bus scan with channel 0 selected. The cameras are both checked to exist.

Listing 3.4: I^2C Test Code

```

39     }
40 }
41 noErrors = 0;
42 //Check cameras exist
43 PCA9542A_Chан_Sel(I2C_CHANNEL_0);
44 if(twim_probe(TWIM, 0x21) != STATUS_OK)
45     print_dbg("\n\rCamera 0 Not Found;");
46 PCA9542A_Chан_Sel(I2C_CHANNEL_1);
47 if(twim_probe(TWIM, 0x21) != STATUS_OK)
48     print_dbg("\n\rCamera 1 Not Found;");

```

Listing 3.5: Result of I^2C bus scan with Channel 0 of the I^2C MUX selected

```

1 Scanning Channel 0
2 h 0 1 2 3 4 5 6 7 8 9 A B C D E F
3 0 - - - - - - - - - - - - - - - -
4 1 - - - - - - - - - - - - - - - -
5 2 - A - - - - - - - - - - - - - -
6 3 - - - - - - - - - - - - - - - -
7 4 - - - - - - - - - - - - - - - -
8 5 - - - - - - - - - - - - - - - -
9 6 - - - - - - - - - - - - - - - -
10 7 - - - - A - - - - - - - - - - -

```

3.4.3.6 Camera Test

This test consists of initialising both cameras and checking it passes. Two photos are then taken and stored to the SD card. Success or failure of the methods is sent to the debug terminal. Two images should exists on the SD card from the two cameras. Listing 3.6 shows the code to conduct this test.

Listing 3.6: Camera Test Code

```

1 ///////////////////////////////////////////////////////////////////
2 // Camera Test ///////////////////////////////////////////////////////////////////
3 ///////////////////////////////////////////////////////////////////
4 print_dbg("\n\rInitialising Cameras");
5 OV7670_Init();
6 FIFO_Reset(CAMERA_LEFT | CAMERA_RIGHT);
7 if(STATUS_OK == OV7670_Status.Error)
{
8     print_dbg("\n\rCamera Initialise Okay!");
9 }
10 else
11     print_dbg("\n\rCamara Initialise Fail.");
12
13 print_dbg("\n\rTaking Photos");
14 TakePhoto(CAMERA_LEFT | CAMERA_RIGHT);
15
16

```

```

17     while(Photos_Ready() == false)
18     ;
19
20     if(Store_Both_Images() == true)
21         print_dbg("\n\rImages Stored Successfully!");
22     else
23         print_dbg("\n\rImages Store Fail.");

```

3.4.3.7 Motor Driver Test

An extensive test of the motor driver is discussed in section 3.3.3. The test code in this application resets the motors so that they are aligned to a white tab on the wheel. This code can be seen in listing 3.7. The robot should move no further than 1cm to reach a white tab and the motors should drive forward. This test is useful here to ensure the motors are connected the correct way around and that the potentiometers are set to an appropriate level.

Listing 3.7: Motor Test Code

```

1 ///////////////////////////////////////////////////////////////////
2 // Motor Test ///////////////////////////////////////////////////////////////////
3 ///////////////////////////////////////////////////////////////////
4 print_dbg("\n\rMotor Testing:\n\rMotor Initialised");
5 Motor_Init();
6 Motors_Reset(); //reset the motors to test them
7 while(Motors_Moving() == true)
8     ;//wait for the motors to finish moving

```

3.4.4 PCB Faults

During the build and test of the PCB, a number of faults were found. Each is explained and the solution for the problem given.

3.4.4.1 TCRT1010 Footprint

The holes in the footprint for the optosensor were not large enough. This was a minor problem as the sensor was soldered in a surface mount style. This didn't affect the location of the sensor so had no other implications other than the connection being weaker than it should be.

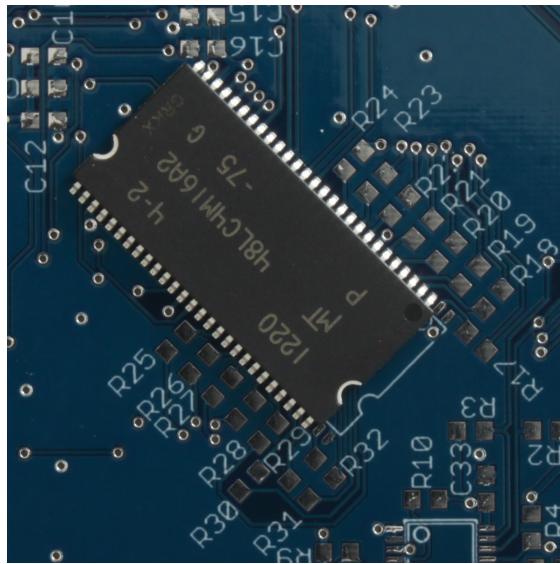


Figure 3.12: SDRAM Chip shown against its footprint.

3.4.4.2 SDRAM Footprint

The SDRAM footprint made was done exactly to the specification of the pad size and locations with no consideration for soldering. This meant the chip fits exactly on to the footprint and made soldering difficult as pads had to be preloaded with solder and the device's pins were heated and bound to the solder. It also put the device at risk as more heat had to be used than usually necessary. Figure 3.12 shows the SDRAM chip slightly offset against the footprint. It can be seen that there is no extra space on the pad to be able to easily solder the device. Though this made building difficult and increased soldering errors, it had no impact on the operation of the device.

To avoid this, existing footprints could be used from other libraries, or double checking the footprints made. The problem meant extra care during soldering had to be taken but has not impeded the operation of the device.

3.4.4.3 SDRAM Chip Select

The code was prototyped on the Atmel UC3C-EK development board prior to the PCB arriving. This used chip select 1 for the SDRAM and the PCB was designed using chip select 0. When the PCB was built, the code did not work. To diagnose this problem, the control lines of the SDRAM were probed with a logic analyser. On the UC3C-EK, the bus was busy with refresh cycles outside of SDRAM access. On the Columbus, no activity was seen.

The reason the correct control wasn't being seen was due to the UC3C device having a dedicated SDRAM controller, attached only to chip select line 1. Chip select 1 was available on an external pin, and the via on the CS0 and CS1 lines were close to each other. Therefore, to overcome the problem, a small enamelled wire was soldered to join the two vias together. This solved the problem and the correct signals were then seen on the control lines. The patch can be seen in figure 3.14(b).

This fault was caused by not reading the datasheet carefully and ignoring a proven circuit diagram. Operation of the device was not hindered and the fix was simple.

3.4.4.4 SDRAM Data Line Resistors

Once the chip select problem was solved, data returned was unreliable. The SDRAM is word (32 bit) addressed, but accessed in 16 bits. This means read cycles are done per word read. Upon investigation of this problem, the 14th, 15th, 30th and 31st (top two bits of each 16 bit access) seemed to read as a 1 the majority of the time. This result wasn't repeatable and sometimes returned correct data. The other bits of the data were always correct. Table 3.6 shows some examples of the problematic data bits. The data written should match the data read back.

Table 3.6: A table showing examples of the incorrect data returned from the SDRAM

Data Written	Data Read
00000000 00000000 00000000 00000000	11000000 00000000 11000000 00000000
00001111 00001111 00001111 00001111	11001111 00001111 11001111 00001111

The problem was traced to resistors **R31** and **R32**. They were soldered on incorrectly so that the two data lines of the SDRAM were connected together and the two AVR GPIO pins were connected together. Data was then read back from, effectively, a high impedance line and therefore varied. Once the resistors were soldered correctly, the issue no longer persisted and the whole SDRAM test passed. By utilising the soldermask more, device orientations could be added to ensure correct placement. This can be extended to other devices, such as diodes and capacitors, especially in densely populated areas.

3.4.4.5 Camera Interrupt Line

As discussed in section [3.1](#), the OV7670 needs an interrupt line to synchronise quickly to the start of the frame and is done by using an interrupt line. The UC3C0512C has 9 external interrupt lines. On the PCB, interrupt lines 0 and 1 were used for this control.

Interrupt line 1 was easily configured and worked as expected. However, interrupt 0 did not seem to trigger the interrupt service routine. It was found that interrupt 0 was a “Non Maskable Interrupt” which has specific uses and cannot be used in to trigger a method.

The external interrupt 4 pin was wired to Junction 8 on the PCB. A wire was attached to the camera’s VSYNC line and attached to the relevant pin on the header. The operation was then easily obtained and the VSYNC line triggered correctly.

This issues would have been avoided with more understanding of the device before hand and checking the datasheet. The patch can also be seen in figure [3.14\(b\)](#).

3.4.4.6 Motor Driver Pinout

An error was made in creating the device for the TB6593FNG Motor Driver in EAGLE. On the device, each motor output has two pins to drive each pin of the motor. The pin assignment was mixed up when created and connected the two outputs together. Figure [3.13](#) shows the track errors on one of the motor drivers.

To solve this, pins 7 and 14 were lifted and removed so that output 1 and output 2 were not connected together. The devices were not damaged in the process of testing this and the motors functioned correctly after this. Double checking the footprints made against the datasheet would have avoided this problem. No impact to the operation of the drivers has been seen, but the patch may hinder the devices ability to sink current to the motors.

3.4.5 PCB Conclusions

A number of faults were made in the PCB design. They are:

- TCRT1010 footprint

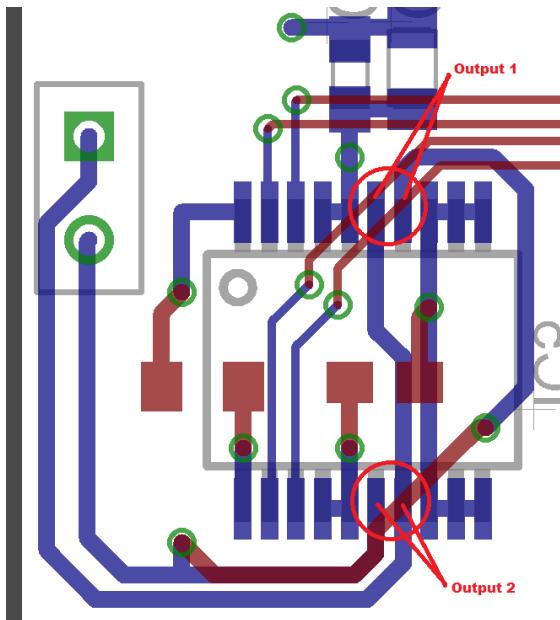


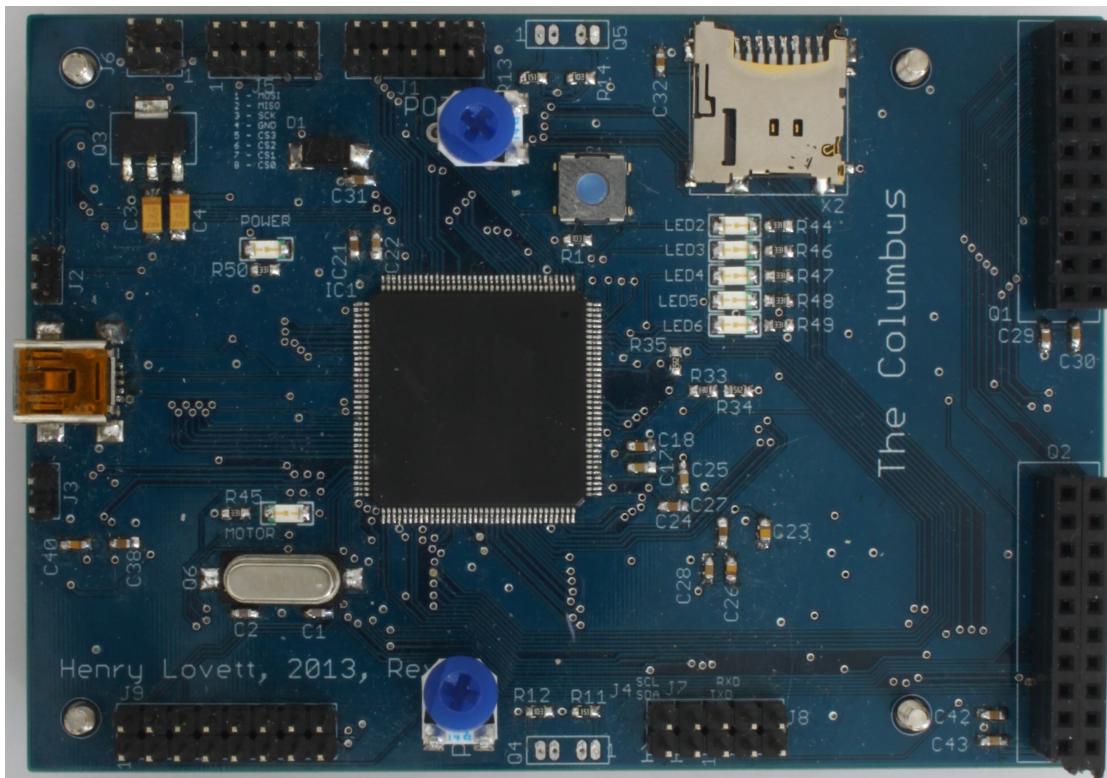
Figure 3.13: Motor Driver error. Outputs incorrectly connected

- SDRAM footprint
- SDRAM chip select line
- SDRAM data line resistors
- Camera interrupt line
- Motor driver pinout

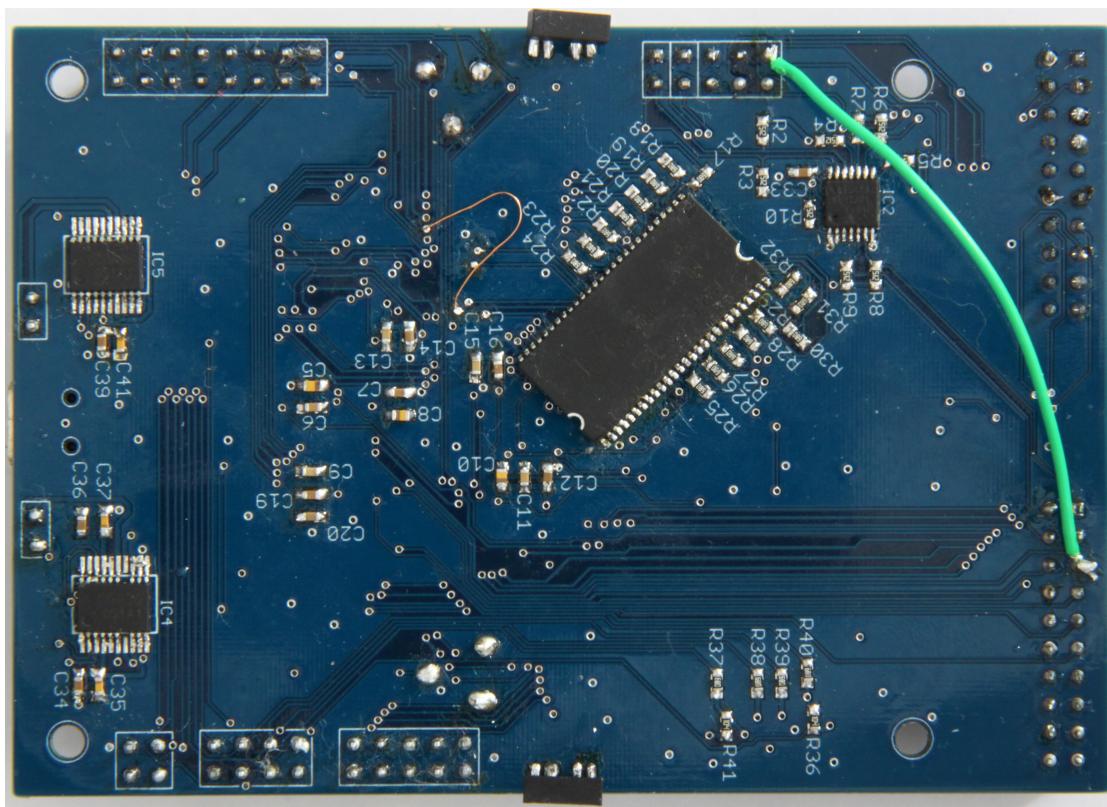
Three of the faults could have been avoided by consulting the datasheet more carefully during the circuit design stage. The footprint error was due to not being experienced in designing footprints and the data line resistors was a mistake due to lack of attention being paid.

For future PCBs, more care will be taken in circuit design, with prototyping of circuits with the hardware that will be used. This will highlight any pin specific operations (e.g. the non maskable interrupt) and reduce debugging post production. The effectiveness of a soldermask is also apparent, so more time spent on utilising this would be helpful during assembly.

The PCB itself, was a success. It was a complex PCB with many potential things that could have gone wrong. All devices are functional (with a few small modifications) on the PCB so firmware development could continue with all hardware able to be used.



(a) Top view of built PCB



(b) Bottom view of built PCB with SDRAM chip select patch

Figure 3.14: Pictures of the built PCB.

3.5 Conclusions

Overall, the hardware design and firmware is a success. A few minor faults were apparent on the PCB, but these were easily patched and caused no problem. Using a firmware test, the components are seen to be fully functional giving the UC3C full ability to control motors, cameras, I^2C multiplexer, memory of both SD card (up to 2GB size) and external 4MB RAM. This provides a good platform for a manoeuvrable, stereoscopic image robot to be developed.

Chapter 4

Investigation into Vision Algorithms

4.1 Matching Algorithms

In computer vision, there are many different ways of comparing two similar images. These include the sum of absolute differences (S.A.D.) ([Hamzah et al., 2010](#)), the sum of squared differences (S.S.D.)([Mrovlje and Vrančić, 2008](#)) and normalised cross correlation (N.C.C.)([Zhao et al., 2006](#)). Each of these methods will be explained and tested to compare them. All testing will use images seen in figure 4.1. Each test uses the same size window (50×50) to compare the two images.



(a) Left Image

(b) Right Image

Figure 4.1: Stereoscopic Test Images from MATLAB Examples

4.1.1 Sum of Absolute Differences

Given two identically sized two dimensional matrices, A, B , of dimensions I, J , SAD is defined as

$$SAD = \sum_{i=0}^{I-1} \sum_{j=0}^{J-1} |A[i, j] - B[i, j]| \quad (4.1)$$

This method subtracts the observed window from the expected. All differences are then added together. This algorithm is simple and requires a small amount of computation. The algorithm returns values where a small result means the two images are well matched.

4.1.2 Sum of Squared Differences

$$SSD = \sum_{i=0}^{I-1} \sum_{j=0}^{J-1} (A[i, j] - B[i, j])^2 \quad (4.2)$$

This is very similar to S.A.D. but adds more complexity by squaring each difference. This removes the ability of equally different but opposite differences cancelling each other out (grey to white of one pixel will cancel out a white to grey difference in the other with SAD). Again, a low result is a match in this case.

test effect of box size?

4.1.3 NCC

$$NCC = \frac{1}{n} \sum_{i,j} \frac{(A[i, j] - \bar{A})(B[i, j] - \bar{B})}{\sigma_A \cdot \sigma_B} \quad (4.3)$$

Where n is the number of pixels in A and B ,
 σ is the standard deviation of the image, and
 \bar{A} is the average pixel value.

NCC is very similar to cross correlation, but normalised to reduce the error if one image is brighter than the other. This is common in computer vision ([Tsai and Lin, 2003](#)) and cross correlation is often used in digital signal processing, so fast algorithms have been made to calculate this.

Unlike S.S.D. and S.A.D., the normalised cross correlation gives a high value for a match. The downside to this algorithm comes with the complexity of the equation as it contains division and the square root of a number in order to calculate the standard deviation. These operations are rarely implemented in hardware and are time consuming to carry out in software. They also require floating point registers and operate slowly on a microcontroller without any.

4.1.4 Comparison

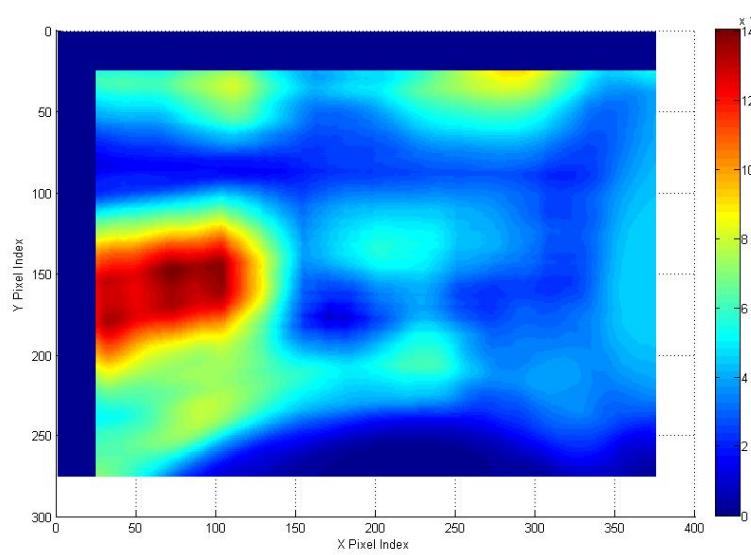
To compare these equations, a 50 by 50 window taken from the right picture was compared with the left image over the entire valid range. The coordinates on the graph give the centre pixel of the calculation.

Each graph shows the correct area being identified as a match, but this also highlights the downfalls of the SAD and SSD. The figures in figure 4.2 are rotated to match the orientation of the images in figure 4.1. Each of the images is tested by attempting to match the desk phone from the right image to the entirety of the left image. The actual match should be around (170, 176). An exact result cannot be estimated as the images are not matched perfectly - there isn't an exact integer of pixel difference between the images. This is the sub pixel problem ([Haller and Nedevschi, 2012](#)).

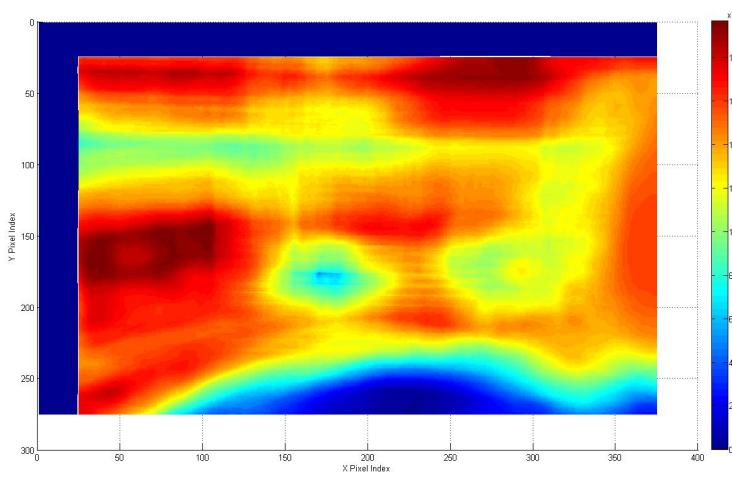
SAD results in figure 4.2(a) show large areas of matching. A minimum occurs around the location expected(170, 175) of a value of 5.66×10^4 . However, along the bottom of the image, where a dark area occurs below the desk in the lower part of figures 4.1, the SAD algorithm detects a greater comparison, with the lowest value in this area being 3370 at (227, 275). This creates a false detection here.

SSD, figure 4.2(b), shows matches in the same two areas: where a match should occur and the dark area beneath the desk. The minimum value where the match should occur is 4.355×10^5 at location (170, 176). However, there is a large match correlation between the dark area under the desk where the actual lowest value of 2.768×10^4 occurs at (225, 274). This, again, is a false match and is a downfall of this algorithm.

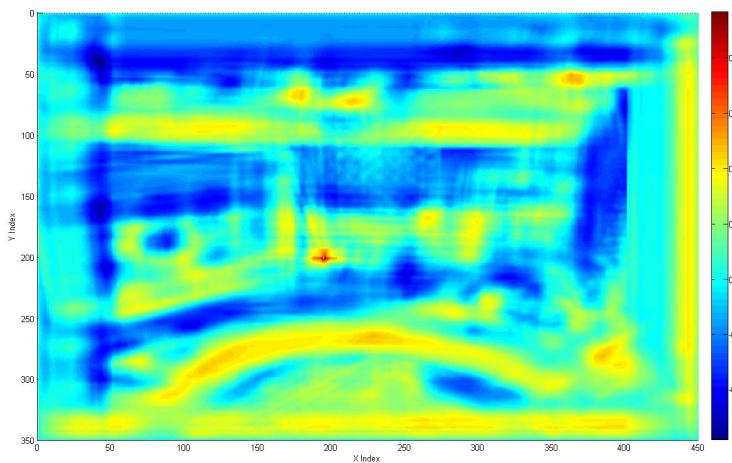
The NCC results are visible in figure 4.2(c). A match can be seen at coordinate (195, 201) with a peak value of 0.9654. The coordinate is different to the previous results because the cross correlation works over the boundary of the image creating more results. The dimensions of the image are 300×400 , but the NCC returns



(a) S.A.D. Results (Low match)



(b) S.S.D. Results (Low match)



(c) N.C.C. Results (High match)

Figure 4.2: Result Graphs of Comparison Algorithms

an data set of dimensions 350×450 when using a window size of 50×50 . To get the actual match, half of the box size must be subtracted from the returned coordinate. This means the match occurs at $(170, 176)$. With this algorithm, there is no area of the image which is close to a false detection.

4.1.5 Conclusion

It can be seen that there is a direct correlation between the complexity of the matching algorithm to the reliability of the match returned. In brightly lit, colourful environments absent of dark colours, SAD and SSD should provide a reliable result, but this cannot be guaranteed to always be the case. Therefore further development of the matching algorithm will start with using the normalised cross correlation. A comprise between complexity and reliability needs to be reached, where reliability is the more desirable of the two. Cross correlation is also a large area of research, so optimised algorithms do exist.

4.2 Range Finding

4.2.1 Derivations

By using two images separated by a horizontal distance, B , the range of an object can be found given some characteristics of the camera. Appendix G contains the derivations for the follow scenarios:

1. Object is between the cameras (Figure G.1)
2. Object is in left or right hand sides of both images (Figure G.2)
3. Object is directly in front of a camera (Figure G.3)

4.2.2 Summary

There are three situations that can occur. These are listed below with their equations.

L (mm)	D (mm)	φ^c
70	104	0.6435
90	135	0.6015
178	285	0.6054
214	345	0.6493
Average		0.6249

Table 4.1: Table of results to calculate the field of view of the camera

Object is between the two cameras:

$$D = \frac{Bx_0}{2 \tan\left(\frac{\varphi_0}{2}\right)(x_1 - x_2)} \quad (4.4)$$

Object is to the same side in both images:

$$D = B \cdot \frac{\cos(\varphi_2) \cdot \cos(\varphi_1)}{\sin(\varphi_2 - \varphi_1)} \quad (4.5)$$

Object is directly in front of a camera:

$$D = B \tan\left(\frac{\pi}{2} - \varphi_2\right) \quad (4.6)$$

Where φ_1 is defined in equation (4.7) and φ_2 is defined in equation (4.8).

$$\varphi_1 = \arctan\left(\frac{2x_1}{x_0} \tan\left(\frac{\varphi_0}{2}\right)\right) \quad (4.7)$$

$$\varphi_2 = \arctan\left(\frac{2x_2}{x_0} \tan\left(\frac{\varphi_0}{2}\right)\right) \quad (4.8)$$

When the images have been matched, these equations can be used to calculate the range to an object.

4.2.3 Field of View

The field of view is an important characteristic to calculate distances and must be measured for the camera. Field of view was measured by placing a ruler at a distance in front of the camera and measuring the total distance seen across the image. Basic trigonometry then found the field of view. This was done multiple times to confirm the measurement. Results can be seen in table 4.1. The field of view used is the average of the data set.

Figure 4.3: Stereo pair of images of a rubber duck on a reel of solder



Figure to show this?

4.2.4 Example

A stereo pair of images were taken from the built robot and can be seen in figure 4.3. A template image of the duck's head, at (108, 103) from the right image was cross correlated with the left image and the result can be seen in figure 4.4. A peak is seen at (269, 180). Using equation (4.4), where $B = 45\text{mm}$, $\varphi_0 = 0.6249^\circ$, $x_0 = 320$ and x_1 and x_2 are from the matched and chosen x coordinates respectively:

$$D = \frac{45 \times 320}{2 \tan\left(\frac{0.6249}{2}\right) (269 - 108)} = 341\text{mm} \quad (4.9)$$

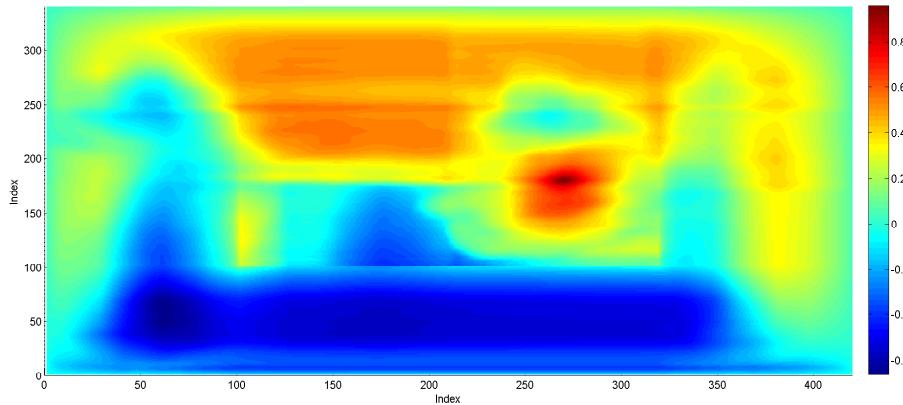
The actual measurement from the front of the duck to the base of the camera was set up to be 300mm. The error could be due to low resolution, incorrect matching, or error in the field of view measurement, but overall, given the small distance between the cameras and low resolution, the result is reasonably accurate.

do more distances!!!

4.2.5 Conclusions

Extensive testing of the effect of separation of the cameras has been done before (Mrovlje and Vrančić, 2008). The robot was designed to be small, but some accuracy still remained.

Figure 4.4: NCC results from matching using the ducks head from the right image as the template to the left image



Finish

4.3 Fourier Transform

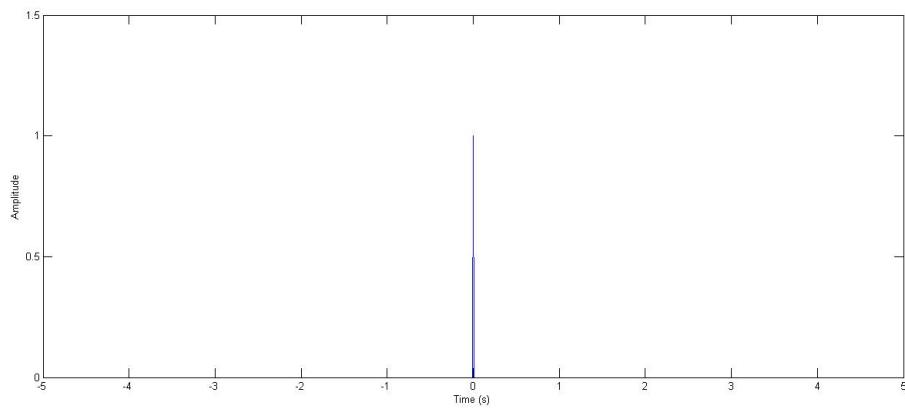
4.3.1 Background Research and the FFT

The Fourier transform is a common tool in signal processing. It transforms a time based signal to the frequency domain showing the frequency components contained in the signal as a complex number. This is often displayed as magnitude and phase. The Fourier Transform is defined in equation (4.10) and two examples of signals and their Fourier Transforms are shown in figures 4.5 and 4.6.

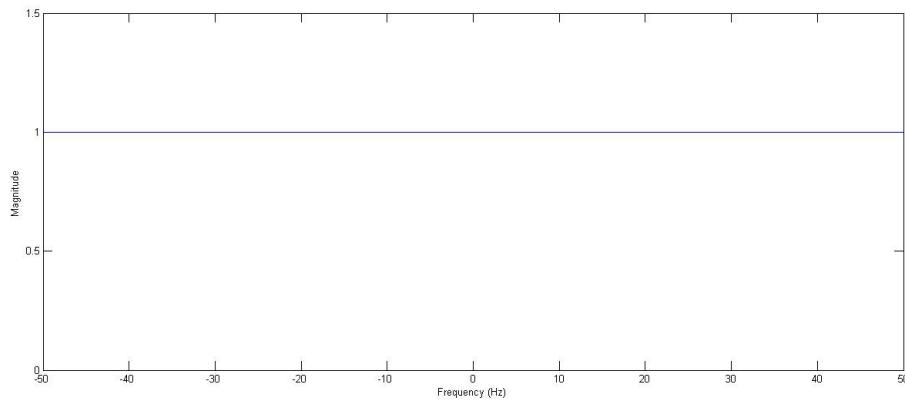
$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft} dt \quad (4.10)$$

The Fourier transform is used in many areas of signal processing. It is used for filter design, system analysis and image processing as well as many others. It shows the frequency components of a time domain signal.

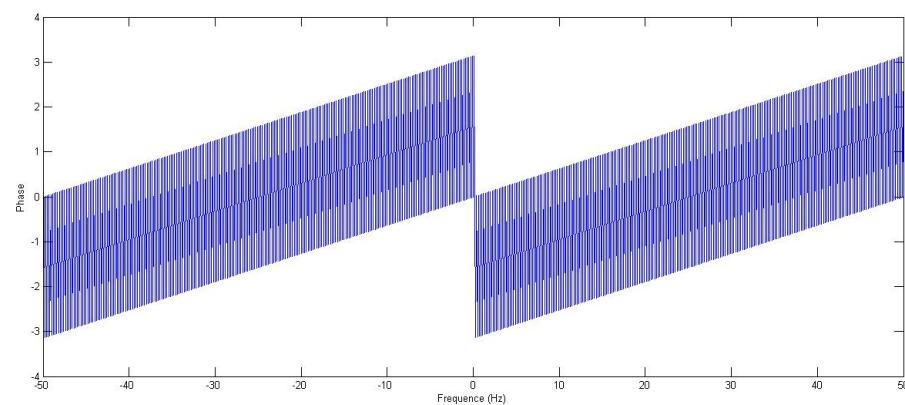
The equation for the Fourier transform in equation (4.10) is for continuous time. A discrete Fourier transform (DFT) exists for finite, equally spaced samples. This is commonly used in digital systems and is defined in equation (4.11). There exists a Fast Fourier Transform (FFT) which gives exactly the same results as the DFT,



(a) A graph showing a Dirac Function

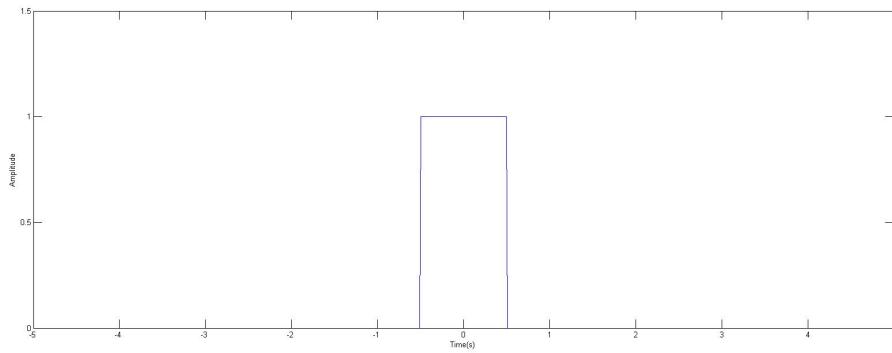


(b) A graph showing the magnitude of the Fourier transform of the Dirac Function

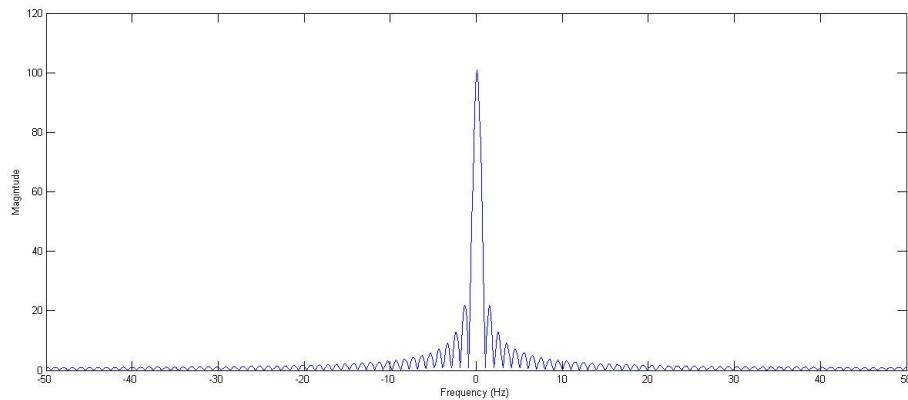


(c) A graph showing the phase of the Fourier transform of the Dirac Function

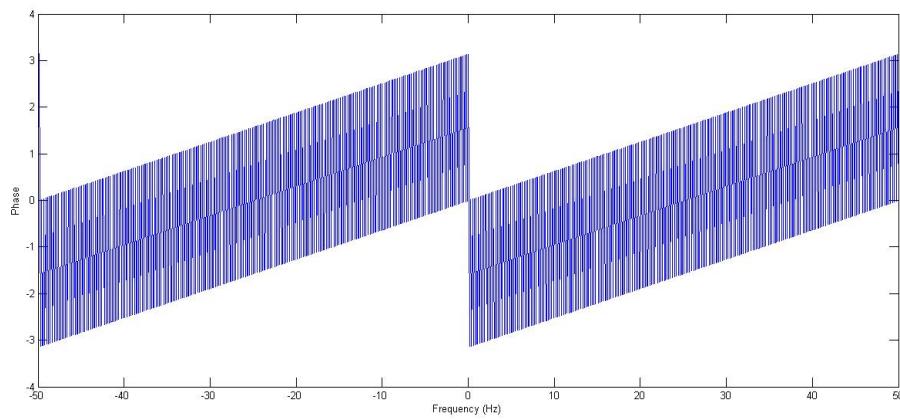
Figure 4.5: A Dirac signal and the phase and magnitude of its Fourier Transform



(a) A graph showing rectangular pulse



(b) A graph showing the magnitude of the Fourier transform of the rectangular pulse



(c) A graph showing the phase of the Fourier transform of the rectangular pulse

Figure 4.6: A 2D Rectangular pulse and the phase and magnitude of its Fourier Transform

but is optimised in terms of number of multiplications done. The FFT will be used in implementation due to availability of code and speed of use.

$$X[k] = \sum_0^{N-1} x[n]e^{-j\Omega_0 kn} \quad (4.11)$$

Where Ω_0 is the sample frequency

A property of the Fourier Transform of interest is the convolution theorem which states that convolution in time is multiplication in frequency and is defined mathematically in equation (4.12). As discussed in section 4.1.3, cross correlation is very similar to convolution. Cross correlation is defined in equation (4.13). With images, $f(t)$ is a real signal, its conjugate is exactly the same, $f(t) \equiv f^*(t)$ given that $f(t) \in \Re$. This means that to compute a cross correlation, the Fourier transform of the image and the template can be used and multiplied together. FFTs are quick and widely available so this should make the implementation more simple and fast.

$$\int_{-\infty}^{\infty} f(\tau)g(t - \tau)d\tau = f(t) * g(t) = X(f) \cdot Y(f) \quad (4.12)$$

$$\int_{-\infty}^{\infty} f^*(\tau)g(t + \tau)d\tau = f(t) \star g(t) = X(f) \cdot Y(f) \quad (4.13)$$

$$f(t) \star g(t) = f(t) * g(-t) = F(f) \cdot G(-f) \quad (4.14)$$

4.3.2 Two Dimensional Fast Fourier Transform

A two dimensional Fourier transform exists for analysing two dimensional signals, namely in this application, an image. The Fourier Transform is shown in equation (4.15) and the discrete version is shown in (4.16)

$$F(u, v) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y)e^{-2\pi j(xu+yv)} dx dy \quad (4.15)$$

$$F(u, v) = \frac{1}{N} \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} f(x, y) e^{-\frac{2\pi j(xu+yv)}{N}} \quad x, y, u, v \in \{0 \dots N-1\} \quad (4.16)$$

Figures 4.7 and 4.8 show the two dimensional equivalent test signals of figures 4.5(a) and 4.6(a) and the phase and magnitudes of their Fourier Transforms. There is a direct similarity between the 1D and 2D spectra; the magnitudes of the Dirac (figures 4.5(b) and 4.7(b)) are both constant values and the rectangular pulses both have a modulus sinc function magnitude (figures 4.6(a) and 4.8(a)).

The 2D Fourier transform can also be optimised to a fast Fourier transform algorithm in a similar way as the 1D case. The algorithm, sometimes referred to as the Butterfly transform, is briefly discussed in Nixon and Aguado (2012) where it is explained that the algorithm can be easily applied to images with equal dimensions that are a power of 2. The algorithm utilises the separability property of the Fourier transform.

The 2D FFT can be implemented using a 1D FFT as follows:

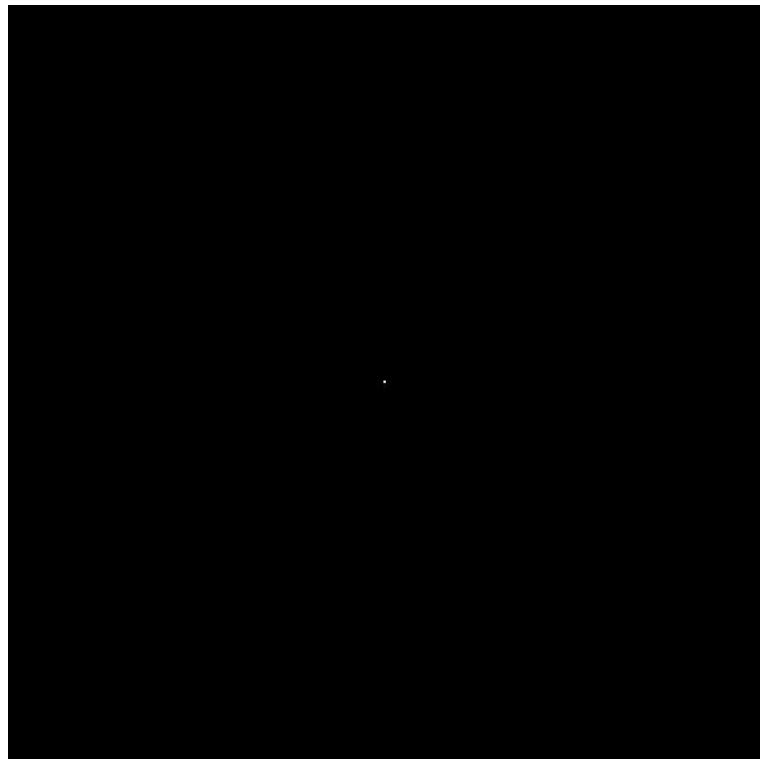
1. Calculate the 1D FFT of each of the rows of the 2D data. (An FFT of data of length n returns an array, also of length n)
2. Calculate the 1D FFT of each of the columns of the 2D data returned from the previous step.

Total number of FFTs done is $2n$ where n is the height/width of the image.

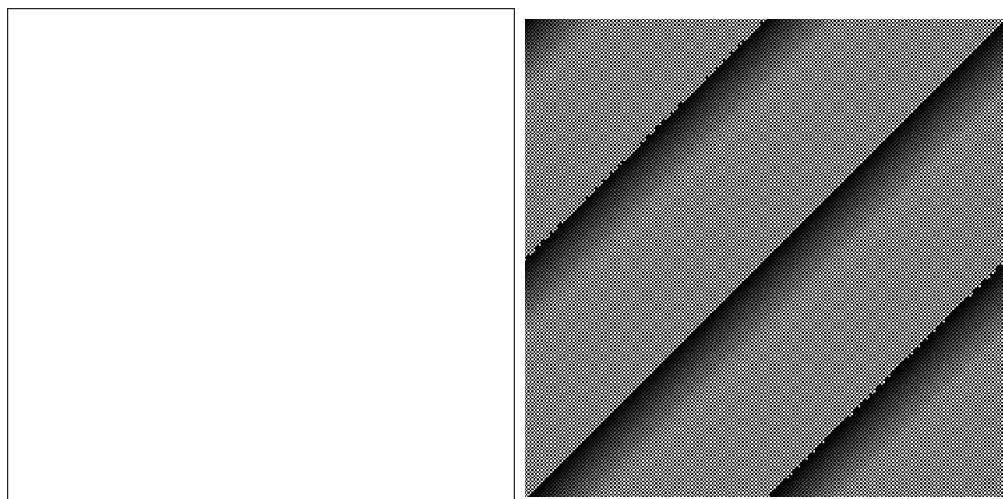
Maybe make a figure to help explain?

4.3.3 Implementing the FFT

The Atmel Software Framework ([Atmel Corporation, 2009](#)) included a digital signal processing library. This contained functions to compute the FFT of a real or complex array, the inverse FFT, magnitude and phase of complex data. Further restrictions are imposed by the DSP library used as the data must be an even power of 2, and that the data is in fixed point notation. This gives a usable dimension of 256×256 for processing images on the AVR. Though the height of an image from the OV7670 camera is 240 pixels, the image can be transformed so that it repeats for 16 rows at the bottom as the Fourier transform works on an assumption of the data being periodic.

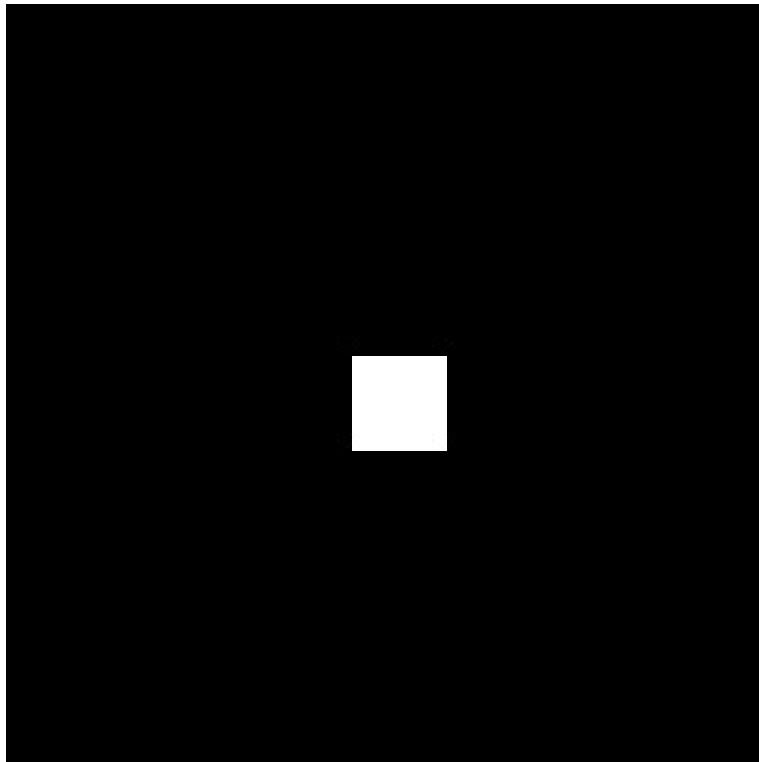


(a) An image of a 2D Dirac Function

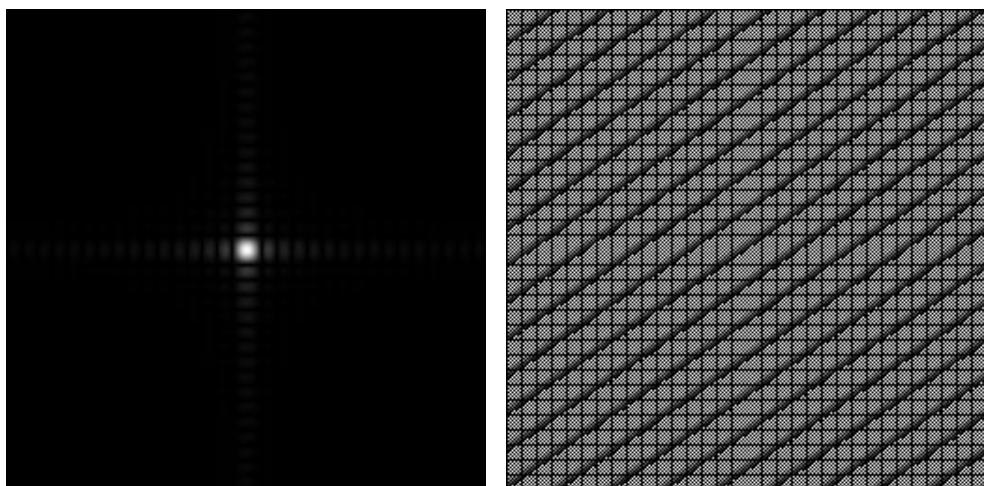


(b) An image of the magnitude of the Fourier transform of the 2D Dirac Function (c) An image of the phase of the Fourier transform of the 2D Dirac Function

Figure 4.7: A 2D Dirac signal and the phase and magnitude of its Fourier Transform



(a) An image of the 2D rectangular pulse



(b) An image of the magnitude of the Fourier transform of the 2D rectangular pulse

(c) An image of the phase of the Fourier transform of the 2D rectangular pulse

Figure 4.8: A 2D Rectangular Pulse signal and the phase and magnitude of its Fourier transform

The function *FFT2DCOMPLEX* in Appendix H.1.1.5 is the realisation of a two dimensional fast Fourier transform on the microcontroller. The FFT function requires the data to be 4 byte aligned (A_ALIGNED) and of type *dsp16_complex_t*. The data must be given in fixed point notation and it is returned in fixed point notation. A 16 bit representation was chosen over 32 bit due to being more functions for 16 bit data available.

4.3.4 Testing of the FFT on AVR

4.3.4.1 1D FFT Test

A Dirac function and a rectangular pulse were used as test signals.

Figure 4.9 shows the input signal given to the AVR. It is a 256 long array of a Dirac function. This was then converted to the internally defined fixed point notation and passed through the Fourier transform method. The resulting complex array was then saved to a Comma Separated Value file and read into MATLAB. Figure 4.10 shows the calculated phase and magnitude plots of the output complex array. The magnitude is relatively flat and around the value of 1. In comparison with figure 4.5(b), they are relatively similar. The phase, however, seems to be very different. Figure 4.5(c) shows what was expected, but the two phase results seem not to match. This could be due to MATLAB having more accurate algorithms and a more accurate representation than the 16 bit fixed point used on the AVR. However, using a function in the DSP library to calculate the magnitude, the spectrum in figure 4.11 is obtained. This, though not exactly 1 as expected, is completely flat. It is computed from the same transformed data. It suggests that there is some internal compensation in the algorithms. The actual value in figure 4.11 is 0.9897 to 4 decimal places giving an overall error of 1.03%.

Figures 4.12, 4.13 and 4.14 show the similar outputs from the AVR when transforming the rectangular pulse. The result was renormalised from fixed point notation and the data was shifted so that the centre of the plot is frequency 0. Again, it can be seen the magnitude calculated from the complex output (figure 4.13) is different to the result when the magnitude is calculated on the AVR (figure 4.14). There are also differences in the result from the AVR and the result from MATLAB in figure 4.6, which can, again, be put down to the algorithms.

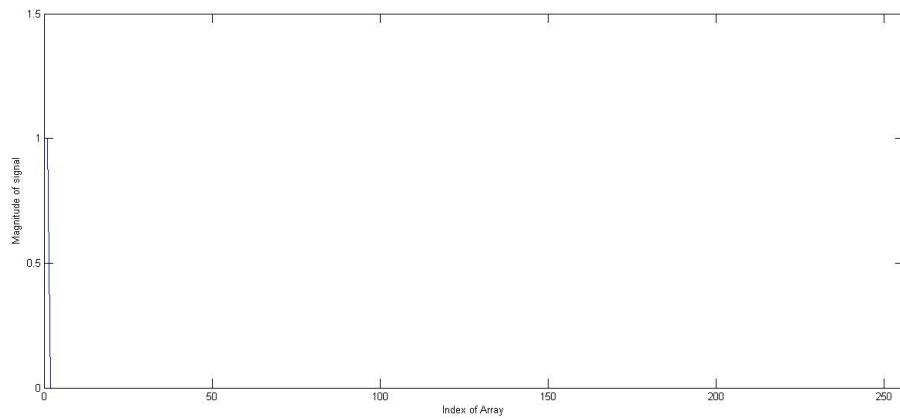


Figure 4.9: Input Dirac Signal for AVR fast Fourier transform

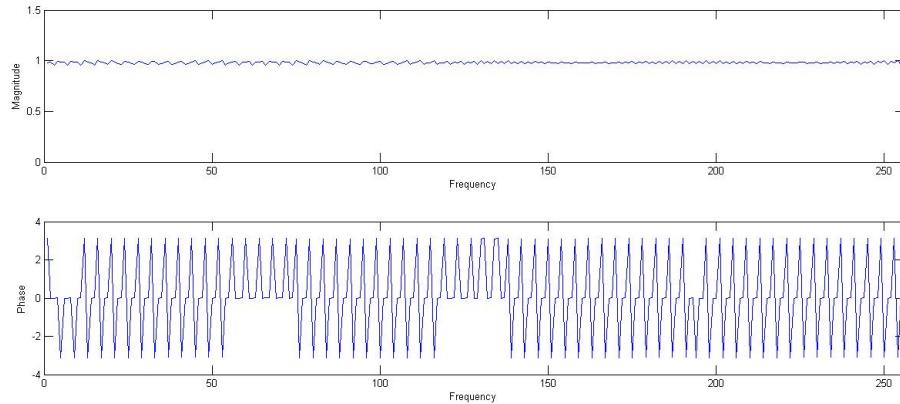


Figure 4.10: Output phase and magnitude of the complex output from AVR fast Fourier transform of a Dirac function

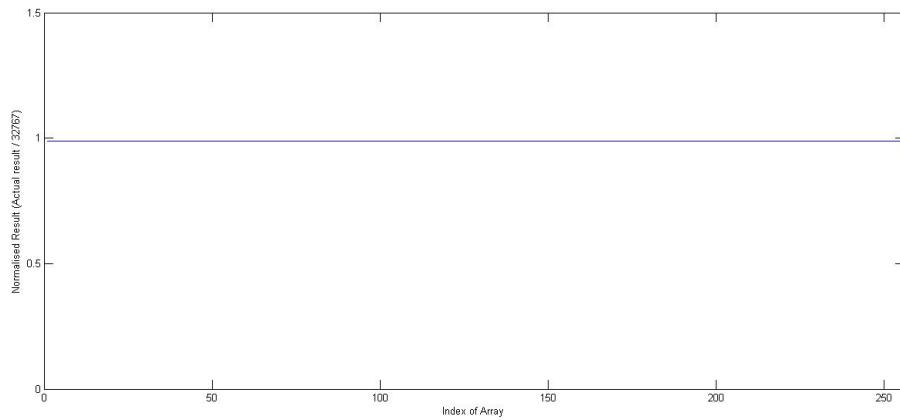


Figure 4.11: Maginitude calculated by the AVR of the Fourier transform of a Dirac function

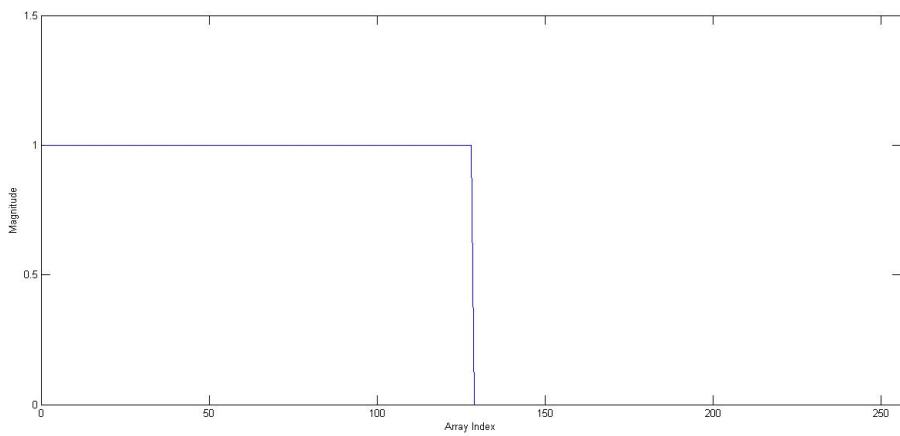


Figure 4.12: Input Rectangular Pulse for AVR fast Fourier transform

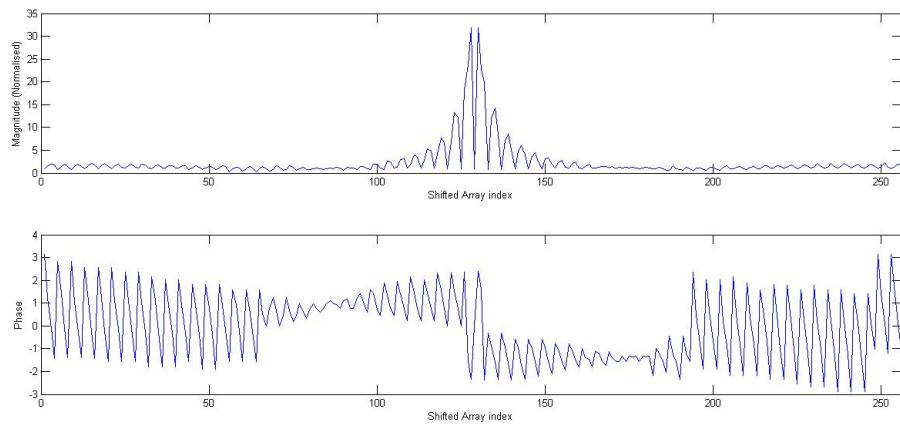


Figure 4.13: Output phase and magnitude of the complex output from AVR fast Fourier transform of a Rectangular Pulse

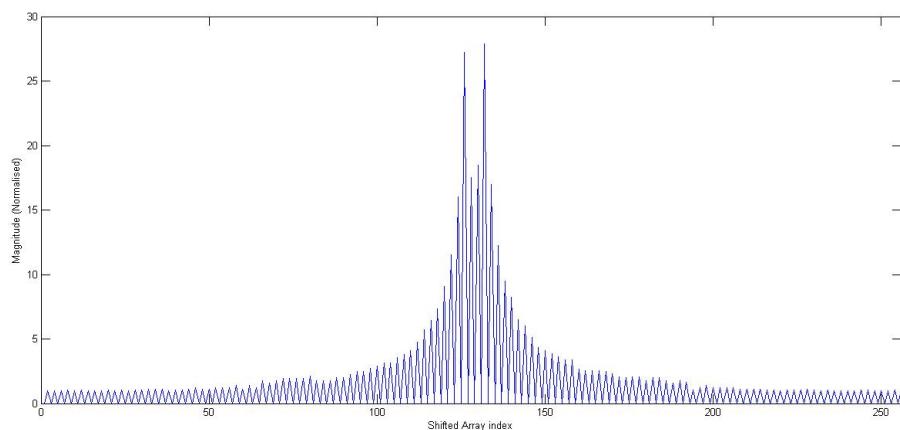


Figure 4.14: Maginitude calculated by the AVR of the Fourier transform of a Rectangular Pulse

Table 4.2: Number of clock cycles taken to calculate the Transform of 64 or 256 long data set

Size of FFT Data		
	64	256
1D	5019	23599
2D	618168	-

4.3.4.2 2D FFT Test

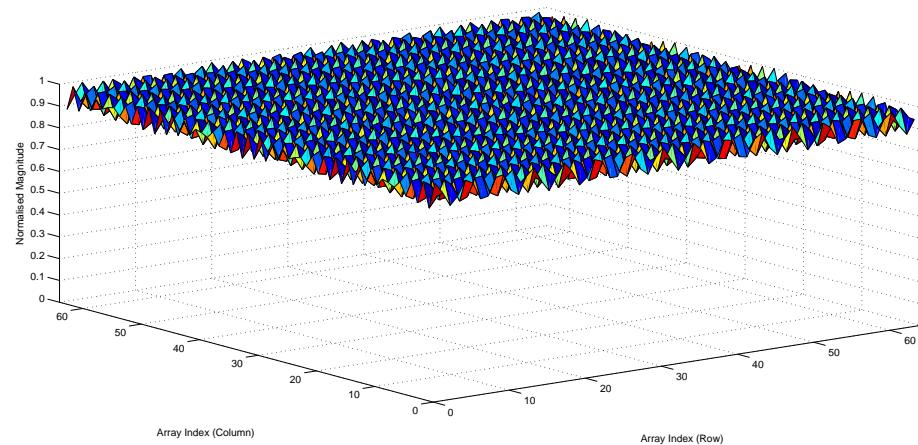
Two test signals were used to test the 2D FFT on the AVR, a Dirac signal and a square wave, seen in figures 4.7(a) and 4.8(a). The internal method on the AVR was not able to compute the magnitude due to the method scaling all the values down causing truncation errors. The complex Fourier transform was obtained, saved to the SD card in CSV format and viewed in MATLAB. All data was normalised to omit the effects of scaling and the data shifted so that frequency 0 is in the centre. These test were done with a 64×64 2D data as with a 256×256 array, the AVR runs out of internal RAM to calculate the transform.

I would like to get this to work by the end but not vital.

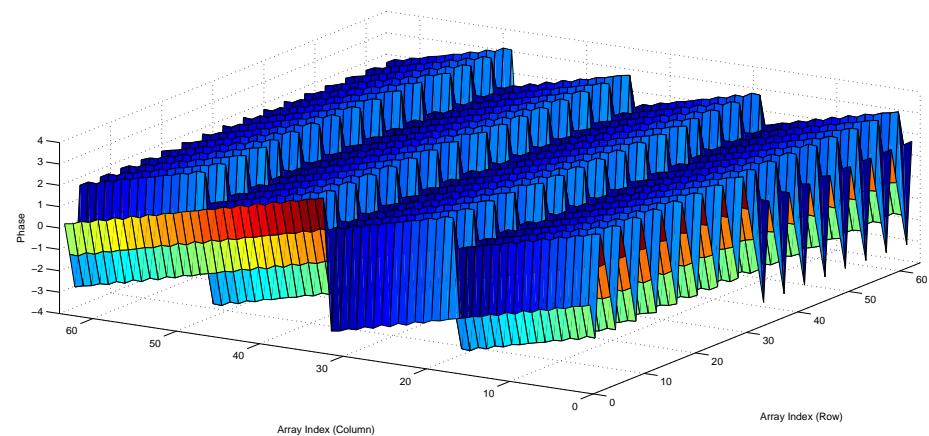
The result of the Dirac test is seen in figure 4.15. A similar error is found in the magnitude, but the spectrum is generally flat with a small amount of ripple as seen with the 1D FFT in figure 4.11. The phase has similar issues as with the 1D FFT. However, there appears to be the correct pattern with the 2D phase, but rotated about 45° . This is also the case with the square wave test. The magnitude in figure 4.16(a) is very similar, with a distinct peak in the centre (frequency 0) and a sinc function extending vertically and horizontally from this. Again, however, the phase (figure 4.16(b)) seems to differ a lot from the expected result in figure 4.8(c).

The transforms are calculated in real time with a 16MHz clock source. Table 4.2 shows the number of clock cycles taken to calculate the relevant sized transform. A 64×64 transform takes 39ms to compute with a 16MHz clock. This could be reduced by increasing the internal clock speed by using the PLLs available on the AVR, potentially taking it up to 33MHz and therefore halving the time to compute. A 64×64 image, however, is not practical for the application and

Show results of actual photo being transformed, need 2D 256 FFT working before



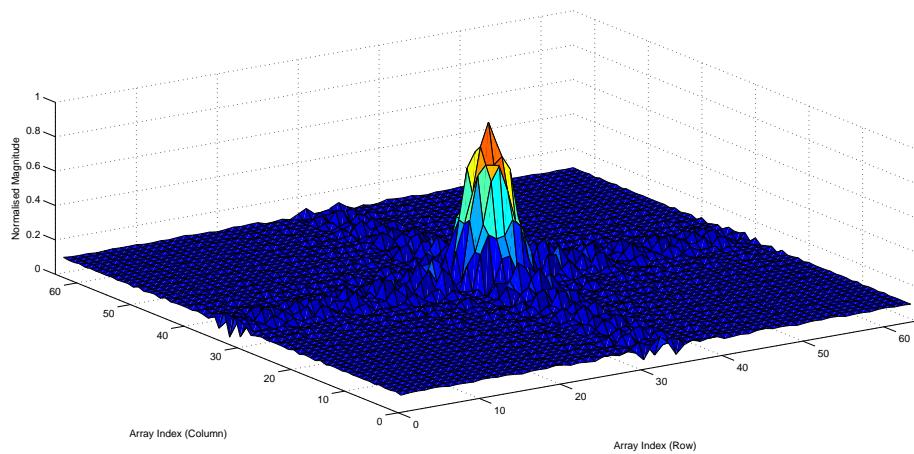
(a) A 3D Plot of the normalised magnitude of the complex data returned by the 2D fast Fourier Transform on the AVR



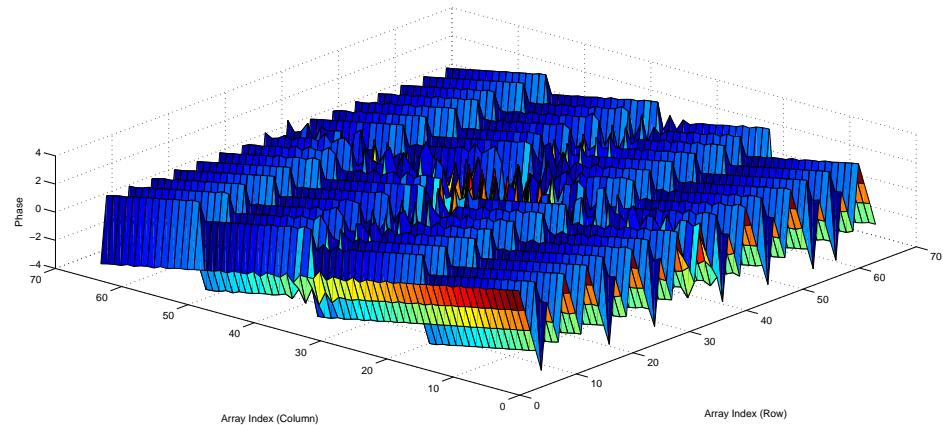
(b) A 3D Plot of the phase of the complex data returned by the 2D fast Fourier Transform on the AVR

Figure 4.15: 3D Plots of the phase and magnitude of the Complex Data returned from the 2D FFT on the AVR of a 2D Dirac Function

Maybe IFFT it too to find total errors in algorithm?



(a) A 3D Plot of the normalised magnitude of the complex data returned by the 2D fast Fourier Transform on the AVR



(b) A 3D Plot of the phase of the complex data returned by the 2D fast Fourier Transform on the AVR

Figure 4.16: 3D Plots of the phase and magnitude of the Complex Data returned from the 2D FFT on the AVR of a 2D Square Function

Chapter 5

Conclusions and Further Work

This work has led to a tested device which is mobile and has the capability to perform stereoscopic image processing. The system has the following parts:

1. Motor driving
2. Stereoscopic Cameras
3. SD Card memory
4. SRAM
5. Image Processing

The motor system is a simple, cheap method to move distances with reasonable accuracy. A better controller would allow variable speed and speed matching between motors. The system was shown to work to 4.5% accuracy over a 300mm distance.

A full image can be read from a camera and stored on an SD card in a FAT32 file system. This gives the ability of removable memory that can be viewed on a computer to see any internal logs. Images are stored in QVGA format (320 by 240 pixels) as a bitmap image.

An additional 4MB of SRAM memory is available to use on the robot allowing for large data arrays of the images to be kept in fast access RAM. The RAM is direct memory accessed so operation is almost seamless from internal memory.

Multiple comparison algorithms have been investigated and compared using the same test images. It was clear that, although at a necessity of more computations, the normalised cross correlation is the best with regard to overall reliability.

The Fourier transform was also investigated and implemented. The system allows for a 2×2 array of a square image with dimensions of 2^{2n} where $n \in \mathbb{N}$ and is limited by RAM space and time. The transform is speed optimised and in tests proved to be fairly accurate.

Range finding equations were then derived, which use the characteristics of the camera and the separation distance between them.

All aspects implemented on the robot have been shown to be functional. A faster processor would have been a good idea to use for image processing, but this could have developed other problems with the PCB. The Raspberry Pi or Steve Gunn's '*L'Imperatrice*', which both run a Linux operating system, would have been a good choice to remove the need for as much hardware design and existing image processing libraries could have been utilised to gain more functionality in the time.

Though the robots original application wasn't achieved, the end device is a base for a stereoscopic application. The system is a tested platform for future applications to be implemented on and additions can be made using the spare pins and bus connections on the PCB headers.

The system could be used in future projects to develop more functionality. Wireless communications could be added to the system to allow a connection to the computer and search algorithms can be implemented alongside distance calculations to make the robot aware of its surroundings.

Appendix A

Gantt Chart

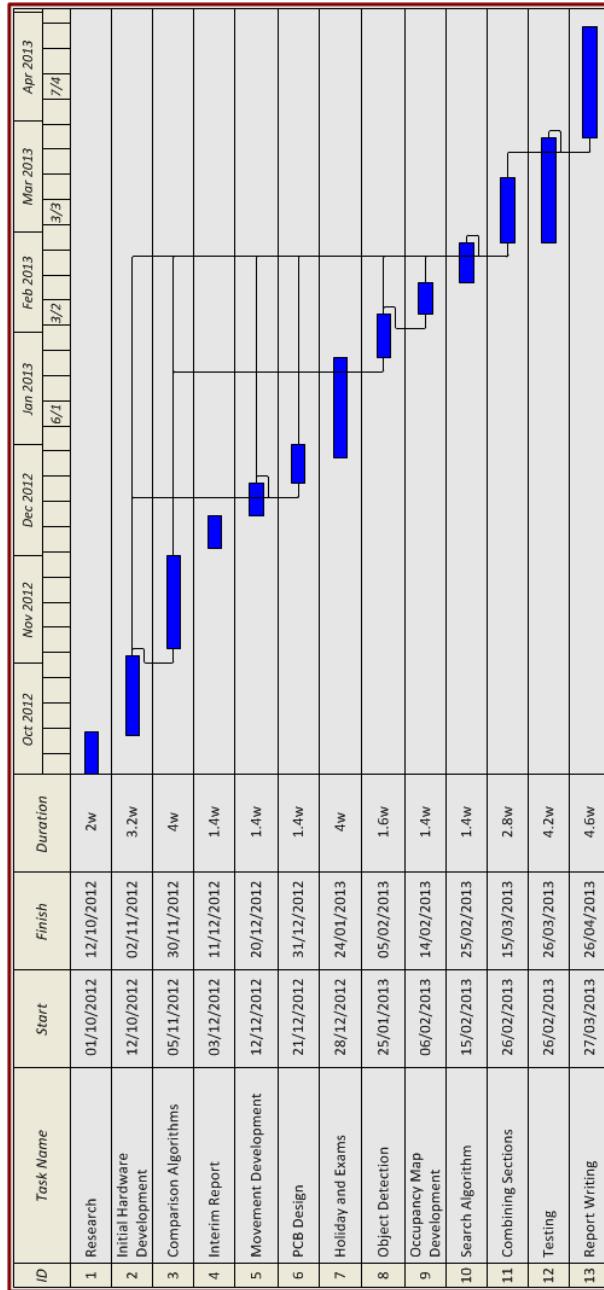


Figure A.1: Gantt Chart of how time will be spent in the areas of the project

Appendix B

Circuit Diagrams

B.1 OV7670 Breakout Board Schematic

B.2 Il Matto and Dual Camera Schematic

B.3 The Columbus Circuit Diagram

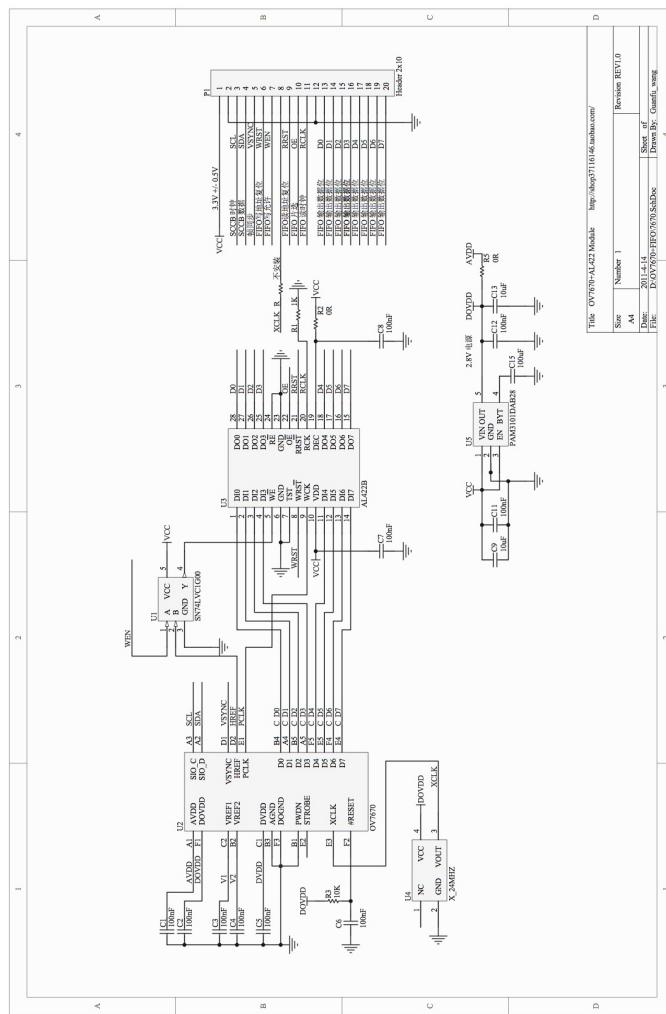


Figure B.1: The circuit diagram for the OV7670 breakout board

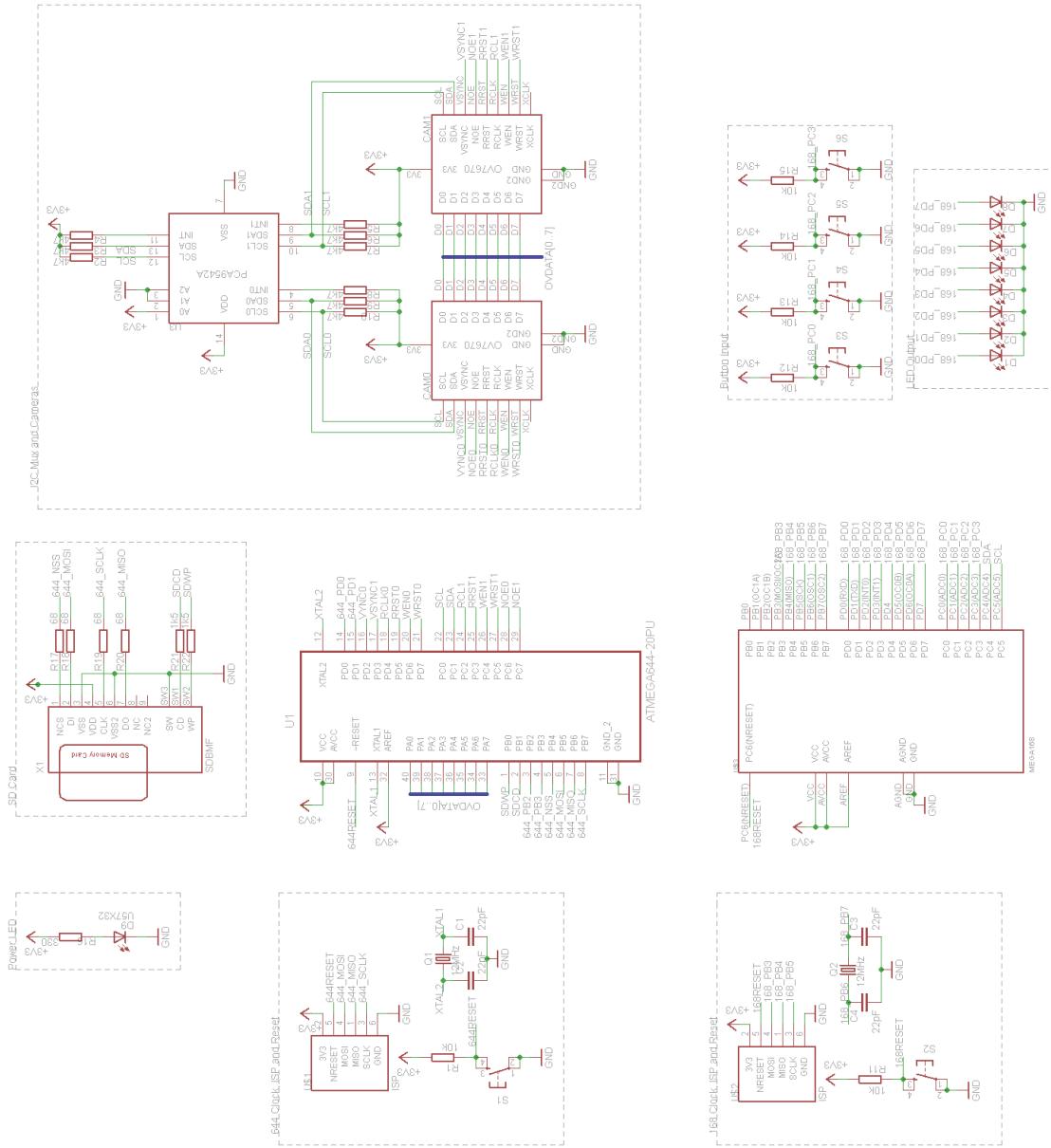


Figure B.2: The circuit diagram for Dual Cameras using the Il Matto Board

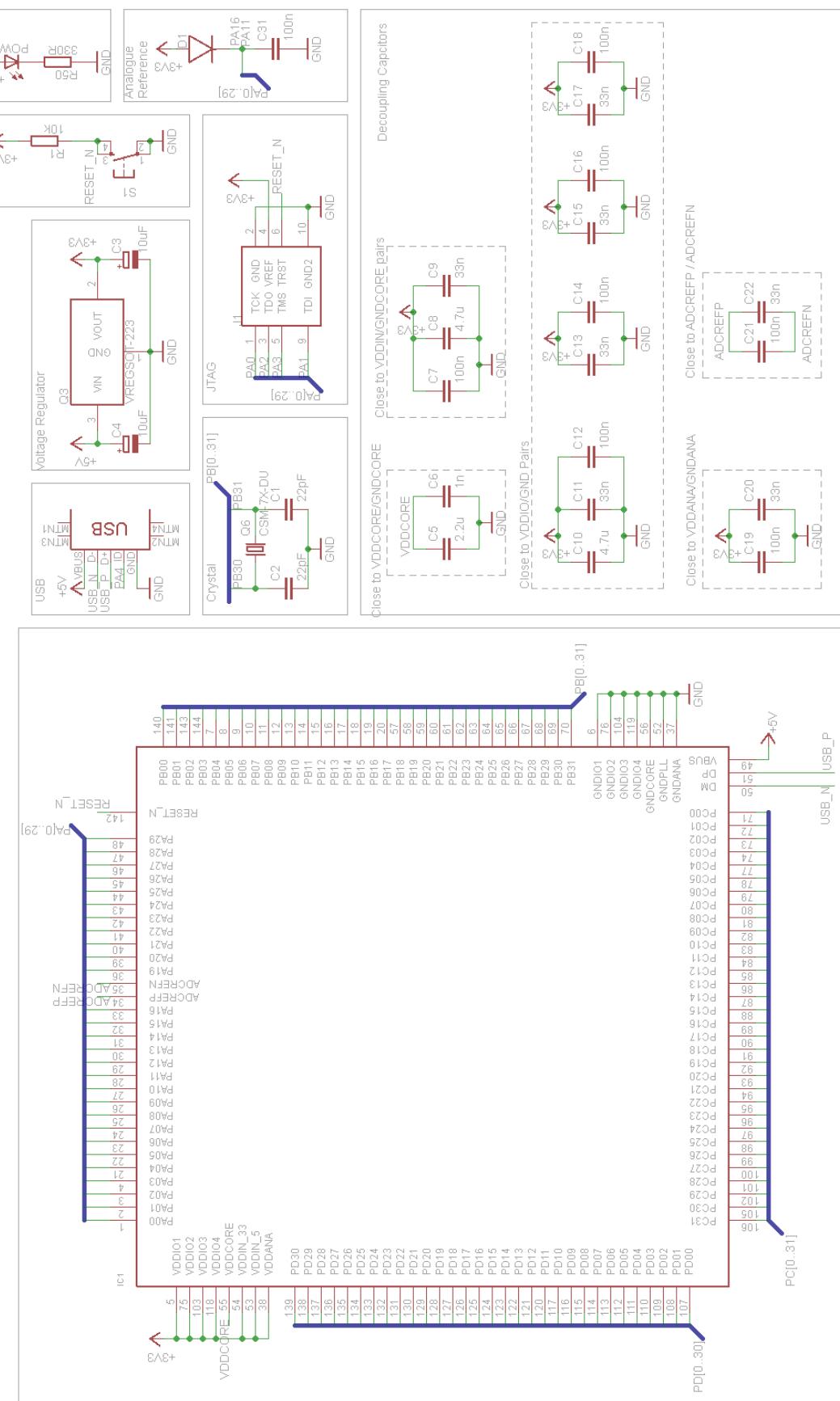


Figure B.3: The Columbus Circuit Diagram Page 1

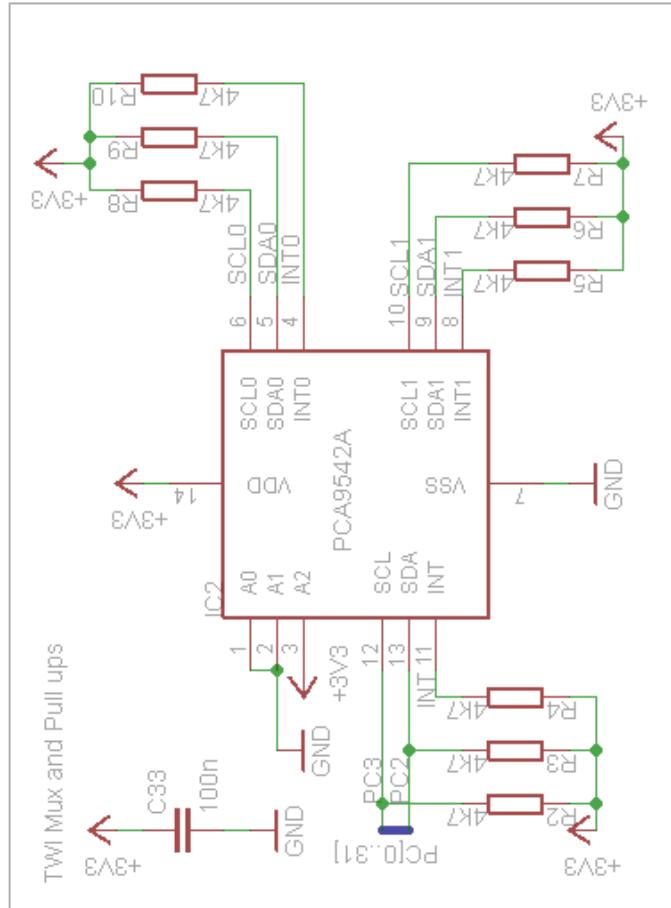
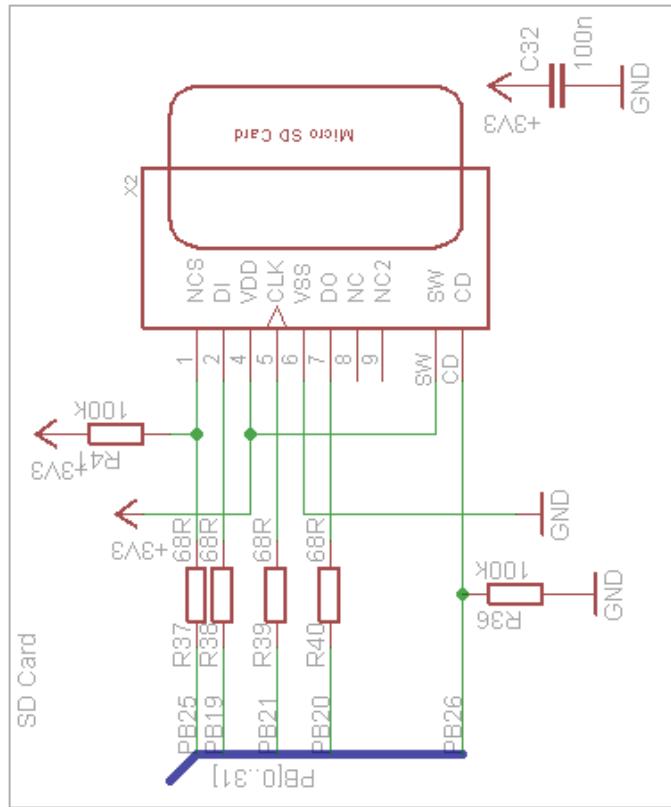


Figure B.4: The Columbus Circuit Diagram Page 2

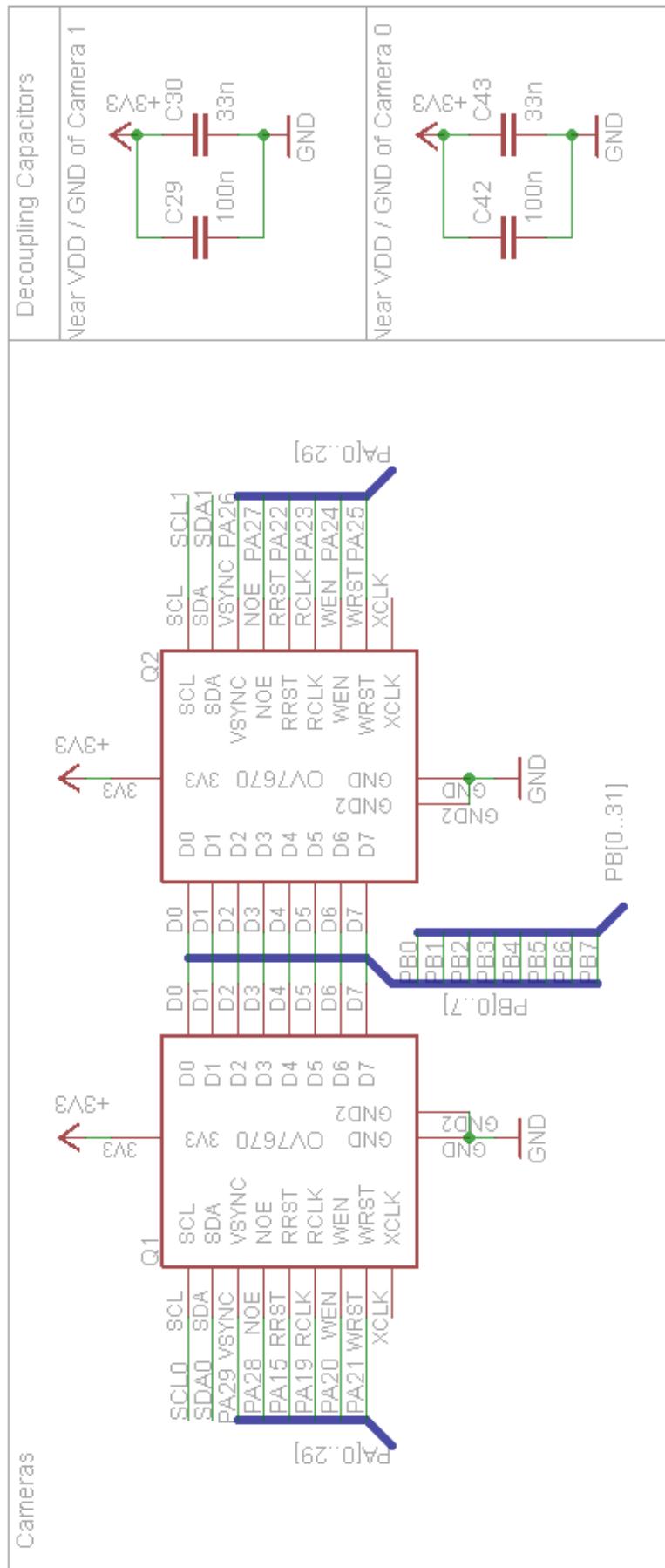


Figure B.5: The Columbus Circuit Diagram Page 3

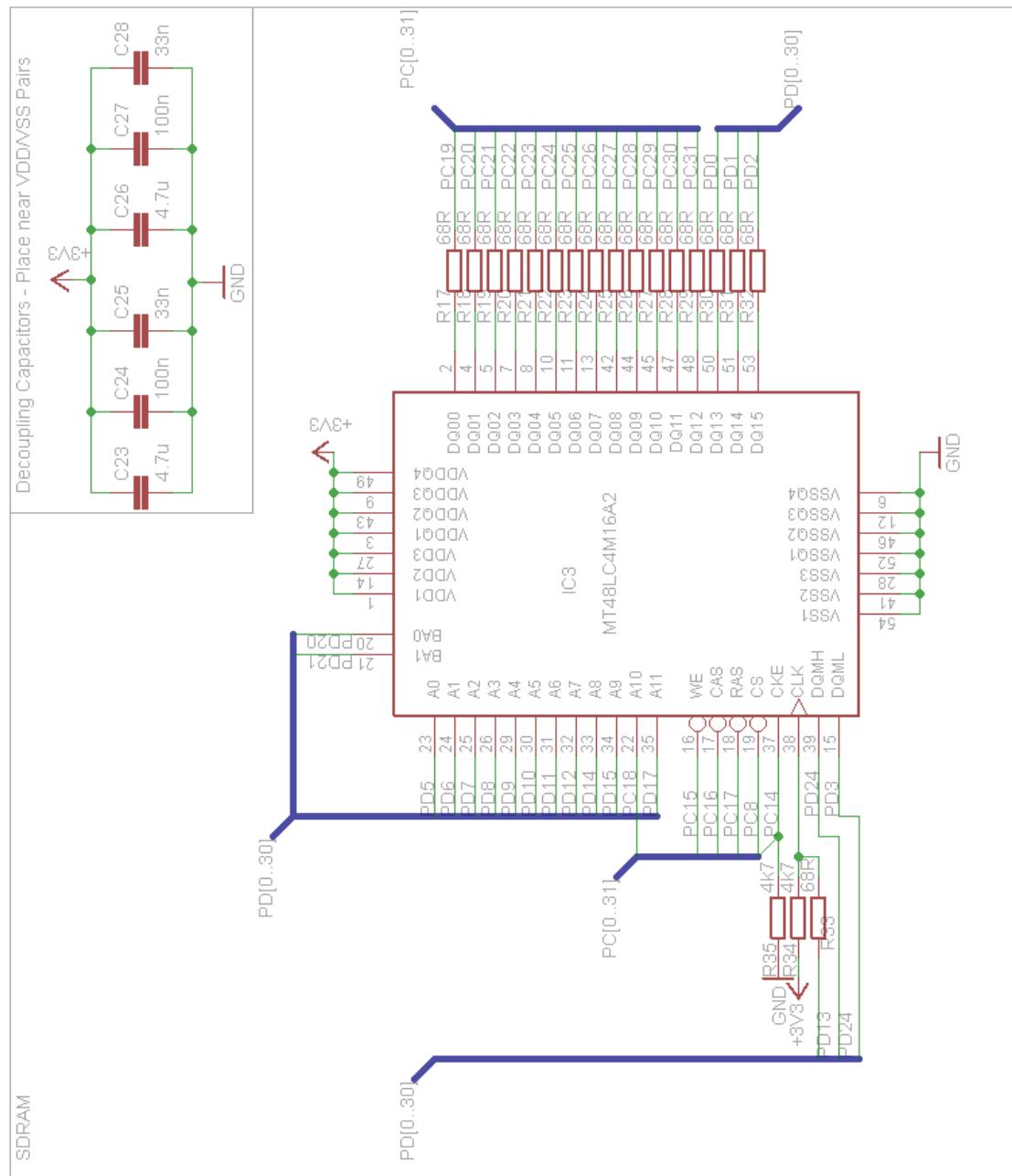


Figure B.6: The Columbus Circuit Diagram Page 4

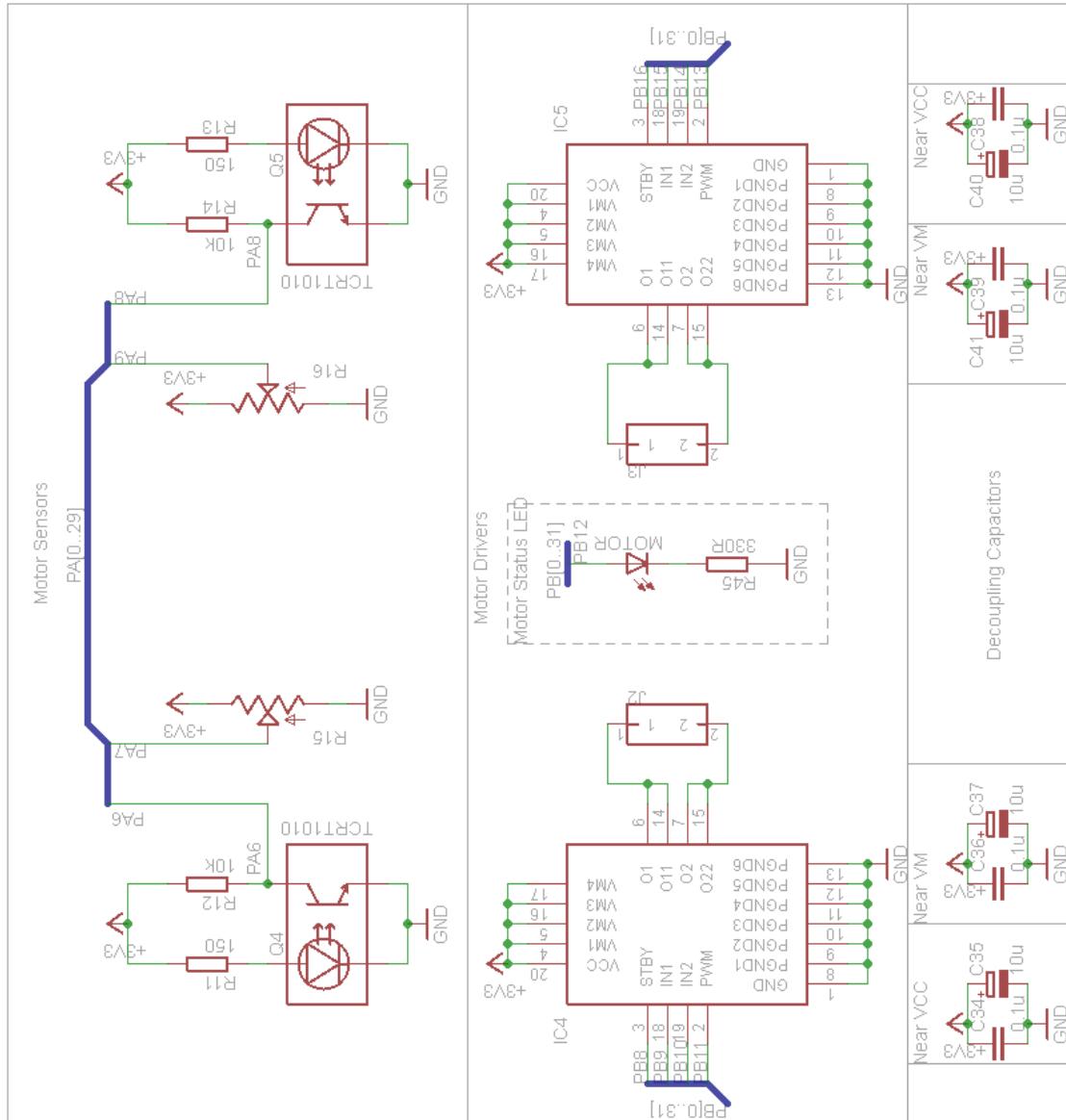


Figure B.7: The Columbus Circuit Diagram Page 5

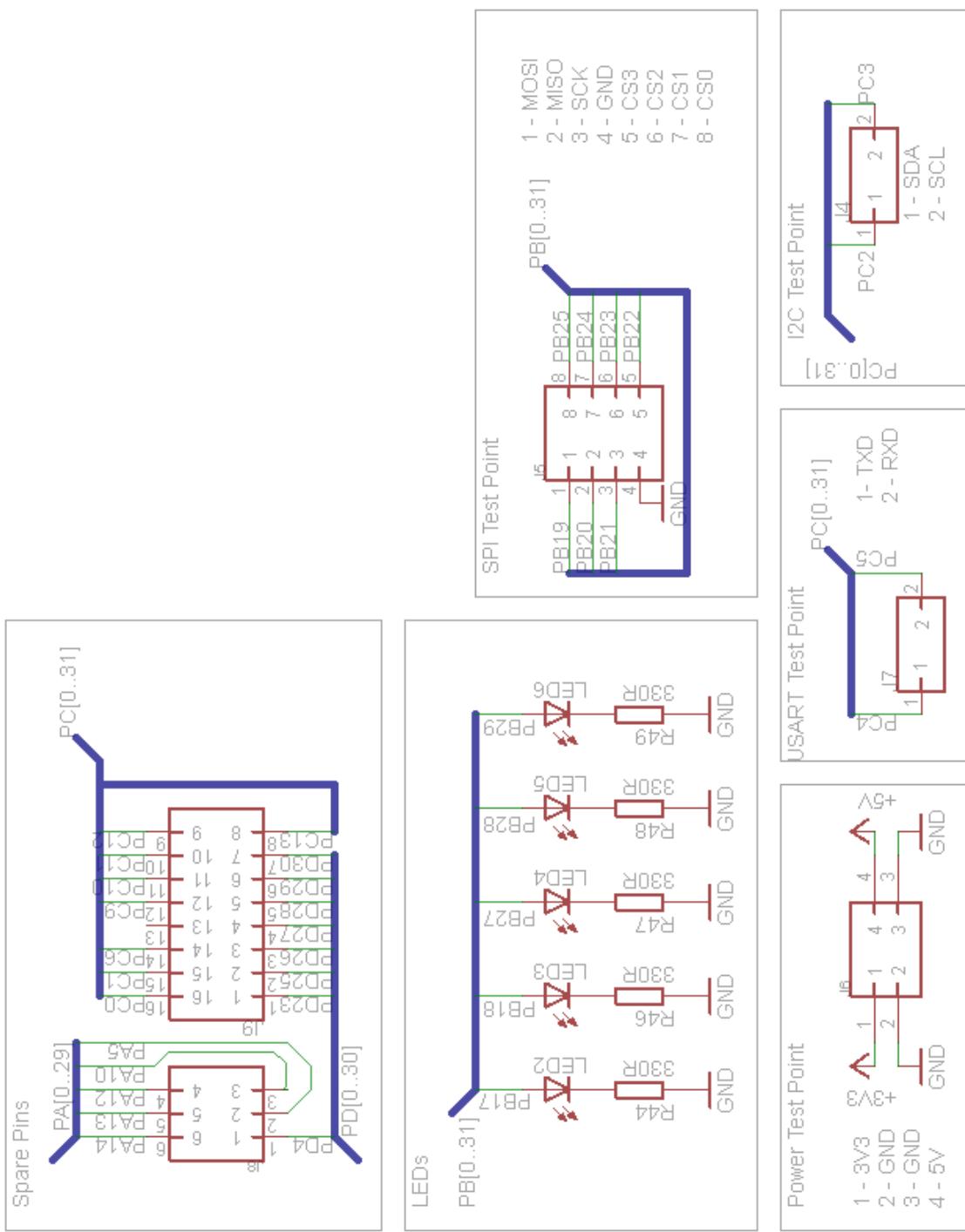


Figure B.8: The Columbus Circuit Diagram Page 6

Appendix C

PCB Design

C.1 PCB Top Side

C.2 PCB Bottom Side

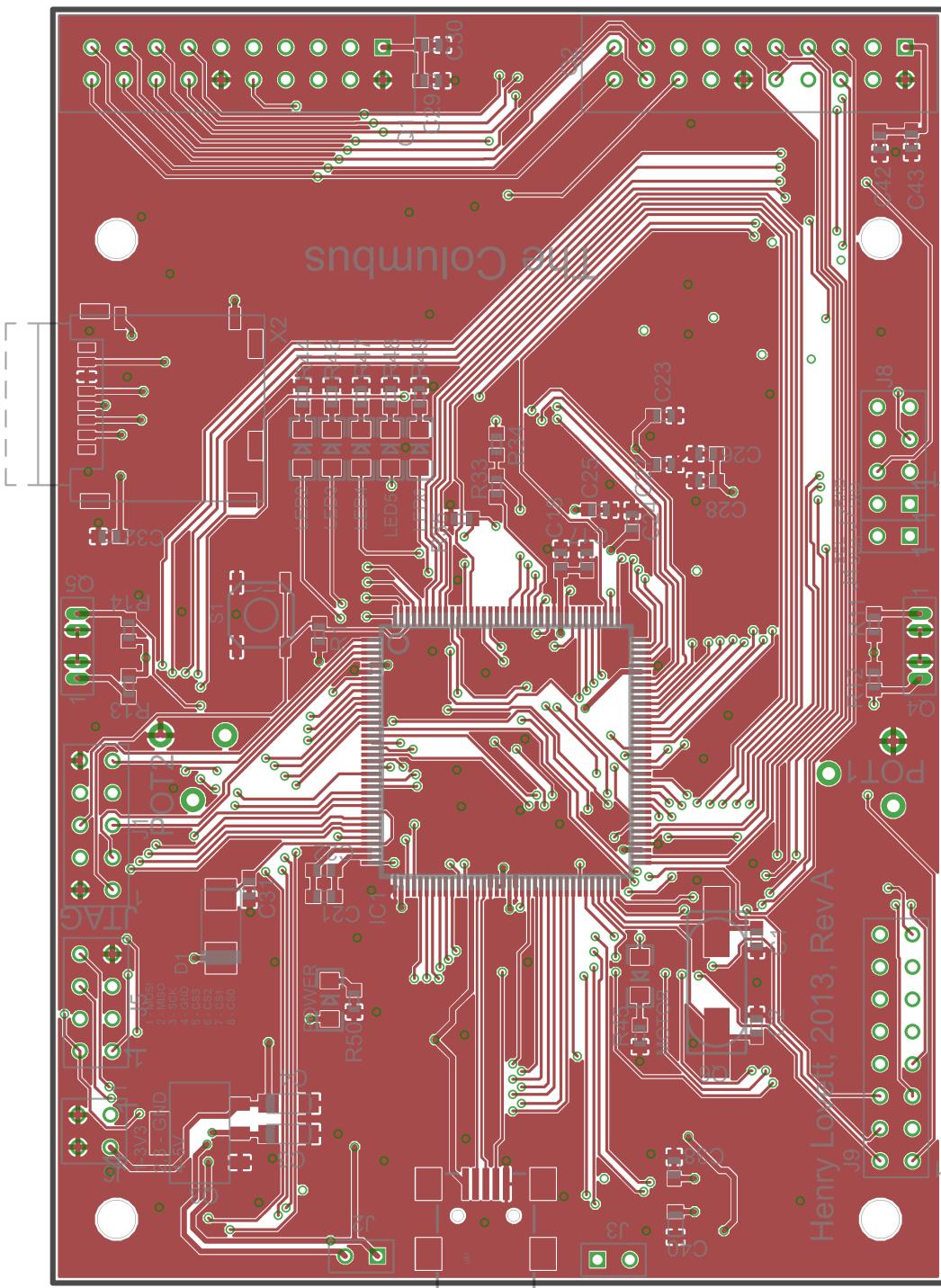


Figure C.1: The Top side of the CAD Design of the PCB

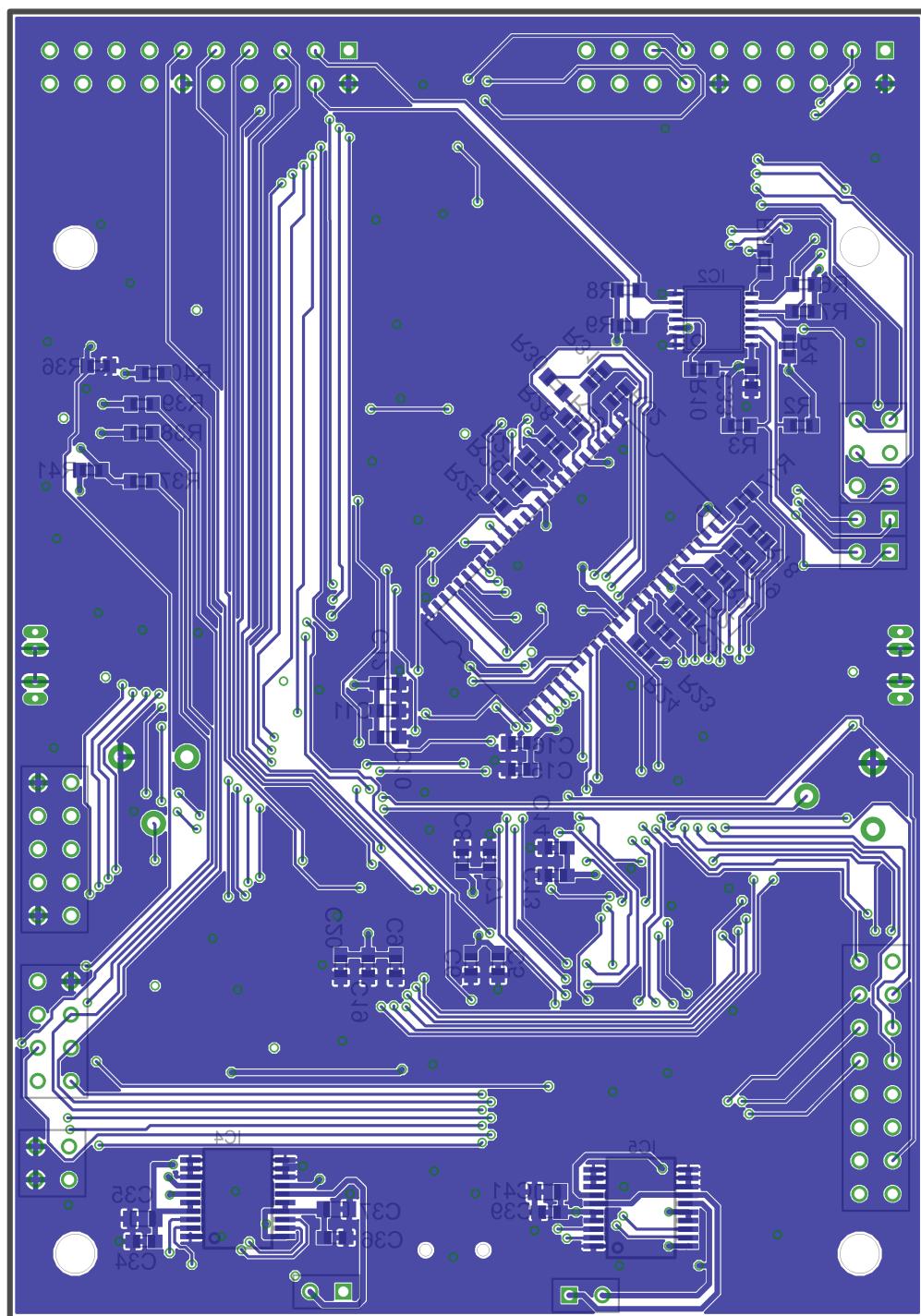


Figure C.2: The Bottom side of the CAD Design of the PCB

Appendix D

Costings and Components

Table D.1: A table of all components used and their costs.

Component	Cost per unit (£)	Quantity	Cost (£)	Source
PCB	205	1	205	PCBCart
Capactiors	0.155	43	6.67	Farnell
Clock	1.48	1	1.48	Farnell
Diode	0.48	1	0.48	Farnell
Headers	0.51	5	2.55	Farnell
I2C Mux PCA9542A	0.81	1	0.81	Farnell
LEDs	0.158	7	1.11	Farnell
Micro SD Card	4	1	4.00	Amazon
Micro SD Card Connector	2.04	1	2.04	Farnell
AT32UC3C0512C	15.39	1	15.39	Farnell
TB6593FNG	1.07	2	2.14	Farnell
Motors	0.42	2	0.84	Rapid
TCRT1010	0.94	2	1.88	Farnell
OV7670	17	2	34.00	
Potentiometer	0.43	2	0.86	Farnell
Resistors	0.066	46	3.04	Farnell
MT48LC4M16A2P	3.24	1	3.24	Farnell
Switch	0.45	1	0.45	Farnell
USB Socket	0.84	1	0.84	Farnell
LM1117MP	1.03	1	1.03	Farnell
		Total Cost	£287.84	

Table D.2: All components and their values (if applicable)

Component(s)	Value
IC1	AT32UC3C0512C
IC2	PCA9542A
IC3	MT48LC4M16A2
IC4, IC5	TB6593FNG
Q1, Q2	OV7670
Q3	LM1117MP-3.3
Q4, Q5	TCRT1010
S1	Tactile Switch
R15, R16	10kΩ Potentiometer
R17, R18, R19, R20, R21, R22, R23, R24, R25, R26, R27, R28, R29, R30, R31, R32, R33, R37, R38, R39, R40	68Ω
R11, R13	150Ω
R44, R45, R46, R47, R48, R49, R50	330Ω
R2, R3, R4, R5, R6, R7, R8, R9, R10, R34, R35	4K7Ω
R1, R12, R14	10kΩ
R36, R41	100kΩ
C1, C2	22pF
C6	1nF
C9, C11, C13, C15, C17, C20, C22, C25, C28, C30, C43	33Nf
C7, C12, C14, C16, C18, C19, C21, C24, C27, C29, C31, C32, C33, C34, C36, C38, C39, C42	100nF
C5	2.2μF
C8, C10, C23, C26	4.7μF
C3, C4, C35, C37, C40, C41	10μF
D1	GF1A - Rectifier Diode
J1, J2, J3, J4, J5, J6, J7, J8, J9	0.1" header
LED2, LED3, LED4, LED5, LED6, Motor LED, Power LED	1206 LED
X2	Micro SD Card Socket

Appendix E

Contents of Files

Appendix F

Bitmap File Format

F.1 Bitmap File Format

Table F.1: Format of a Bitmap file with values used, to write an image from the camera to an SD Card

Section	Field	Description	Size (Bytes)	Value (hex)
Bitmap Header	Signature	Declares the file is a Bitmap Image	2	424D
	File Size	Size of the whole file including headers	4	36580200 (153654) ¹
	Reserved		4	00000000
	Offset to Pixel Array	The address of the start of the pixel data from the beginning of the file	4	36000000
DIB (Device Independent Bitmap) Header	Size	Size of the DIB Header (dictates the version)	4	7C000000
	Width	Width of the image (320 pixels)	4	40010000

Continued on next page

¹This is different to the 225kB stated in Table 3.1 due to omitting many optional fields

Table F.1 – continued from previous page

Section	Field	Description	Size (Bytes)	Value (hex)
	Height	Height of the image (240 pixels)	4	F0000000
	Planes	Number of colour planes	2	0100
	Bit Count	Number of bits per pixel	2	1000
	Compression	Compression Being Used, RGB Bit Fields	4	03 00 00 00
	Image Size	Size of the image	4	00 86 25 00
	X Resolution	Horizontal resolution in pixels per metre	4	13 0B 00 00
	Y Resolution	Vertical resolution in pixels per metre	4	13 0B 00 00
	Colours in Table	Number of colours in the colour table (not used)	4	00 00 00 00
	Important Colours	Number of Important Colours (0 means all colours are important)	4	00 00 00 00
	Red Mask	Bit mask of Red field	4	00 F8 00 00
	Green Mask	Bit mask of Green field	4	E0 07 00 00
	Blue Mask	Bit mask of Blue field	4	1F 00 00 00
	Alpha Mask	Bit mask of Alpha field	4	00 00 00 00
	Colour Space Type	Colour Space of the DIB	4	01 00 00 00
	Colour Space Endpoints	Sets endpoints for colours within the bitmap (not used)	36	Whole Field = 0
	Gamma Red	Gamma Value of Red Field (not used)	4	00 00 00 00

Continued on next page

Table F.1 – continued from previous page

Section	Field	Description	Size (Bytes)	Value (hex)
	Gamma Green	Gamma Value of Green Field (not used)	4	00 00 00 00
	Gamma Blue	Gamma Value of Blue Field (not used)	4	00 00 00 00
	Intent	Enum dictating the intent of the image (Picture)	4	03 00 00 00
	ICC Profile Data	Offset from the file start to the ICC Colour Profile (Not Used)	4	00 00 00 00
	ICC Profile Size	Size of the ICC Colour Profile (not used)	4	00 00 00 00
	Reserved		4	00 00 00 00
Image Data Format	Each field contains all the pixel data	Padding is used to make the table width a multiple of 4 (Not always needed)		
Pix[0, h-1]	Pix[1, h-1]	...	Pix[w-1, h-1]	Padding
:	:	:	:	:
Pix[0, 1]	Pix[1, 1]	...	Pix[w-1, 1]	Padding
Pix[0, 0]	Pix[1, 0]	...	Pix[w-1, 0]	Padding

Appendix G

Range Finding Derivations

G.1 Object is between the Cameras

Derivation from [Mrovlje and Vrančić \(2008\)](#).

$$B = B_1 + B_2 = D \tan(\varphi_1) + D \tan(\varphi_2) \quad (\text{G.1})$$

$$D = \frac{B}{\tan(\varphi_1) + \tan(\varphi_2)} \quad (\text{G.2})$$

$$D \tan\left(\frac{\varphi_0}{2}\right) = \frac{x_0}{2} \quad (\text{G.3})$$

$$D \tan(\varphi_1) = x_1 \quad (\text{G.4})$$

Dividing (G.4) by (G.3)

$$\frac{\tan(\varphi_1)}{\tan\left(\frac{\varphi_0}{2}\right)} = \frac{2x_1}{x_0} \quad (\text{G.5})$$

$$\tan(\varphi_1) = \frac{2x_1 \tan\left(\frac{\varphi_0}{2}\right)}{x_0} \quad (\text{G.6})$$

This can also be shown for the right camera:

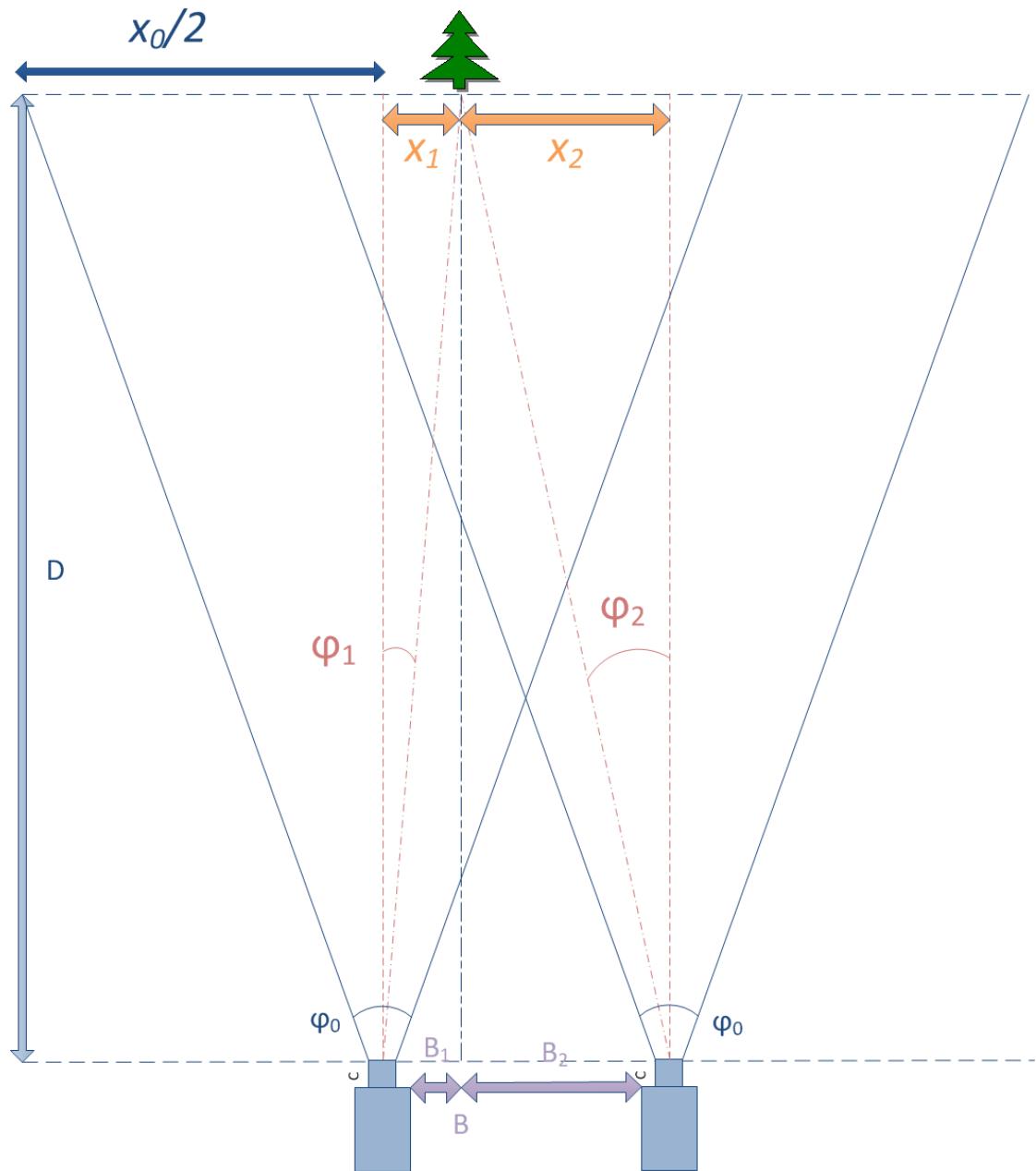


Figure G.1: Problem 1 - Object is between the Cameras

$$\tan(\varphi_2) = \frac{-2x_2 \tan(\frac{\varphi_0}{2})}{x_0} \quad (\text{G.7})$$

Substitution equations (G.6) and (G.7) into (G.2) gives

$$D = \frac{Bx_0}{2 \tan(\frac{\varphi_0}{2})(x_1 - x_2)} \quad (\text{G.8})$$

G.2 Object is to the same side in each camera

Derivation is based on the derivation from Tjandranegara (2005). Using figure G.2:

$$D \cdot \tan(\varphi_1) = x_1 \quad (\text{G.9})$$

$$D \cdot \tan\left(\frac{\varphi_0}{2}\right) = \frac{x_0}{2} \quad (\text{G.10})$$

$$\frac{\tan(\varphi_1)}{\tan\left(\frac{\varphi_0}{2}\right)} = \frac{2x_1}{x_0} \quad (\text{G.11})$$

$$\varphi_1 = \arctan\left(\frac{2x_1}{x_0} \tan\left(\frac{\varphi_0}{2}\right)\right) \quad (\text{G.12})$$

and similarly

$$\varphi_2 = \arctan\left(\frac{2x_2}{x_0} \tan\left(\frac{\varphi_0}{2}\right)\right) \quad (\text{G.13})$$

$$\theta = \varphi_2 - \varphi_1 \quad (\text{G.14})$$

Using the sine equality rule:

$$\frac{R}{\sin\left(\frac{\pi}{2} - \varphi_2\right)} = \frac{B}{\sin(\theta)} \quad (\text{G.15})$$

$$R = B \cdot \frac{\sin\left(\frac{\pi}{2} - \varphi_2\right)}{\sin(\theta)} = B \frac{\cos(\varphi_2)}{\sin(\theta)} \quad (\text{G.16})$$

$$D = \cos(\varphi_1) \cdot R \quad (\text{G.17})$$

Substituting (G.14) into (G.16), and then into (G.17):

$$D = B \cdot \frac{\cos(\varphi_2) \cdot \cos(\varphi_1)}{\sin(\varphi_2 - \varphi_1)} \quad (\text{G.18})$$

Where φ_1 is defined in equation (4.7) and φ_2 is defined in equation (4.8).

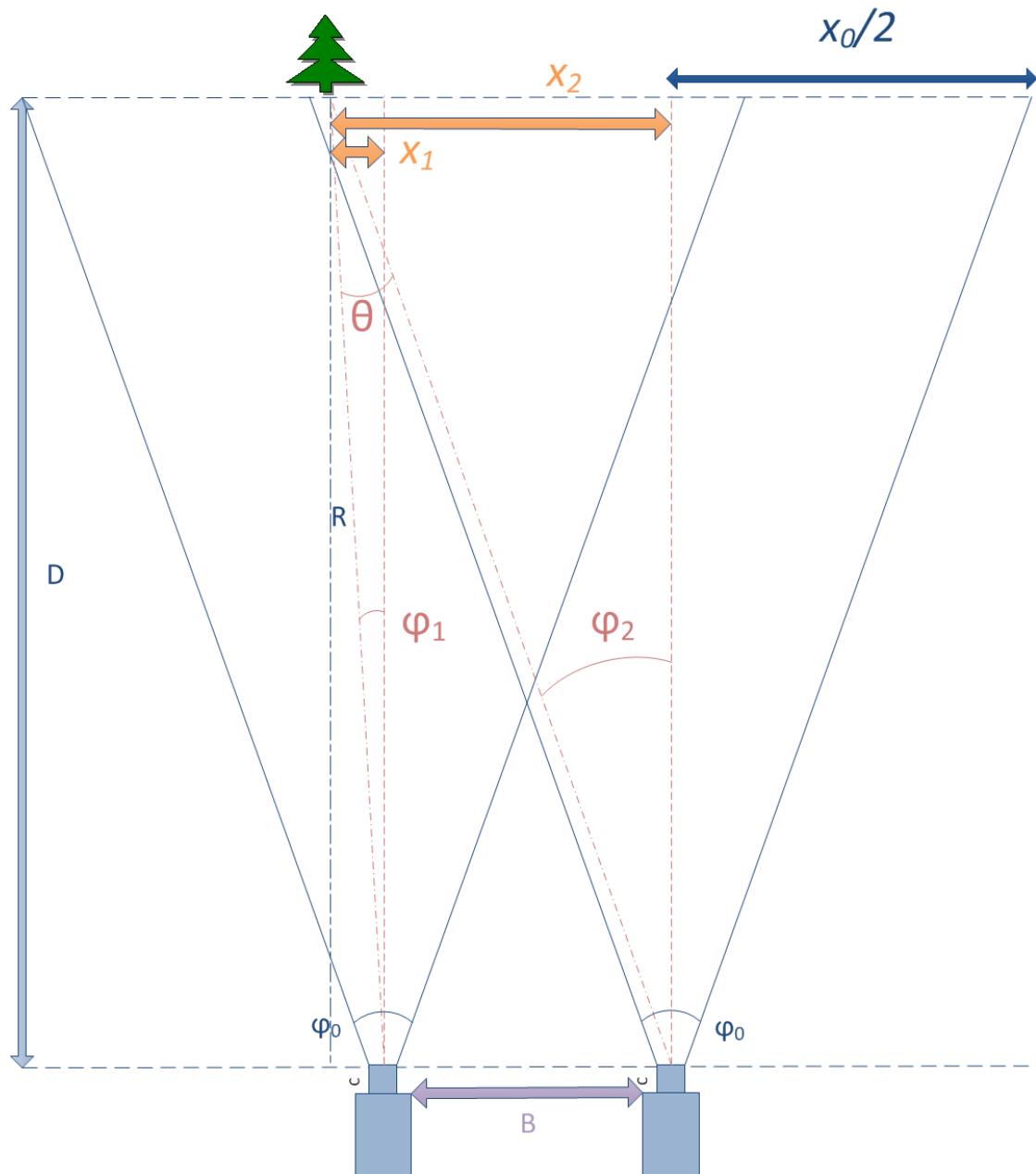


Figure G.2: Problem 2 - Object is to the same side in both cameras

G.3 Object is in front of a camera

The distance, D , in this problem is given by:

$$D = B \tan \left(\frac{\pi}{2} - \varphi_2 \right) \quad (\text{G.19})$$

Where φ_2 can be found from equation 4.8.

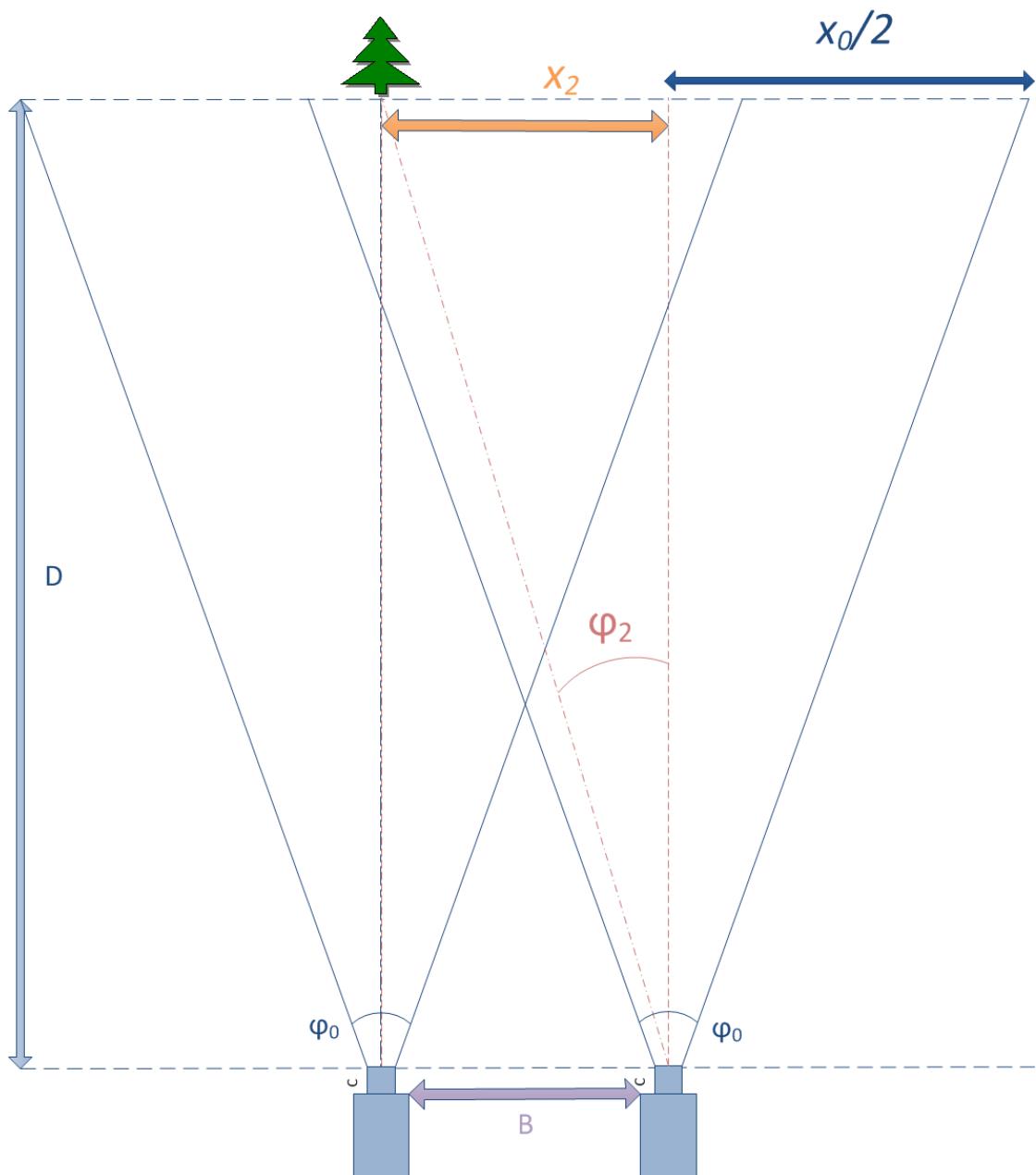


Figure G.3: Problem 3 - Object is directly in front of a camera

Appendix H

Source Code

H.1 C Code for AVR

H.1.1 The Columbus Source Code

H.1.1.1 main.c

..../Code/The_Columbus/ColumbusTest/src/main.c

```
1  /**
2  * \file
3  *
4  * \brief Empty user application template
5  *
6  */
7
8 /*
9  * Include header files for all drivers that have been imported from
10 * Atmel Software Framework (ASF).
11 */
12 #define DSP16_FORMAT 10
13 #include <asf.h>
14 #include <conf_board.h>
15 #include "CustomDevices/CustomDevices.h"
16 #include "conf_sd_mmc_spi.h"
17 #include "fat.h"
18 #include "file.h"
19 #include "navigation.h"
20 #include "fastmath.h"
21 #include "delay.h"
22 #include "stdio.h"
23
24 //REF : http://www.chris.com/ASCII/index.php?art=transportation/nautical
```



```
65 #define COMMAND_BUFFER_SIZE    128
66 int main (void)
67 {
68     Image_t image;
69     unsigned long i, j, tmp = 0;
70     char *Ptr;
71 //  volatile unsigned long *sdram = SDRAM;
72     char CommandBuffer[COMMAND_BUFFER_SIZE];
73     int *Working_Buffer = NULL;
74     int SizeOfWorking_Buffer = 0;
75     A_ALIGNED dsp16_complex_t *ComplexBuffer;
76     int SizeOfComplex_Buffer = 0;
77     Columbus_Status.SD_Card = &SD_Status;
78     Columbus_Status.Cameras = &OV7670_Status;
79     Columbus_Status.I2CMux = &PCA9542A;
80     Columbus_Status.SD_Card = &SD_Status;
81     Columbus_Status.Motors = &Motor_Control;
82     board_init();
83     print_dbg("\n\r");
84     print_dbg(THE);
85     print_dbg(COLUMBUS);
86     print_dbg(ASCII_SHIP);
87     System_Test();

88 if(Columbus_Status.Status != STATUS_OK)
89 {
90     while(1)
91     {
92         LED2_SET;
93         LED3_SET;
94         LED4_SET;
95         LED5_SET;
96         LED6_SET;
97         delay_ms(500);
98         LED2_CLR;
99         LED3_CLR;
100        LED4_CLR;
101        LED5_CLR;
102        LED6_CLR;
103        delay_ms(500);
104    }//inifinte loop
105 }

106

107 print_dbg("\n\rColumbus Ready!");
108 // Insert application code here, after the board has been initialized.
109 while(1)
110 {
111     {
112         print_dbg(PROMPT);
113         Get_Line(CommandBuffer);
114         Ptr = CommandBuffer;
115         switch(*Ptr++)
116         {
117             case '?':
118                 print_dbg(HELP);
119                 break;
```

```

122     case '1'://1d FFT (w/ memallocs)
123         print_dbg("\r1D FFT;");
124         SizeOfComplex_Buffer = FFT_SIZE;
125         ComplexBuffer = mspace_malloc(sdram_msp, SizeOfComplex_Buffer *
126                                         sizeof(ComplexBuffer));
126         i = Get_sys_count();
127         FFT1D(Working_Buffer, ComplexBuffer);
128         i = Get_sys_count() - i;
129         print_dbg("\n\rCycles Taken for 1D FFT = ");
130         print_dbg_ulong(i);
131         break;
132     case '2':
133         print_dbg("\r2D FFT;");
134         FFT2Dabs(Working_Buffer);
135         break;
136     case '3':
137         print_dbg("\rComplex FFT2D:");
138         SizeOfComplex_Buffer = FFT_SIZE * FFT_SIZE;
139         ComplexBuffer = mspace_malloc(sdram_msp, SizeOfComplex_Buffer *
140                                         sizeof(ComplexBuffer));
140         i = Get_sys_count();
141         FFT2DCOMPLEX(Working_Buffer, ComplexBuffer, SizeOfWorking_Buffer);
142         i = Get_sys_count() - i;
143         print_dbg("\n\rCycles Taken for 2D FFT = ");
144         print_dbg_ulong(i);
145         break;
146     case 'm':
147         print_dbg("\r1D FFT Magnitude");
148         FFT1D_Abs(Working_Buffer);
149         break;
150     case 'B':
151         print_dbg("\rReading Bitmap");
152         ReadBitmap("Image_R_0.bmp", &image);
153         print_dbg("\n\rBitmap Data Returned:\n\rImage Height = ");
154         print_dbg_ulong(image.Height);
155         print_dbg("\n\rImage Width = ");
156         print_dbg_ulong(image.Width);
157         break;

159     case 'c':
160         print_dbg("\rConverting Working Buffer to Fixed Point");
161         for(i = 0; i < SizeOfWorking_Buffer ; i++)
162         {
163             Working_Buffer[i] = DSP16_Q (Working_Buffer[i]);
164         }
165         break;

167     case 'C':
168         print_dbg("\rConverting Working Buffer back from Fixed Point");
169         j = DSP16_Q(1);
170         for(i = 0; i < SizeOfWorking_Buffer ; i++)
171         {
172             Working_Buffer[i] = Working_Buffer[i] / j;
173         }
174         break;

176     case 'D':
177         print_dbg("\rFreeing Working Buffer");

```

```
178     mspace_free(sdram_msp, Working_Buffer);
179     break;
180
181     case 'i':
182         print_dbg("\rImage info:");
183         print_dbg("\n\rImage Pointer = ");
184         print_dbg_ulong(image.ImagePtr);
185         print_dbg("\n\rImage Height = ");
186         print_dbg_ulong(image.Height);
187         print_dbg("\n\rImage Width = ");
188         print_dbg_ulong(image.Width);
189         break;
190
191     case 'I':
192         print_dbg("\rInverse Fourier Transform");
193         IFFT2D(ComplexBuffer);
194         break;
195
196     case 'k':
197         print_dbg("\rComplex Buffer:\n[r[");
198         for (i = 0; i < SizeOfComplex_Buffer; i++)
199         {
200             //         print_dbg_ulong(ComplexBuffer[i].real);
201             //         print_dbg(" + ");
202             //         print_dbg_ulong(ComplexBuffer[i].imag);
203             //         print_dbg(", ");
204             if(ComplexBuffer[i].imag >= 0)
205                 sprintf(CommandBuffer, "%d + %dj,", ComplexBuffer[i].real,
206 ComplexBuffer[i].imag);
207             else
208                 sprintf(CommandBuffer, "%d %dj,", ComplexBuffer[i].real,
209 ComplexBuffer[i].imag);
210             print_dbg(CommandBuffer);
211         }
212         print_dbg("]\n\r");
213         break;
214     case 'M': //Motor Related
215         while(*Ptr == ' ')
216             Ptr++; //Find next non - space char
217
218         switch(*(Ptr++))
219         {
220             case 'q': // Reset Motors
221                 print_dbg("\rResetting Motors");
222                 Motors_Reset();
223                 break;
224
225             case 'F': //Move Forward
226                 while(*Ptr == ' ')
227                     Ptr++; //Find next non - space char
228                 i = atoi(Ptr);
229                 Motors_Move(i);
230                 break;
231             case 'T':
232                 while(*Ptr == ' ')
233                     Ptr++; //Find next non - space char
234                 i = atoi(Ptr);
235                 Motors_Rotate(i);
```

```

234         break;
235     case 'l':
236         Motor_Stop(MOTOR_L);
237         break;
238     case 'L':
239         Columbus_Status.Motors->Left_Count = GAMMA + 1;
240         Columbus_Status.Motors->Left_State = FORWARD;
241         Motor_Start(MOTOR_L);
242         Motors_Execute();
243         break;
244     case 'r':
245         Motor_Stop(MOTOR_R);
246         break;
247     case 'R':
248         Columbus_Status.Motors->Right_Count = GAMMA + 1;
249         Columbus_Status.Motors->Right_State = FORWARD;
250         Motor_Start(MOTOR_R);
251         Motors_Execute();
252         break;
253     default:
254         print_dbg("\rCommand Not Recognised");
255         break;
256     }

258     break;

260 case 'p':
261     print_dbg("\rPreparing Image;");
262     PrepareImage(&image);
263     print_dbg("\rImage Prepared!");
264     break;

266 case 'P'://take a photo
267     FIFO_Reset(CAMERA_LEFT | CAMERA_RIGHT);
268     print_dbg("\rTaking Photos");
269     if(TakePhoto(CAMERA_LEFT | CAMERA_RIGHT) == CAMERAS_BUSY){
270         print_dbg("Cameras Busy");
271         break;
272     }
273     while(Photos_Ready() == false)
274     ;

276     if(Store_Both_Images() == true)
277         print_dbg("\n\rImages Stored Successfully!");
278     break;

280 case 'r':
281     if (Working_Buffer == 0)
282     {
283         print_dbg("\rWorking Buffer Not Initialised");
284         break;
285     }
286     print_dbg("\rWorking Buffer:\n\r[");
287     for(i = 0; i < SizeOfWorking_Buffer; i++)
288     {
289 //         print_dbg_ulong(Working_Buffer[i]);
290 //         print_dbg(", ");
291         sprintf(CommandBuffer, "%d,", (dsp16_t)Working_Buffer[i]);

```

```

292         print_dbg(CommandBuffer);
293     }
294     print_dbg("\b\b]\n\r");
295     break;
296 case 'R':
297     Working_Buffer = mspace_malloc(sdram_msp, FFT_SIZE);
298     SizeOfWorking_Buffer = FFT_SIZE;
299     print_dbg("\rReading in signal.bin");
300     ReadSignal(Working_Buffer);
301     break;

303 case 's'://save the working buffer
304     print_dbg("\rSaving Working Buffer;");
305     SaveBuff(Working_Buffer, SizeOfWorking_Buffer);
306     break;
307 case 'd':
308     print_dbg("\rSaving Working Buffer as CSV;");
309     SaveBuff_CSV("Buffer_result.csv", Working_Buffer, SizeOfWorking_Buffer
());
310     break;
311 case 'g':
312     print_dbg("\rSaving Complex Buffer as CSV");
313     SaveCBuff_CSV("Buffer_Complex.csv", ComplexBuffer,
SizeOfComplex_Buffer);
314     break;
315 case 'f':
316     SizeOfWorking_Buffer = FFT_SIZE*FFT_SIZE;
317     Working_Buffer = mspace_malloc(sdram_msp, SizeOfWorking_Buffer);

319     print_dbg("\rReading in Buffer.csv");
320     Read_CSV("Buffer.csv", Working_Buffer, SizeOfWorking_Buffer);
321     print_dbg("\n\rComplete!");
322     break;

324 case 'S':
325     print_dbg("\rSaving Bitmap;");
326     SaveBitmap(image.ImagePtr, image.Width, image.Height, "ResavedImage.
bmp");
327     print_dbg("\rSaved Bitmap!");
328     break;

330 case 'T':
331     print_dbg("\rReading in 2D Signal");
332     Working_Buffer = mspace_malloc(sdram_msp, FFT_SIZE * FFT_SIZE);
333     SizeOfWorking_Buffer = FFT_SIZE * FFT_SIZE;
334     Read2DSignal(Working_Buffer);
335     break;
336 case 'v':
337     print_dbg("\rColumbus Status:");
338     print_dbg("\n\rSD Card:\n\rStatus: ");
339     print_dbg_ulong(Columbus_Status.SD_Card->Status);
340     print_dbg("\n\rMemory Size : ");
341     print_dbg_ulong(Columbus_Status.SD_Card->Memory_size);
342     print_dbg("\n\rMotors:");
343     print_dbg("\n\rLeft State : ");
344     print_dbg_ulong(Columbus_Status.Motors->Left_State);
345     print_dbg("\n\rLeft Count : ");
346     print_dbg_ulong(Columbus_Status.Motors->Left_Count);

```

```

347     print_dbg("\n\rRight State : ");
348     print_dbg_ulong(Columbus_Status.Motors->Right_State);
349     print_dbg("\n\rRight Count : ");
350     print_dbg_ulong(Columbus_Status.Motors->Right_Count);
351     print_dbg("\n\rCameras:");
352     print_dbg("\n\rStatus : ");
353     print_dbg_ulong(Columbus_Status.Cameras->Status);
354     print_dbg("\n\rVSYNC0 State : ");
355     print_dbg_ulong(Columbus_Status.Cameras->VSYNC0_State);
356     print_dbg("\n\rVSYNC1 State : ");
357     print_dbg_ulong(Columbus_Status.Cameras->VSYNC1_State);
358     print_dbg("\n\rI2C Mux:");
359     print_dbg("\n\rStatus : ");
360     print_dbg_ulong(Columbus_Status.I2CMux->Status);
361     print_dbg("\n\rChannel Selected : ");
362     print_dbg_ulong(Columbus_Status.I2CMux->ChannelSelected);
363     break;
364 case 'o':
365     print_dbg("\r1 in Fixed point = ");
366     i = DSP16_Q(1);
367     print_dbg_ulong(i);
368     break;
369 //    case 'o'://testing storing a complex
370 //        print_dbg("\rFreeing Complex Buffer");
371 //        mspace_free(sdram_msp, ComplexBuffer);
372 //        print_dbg("\n\rAssigning Space to the Complex Buffer;");
373 //        SizeOfComplex_Buffer = 10;
374 //        ComplexBuffer = mspace_malloc(sdram_msp, 10*sizeof(ComplexBuffer));
375 //        if(ComplexBuffer == NULL)
376 //        {
377 //            print_dbg("\n\rAssign Failed");
378 //            break;
379 //        }
380 //        for(i = 0; i < SizeOfComplex_Buffer; i++)
381 //        {
382 //            ComplexBuffer[i].imag = i;
383 //            ComplexBuffer[i].real = i;
384 //        }
385 //        for(i = 0; i < SizeOfComplex_Buffer; i++)
386 //        {
387 //            print_dbg("\n\r");
388 //            print_dbg_ulong(ComplexBuffer[i].real);
389 //            print_dbg(" + j");
390 //            print_dbg_ulong(ComplexBuffer[i].imag);
391 //        }
392 //        print_dbg("\n\rFreeing Complex Buffer");
393 //        mspace_free(sdram_msp, ComplexBuffer);
394 //        SizeOfComplex_Buffer = 0;
395 //        break;

396     default:
397         print_dbg("\rCommand Not Recognised");
398         break;
399     }
400 }
401 }
402 }
```

H.1.1.2 Bitmap.c

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/Bitmap.c

```

1  /*
2   * Bitmap.c
3   *
4   * Created: 16/02/2013 23:14:34
5   * Author: hslovett
6   */
7  #include "CustomDevices/CustomDevices.h"

9  const uint8_t DIBHead[DIBHEADERSIZE] = { 0x7C, 0x00, 0x00, 0x00, //Number of
10    bytes
11      0x40, 0x01, 0x00, 0x00, //Width - 320
12      0xF0, 0x00, 0x00, 0x00, //Height - 240
13      0x01, 0x00,           //Planes
14      0x10, 0x00,           //Bits per Pixel
15      0x03, 0x00, 0x00, 0x00, //Compression
16      0x00, 0x58, 0x02, 0x00, //Size of Raw Data
17      0x13, 0x0B, 0x00, 0x00, //Horizontal Resolution
18      0x13, 0x0B, 0x00, 0x00, //Vertical Resolution
19      0x00, 0x00, 0x00, 0x00, //Colours in Palette
20      0x00, 0x00, 0x00, 0x00, //Important Colours
21      0x00, 0xF8, 0x00, 0x00, //Red Mask
22      0xE0, 0x07, 0x00, 0x00, //Green Mask
23      0x1F, 0x00, 0x00, 0x00, //Blue Mask
24      0x00, 0x00, 0x00, 0x00, //Alpha Mask
25      0x01, 0x00, 0x00, 0x00, //Colour Space Type
26      0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
27      0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
28      0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
29      0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
30      0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
31      0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
32      0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
33      0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
34      0x00, 0x00, 0x00, 0x00, //Gamma Red
35      0x00, 0x00, 0x00, 0x00, //Gamma Green
36      0x00, 0x00, 0x00, 0x00, //Gamma Blue
37      0x03, 0x00, 0x00, 0x00, //Intent - Photo
38      0x00, 0x00, 0x00, 0x00, //ICC Profile Data
39      0x00, 0x00, 0x00, 0x00, //ICC Profile Size
40      0x00, 0x00, 0x00, 0x00}; //Reserved

42  const uint8_t BMPHeader[BMPHEADERSIZE] = { 0x42, 0x4D,
43      0x8A, 0x58, 0x02, 0x00, //Size
44      0x00, 0x00, 0x00, 0x00, //Reserved
45      0x8A, 0x00, 0x00, 0x00 //Offset to Pixel Array
46  };

```

H.1.1.3 CustomDevices.h

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/CustomDevices.h

```
1  /*
2   *  CustomDevices.h
3   *
4   *  * Created: 16/02/2013 14:30:50
5   *  Author: hslovett
6   */
7
8
9 #ifndef CUSTOMDEVICES_H_
10 #define CUSTOMDEVICES_H_
11
12 //Camera
13 #include "CustomDevices/0V7670.h"
14 //I2C Mux
15 #include "CustomDevices/PCA9542A.h"
16 //MotorDriver
17 #include "CustomDevices/MotorDriver.h"
18 //SDCard
19 #include "CustomDevices/SD_Card.h"
20 //Image Processing Functions
21 #include "CustomDevices/ImageProcessor.h"
22
23 typedef struct {
24     int Status;
25     SD_Status_t *SD_Card;
26     Motor_Control_t *Motors;
27     OV7670_t *Cameras;
28     PCA9542A_t *I2CMux;
29 } Columbus_Status_t;
30
31 #define SD_ERR      0x1
32 #define CAM_ERR     0x2
33 #define I2CMux_ERR  0x4
34
35 #define FFT_SIZE 64
36
37 mspace sdram_msp;
38 Columbus_Status_t Columbus_Status;
39 //TWI Methods
40 void twim_init (void);
41 void System_Test();
42 #endif /* CUSTOMDEVICES_H_ */
```

H.1.1.4 ImageProcessor.h

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/ImageProcessor.h

```
1  /*
2   * ImageProcessor.h
3   *
4   * Created: 28/02/2013 17:46:37
5   * Author: hslovett
```

```

6   */

9 #ifndef IMAGEPROCESSOR_H_
10 #define IMAGEPROCESSOR_H_

12 #define BMP_FORMAT_RGB565      1
13 #define BMP_FORMAT_RGB555      2
14 #define BMP_FORMAT_GREYSCALE    3
15 #define BMP_FORMAT_1xUINT       4
16 #define BMP_FORMAT_2xUINT8T     5
17 typedef struct {
18     uint16_t *ImagePtr;
19     int Height;
20     int Width;
21     uint8_t Format;
22 } Image_t;

26 void FFT1D( int *Signal, dsp16_complex_t *ComplexBuffer);
27 int FFT2Dabs(int *Signal);
28 int log_2(int i);

30 void FFT2DCOMPLEX( int *Signal, dsp16_complex_t *ComplexBuffer, int size );
31 void PrepareImage(Image_t *Image);
32 //int* IFFT2D (dsp16_complex_t *Result, dsp16_complex_t *Input);
33 void IFFT2D (dsp16_complex_t *Signal); /*Need to test this! */;
34 int FFT1D_Abs( int *Signal);
35 void Complex_Abs( int *Signal, dsp16_complex_t *ComplexBuffer, int size);
36 #endif /* IMAGEPROCESSOR_H_ */

```

H.1.1.5 ImageProcessor.c

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/ImageProcessor.c

```

1 /*
2  * ImageProcessor.c
3  *
4  * Created: 28/02/2013 17:46:50
5  * Author: hslovett
6  */
7 #include <asf.h>
8 #include "CustomDevices/CustomDevices.h"

10 /*#define FFT_SIZE 64*/
11 //Returns log base 2 of i - checks if it is an integer power of 2
12 int log_2(int i)
13 {
14     int ret = 0;
15     if((i & (i - 1)) != 0)
16     {
17         return -1;
18     }

```

```

19     while((i & 1) == 0) //while the bit isn't in the lowest bit (already
20         established this is a integer power of 2)
21     {
22         i >>= 1;
23         ret++;
24     }
25
26     return ret;
27 }
28 //*****
29 // Method:      FFT2DCOMPLEX
30 // FullName:   FFT2DCOMPLEX
31 // Access:     public
32 // Returns:    int*
33 // Qualifier:
34 // Parameter:  int * Signal
35 // Parameter:  A_ALIGNED dsp16_complex_t * ComplexBuffer
36 // Parameter:  int size
37 //*****
38 void FFT2DCOMPLEX( int *Signal, dsp16_complex_t *ComplexBuffer, int size )
39 {
40     int i, j = 0;
41     int Ptr;
42     Ptr = 0;
43     A_ALIGNED dsp16_complex_t Input_C_1D[FFT_SIZE];
44     A_ALIGNED dsp16_complex_t Result_C_1D[FFT_SIZE];
45     A_ALIGNED dsp16_complex_t Result_C_2D[FFT_SIZE*FFT_SIZE];
46     A_ALIGNED dsp16_t Input_R_1D[FFT_SIZE];
47     //Stage 1 - FFT Real values from Signal. Store VERTICALLY in Result_2D
48     //print_dbg("\n\rStage 1 Reached. Iteration: \n\r");
49     for(i = 0; i < FFT_SIZE; i++){ //for each row
50         for(j = 0; j < FFT_SIZE; j++){
51             Input_R_1D[j] = Signal[Ptr++]; //copy the data across
52         }
53         //Do the FFT
54         //    print_dbg("\r");
55         //    print_dbg_ulong(i);
56
57         dsp16_trans_realcomplexfft(Result_C_1D, Input_R_1D, log_2(FFT_SIZE));
58         //Copy data into 2D result TRANSPOSED
59         for(j = 0; j < FFT_SIZE; j++){
60             Result_C_2D[i + (j * FFT_SIZE)].imag = Result_C_1D[j].imag * FFT_SIZE;//
61             scale back up
62             Result_C_2D[i + (j * FFT_SIZE)].real = Result_C_1D[j].real * FFT_SIZE;
63         }
64         //print_dbg("\n\rStage 2 Reached. Iteration: \n\r");
65         //Stage 2 - FFT Complex Values from Result_2D, put back into Rows
66         for(i = 0; i < FFT_SIZE; i++){//for each row
67             for(j = 0; j < FFT_SIZE; j++){//copy the data across
68                 Input_C_1D[j].imag = Result_C_2D[j + i * FFT_SIZE].imag;
69                 Input_C_1D[j].real = Result_C_2D[j + i * FFT_SIZE].real;
70             }
71             //    print_dbg("\r");
72             //    print_dbg_ulong(i);
73             //Do Fourier
74             dsp16_trans_complexfft(Result_C_1D, Input_C_1D, log_2(FFT_SIZE));
75             //Copy back
76     }

```

```

75     for(j = 0; j < FFT_SIZE; j++){
76         ComplexBuffer[i + j * FFT_SIZE].imag = Result_C_1D[j].imag;
77         ComplexBuffer[i + j * FFT_SIZE].real = Result_C_1D[j].real;
78     }
79 }
80 return;
81 }

83 //One Dimensional Fast Fourier Transform
84 int FFT1D_Abs( int *Signal)
85 {
86     int log2Size, i =0;
87     A_ALIGNED dsp16_complex_t vect1[FFT_SIZE];
88     A_ALIGNED dsp16_t vect2[FFT_SIZE];
89     for(i = 0; i < FFT_SIZE; i++)
90     {
91         vect2[i] = (dsp16_t)Signal[i];
92     }
93     dsp16_trans_realcomplexfft(vect1, vect2, log_2(FFT_SIZE));
94     for(i = 0; i < FFT_SIZE; i++)
95     {
96         vect1[i].imag = vect1[i].imag * FFT_SIZE;
97         vect1[i].real = vect1[i].real * FFT_SIZE;
98     }
99     dsp16_vect_complex_abs(vect2, vect1, FFT_SIZE);
100    for(i = 0; i < FFT_SIZE; i++)
101    {
102        Signal[i] = vect2[i];// * FFT_SIZE;
103    }

105    return Signal;
106}

108 void Complex_Abs( int *Signal, dsp16_complex_t *ComplexBuffer, int size)
109 {
110     int log2Size, i =0;
111     A_ALIGNED dsp16_complex_t vect1[FFT_SIZE];
112     A_ALIGNED dsp16_t vect2[FFT_SIZE];
113     for(i = 0; i < FFT_SIZE; i++)
114     {
115         vect1[i].imag = ComplexBuffer[i].imag;
116         vect1[i].real = ComplexBuffer[i].real;
117     }
118     dsp16_vect_complex_abs(vect2, vect1, FFT_SIZE);
119     for(i = 0; i < FFT_SIZE; i++)
120     {
121         Signal[i] = vect2[i];// * FFT_SIZE;
122     }
123 }
124 //One Dimensional Fast Fourier Transform returning complex values
125 void FFT1D( int *Signal, dsp16_complex_t *ComplexBuffer)
126 {
127     int log2Size, i =0;
128     A_ALIGNED dsp16_complex_t vect1[FFT_SIZE];
129     A_ALIGNED dsp16_t vect2[FFT_SIZE];
130     for(i = 0; i < FFT_SIZE; i++)
131     {
132         vect2[i] = Signal[i];

```

```

133 }
134 dsp16_trans_realcomplexfft(vect1, vect2, log_2(FFT_SIZE));
135 for(i = 0; i < FFT_SIZE; i++)
136 {
137     ComplexBuffer[i].imag = vect1[i].imag * FFT_SIZE;
138     ComplexBuffer[i].real = vect1[i].real * FFT_SIZE;
139 }
140 }
141 int FFT2Dabs( int *Signal )
142 {
143     int i, j = 0;
144     int Ptr;
145     Ptr = 0;
146     A_ALIGNED dsp16_complex_t Input_C_1D[FFT_SIZE];
147     A_ALIGNED dsp16_complex_t Result_C_1D[FFT_SIZE];
148     A_ALIGNED dsp16_complex_t Result_C_2D[FFT_SIZE*FFT_SIZE];
149     A_ALIGNED dsp16_t Input_R_1D[FFT_SIZE];

150     //Stage 1 - FFT Real values from Signal. Store VERTICALLY in Result_2D
151     for(i = 0; i < FFT_SIZE; i++) //for each row
152     {
153         //    print_dbg("\n\rInput to FFT: \n\r[");

154         for(j = 0; j < FFT_SIZE; j++)
155         {
156             Input_R_1D[j] = Signal[Ptr++]; //copy the data across
157             //    print_dbg_ulong(Input_R_1D[j]);
158             //    print_dbg(" , ");
159         }
160         //    print_dbg("\b\b]");
161         //Do the FFT
162         dsp16_trans_realcomplexfft(Result_C_1D, Input_R_1D, log_2(FFT_SIZE));
163         //Copy data into 2D result TRANSPOSED
164         //    print_dbg("\n\rOutput of FFT:\n\r[");

165         for(j = 0; j < FFT_SIZE; j++)
166         {
167             Result_C_2D[i + (j * FFT_SIZE)].imag = Result_C_1D[j].imag * FFT_SIZE;//
168             scale back up
169             Result_C_2D[i + (j * FFT_SIZE)].real = Result_C_1D[j].real * FFT_SIZE;
170             //    print_dbg_ulong(Result_C_2D[i + (j * FFT_SIZE)].real);
171             //    print_dbg(" + j");
172             //    print_dbg_ulong(Result_C_2D[i + (j * FFT_SIZE)].imag);
173             //    print_dbg(" , ");
174         }
175         //    print_dbg("\b\b]");
176     }
177     //Stage 2 - FFT Complex Values from Result_2D, put back into Rows

178     for(i = 0; i < FFT_SIZE; i++)//for each row
179     {
180         //    print_dbg("\n\rInput to FFT: \n\r[");

181         for(j = 0; j < FFT_SIZE; j++)//copy the data across
182         {
183             Input_C_1D[j].imag = Result_C_2D[j + i * FFT_SIZE].imag;
184             Input_C_1D[j].real = Result_C_2D[j + i * FFT_SIZE].real;
185             //    print_dbg_ulong(Input_C_1D[j].real);
186             //    print_dbg(" + j");
187             //    print_dbg_ulong(Input_C_1D[j].imag);
188             //    print_dbg(" , ");
189         }

```

```

190     }
191     //    print_dbg("\b\b]");
192     //Do Fourier
193     dsp16_trans_complexfft(Result_C_1D, Input_C_1D, log_2(FFT_SIZE));
194     //Copy back

196     //    print_dbg("\n\rOutput to FFT: \n\r[" );
197     //    for(j = 0; j < FFT_SIZE; j++)//copy the data across
198     //{
199     //        print_dbg_ulong(Result_C_1D[j].real);
200     //        print_dbg(" + j");
201     //        print_dbg_ulong(Result_C_1D[j].imag);
202     //        print_dbg(" , ");
203     //}
204     //    print_dbg("\b\b]");
205     //Calculate Abs and put back into Signal TRANSPOSED
206     dsp16_vect_complex_abs(Input_R_1D, Result_C_1D, FFT_SIZE);

208     for(j = 0; j < FFT_SIZE; j++)
209     {
210         Signal[i + (j*FFT_SIZE)] = Input_R_1D[j] * FFT_SIZE;
211     }
212 }
213 return Signal;
214 }

219 void PrepareImage(Image_t *Image)
{
220     int row, col;
221     uint16_t *PreparedImage;
222     //Allocate some memory in the RAM
223     PreparedImage = mspace_malloc(sdram_msp, 256*256 );

226     //print_dbg("\n\rPrepared Image Pointer = ");
227     //print_dbg_ulong(PreparedImage);
228     for(row = 0; row < 256; row++)
229     {
230         for(col = 0; col < 256; col++)
231         {
232             if(row < 240)
233                 PreparedImage[row*256 + col] = Image->ImagePtr[row * 256 + col];
234             else
235                 PreparedImage[row *256 + col] = 0;//Image->ImagePtr[(row - 240) * 256
236 + col + 32];
237         }
238     }

239     mspace_free(sdram_msp, Image->ImagePtr); //free up the old image
240     Image->ImagePtr = PreparedImage; //move the pointer to the prepared image
241     Image->Height = 256;
242     Image->Width = 256;
243     //SaveBitmap(PreparedImage, 256, 256, "PreparedImage.bmp");
244     //mspace_free(sdram_msp, PreparedImage);
245     //return PreparedImage;
246 }

```

```

249 //*****
250 // Method: IFFT2D
251 // FullName: IFFT2D
252 // Access: public
253 // Returns: void
254 // Qualifier:
255 // Parameter: dsp16_complex_t * Signal
256 //*****
257 void IFFT2D (dsp16_complex_t *Signal) //Need to test this!
{
258     int i, j = 0;
259     int Ptr;
260     Ptr = 0;
261     A_ALIGNED dsp16_complex_t Input_C_1D[FFT_SIZE];
262     A_ALIGNED dsp16_complex_t Result_C_1D[FFT_SIZE];
263     A_ALIGNED dsp16_complex_t Result_C_2D[FFT_SIZE*FFT_SIZE];
264     A_ALIGNED dsp16_t Input_R_1D[FFT_SIZE];

265
266     //Stage 1 - FFT Real values from Signal. Store VERTICALLY in Result_2D
267     for(i = 0; i < FFT_SIZE; i++) //for each row
268     {
269         for(j = 0; j < FFT_SIZE; j++)
270         {
271             Input_C_1D[j].real = Signal[Ptr].real; //copy the data across
272             Input_C_1D[j].imag = Signal[Ptr].imag;
273         }
274
275         //Do the FFT
276         dsp16_trans_complexifft(Result_C_1D, Input_C_1D, log_2(FFT_SIZE));
277         //Copy data into 2D result TRANSPOSED
278
279         for(j = 0; j < FFT_SIZE; j++)
280         {
281             Result_C_2D[i + (j * FFT_SIZE)].imag = Result_C_1D[j].imag * FFT_SIZE;//
282             scale back up
283             Result_C_2D[i + (j * FFT_SIZE)].real = Result_C_1D[j].real * FFT_SIZE;
284         }
285
286     }
287     //Stage 2 - FFT Complex Values from Result_2D, put back into Rows
288
289     for(i = 0; i < FFT_SIZE; i++)//for each row
290     {
291
292         for(j = 0; j < FFT_SIZE; j++)//copy the data across
293         {
294             Input_C_1D[j].imag = Result_C_2D[j + i * FFT_SIZE].imag;
295             Input_C_1D[j].real = Result_C_2D[j + i * FFT_SIZE].real;
296
297         }
298
299         //Do Fourier
300         dsp16_trans_complexifft(Result_C_1D, Input_C_1D, log_2(FFT_SIZE));
301         //Copy back
302
303

```

```

306     //Put back into Signal TRANSPOSED
307     //dsp16_vect_complex_abs(Input_R_1D, Result_C_1D, FFT_SIZE);

309     for(j = 0; j < FFT_SIZE; j++)
310     {
311         Signal[i + j * FFT_SIZE].imag = Result_C_1D[j].imag;
312         Signal[i + j * FFT_SIZE].real = Result_C_1D[j].real;
313         //Signal[i + (j*FFT_SIZE)] = Input_R_1D[j] * FFT_SIZE;
314     }
315 }

317     //return Signal;
318 }

320 void ComplexMultiply(dsp16_complex_t *Result_Input1, dsp16_complex_t *Input2,
321     int size)
322 {
323     int i = 0;
324     dsp16_complex_t c;
325     for(i = 0; i < size; i++)
326     {
327         //((a+jb).(c+jd) = (ac - bd) + j(ad + bc)
328         c.real = (Result_Input1[i].real * Input2[i].real) - (Result_Input1[i].imag
329             * Input2[i].imag);
330         c.imag = (Result_Input1[i].real * Input2[i].imag) + (Result_Input1[i].imag
331             * Input2[i].real);
332         Result_Input1[i].imag = c.imag;
333         Result_Input1[i].real = c.real;
334     }
335 }
```

H.1.1.6 MotorDriver.h

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/MotorDriver.h

```

1  /*
2   * MotorDriver.h
3   *
4   * Created: 10/02/2013 18:11:55
5   * Author: hslovett
6   */

9  #ifndef MOTORDRIVER_H_
10 #define MOTORDRIVER_H_
11 #include <asf.h>
12 //Definitions
13 #define MOTOR_L      ML_PWM_CHANNEL_ID
14 #define MOTOR_R      MR_PWM_CHANNEL_ID

16 #define FORWARD      2
17 #define BACKWARD     3
```

```

18 #define LEFT_SPOT    4
19 #define RIGHT_SPOT   5
20 #define SPOT_PIVOT   6
21 #define STOP         7

24 #define ENABLE ACA_INTERRUPT // {AVR32_ACIFA1.iер = 1; }
25 #define DISABLE ACA_INTERRUPT // {AVR32_ACIFA1.iдр = 1; }
26 #define ENABLE ACB_INTERRUPT // {AVR32_ACIFA1.iер = 2; }
27 #define DISABLE ACB_INTERRUPT // {AVR32_ACIFA1.iдр = 2; }
28 #define GAMMA 10 // Interrupts caused per full rotation of a wheel
29 #define CIRCUMFERENCE_WHEEL_MM 116 // in millimeters
30 // #define CIRCUMFERENCE_WHEEL_CM 12 // in centimeters
31 #define MIN_DISTANCE_RESOLUTION CIRCUMFERENCE_WHEEL_MM / GAMMA
32 #define MIN_ROTATION_RESOLUTION (CIRCUMFERENCE_WHEEL_MM * 360) / (GAMMA * C_b)
33 #define C_b 282
34 #define ROTATION_CONST (GAMMA * C_b) / (CIRCUMFERENCE_WHEEL_MM * 360)
35 #define ROTATION_CONST_INV (CIRCUMFERENCE_WHEEL_MM * 360) / (GAMMA *
36     C_b)

37 // Type Defs
38 typedef struct {
39     int Left_State;
40     int Right_State;
41     int Left_Count;
42     int Right_Count;
43 } Motor_Control_t;

44 // Globals
45 pwm_opt_t pwm_opt; // PWM option config.
46 avr32_pwm_channel_t pwm_channel;
47 Motor_Control_t Motor_Control;

48 void Motor_Init();
49 void Motor_Go();
50 //void Analogue_Comparator_Init();
51 void Motor_Start(int Motors);
52 void Motors_Reset(void);
53 void Motor_Stop(int Motors);
54 bool Motors_Moving();
55 int Motors_Move(int centimetres_fwd) /* Move this amount forward in centimeters
56     */;
57 void Motors_Execute();
58 int Motors_Rotate(int angle_degs);
59 /* static void ACInterruptHandler(void); */
60 #endif /* MOTORDRIVER_H_ */

```

H.1.1.7 MotorDriver.c

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/MotorDriver.c

```

1 /*
2  * MotorDriver.c
3  *
4  * Created: 10/02/2013 18:12:07

```

```

5   * Author: hslovett
6   */
7 #include <asf.h>
8 #include "CustomDevices/CustomDevices.h"
9 #include <delay.h>

13 static void local_start_highfreq_clock(void)
14 {
15     const scif_pll_opt_t opt = {
16         .osc = SCIF_OSC0,           // Sel Osc0/PLLO or Osc1/PLL1
17         .lockcount = 16,            // lockcount in main clock for the PLL wait
18         .lock
19         .div = 1,                  // DIV=1 in the formula
20         .mul = 6,                  // MUL=7 in the formula
21         .pll_div2 = 1,              // pll_div2 Divide the PLL output frequency
22         by 2 (this settings does not change the FVCO value)
23         .pll_wbwdisable = 0,        // pll_wbwdisable 1 Disable the Wide-Bandith
24         Mode (Wide-Bandwith mode allow a faster startup time and out-of-lock time
25         ). 0 to enable the Wide-Bandith Mode.
26         .pll_freq = 1,              // Set to 1 for VCO frequency range 80-180
27         MHz, set to 0 for VCO frequency range 160-240Mhz.
28     };
29     // Switch main clock to Osc0.
30     // pcl_switch_to_osc(PCL_OSC0, FOSCO, OSCO_STARTUP);

31     /* Setup PLL0 on Osc0, mul=7 ,no divisor, lockcount=16, ie. (16Mhzx7)/(div2)
32      = 56MHz output */
33     scif_pll_setup(SCIF_PLL0, &opt); // lockcount in main clock for the PLL wait
34     lock

35     /* Enable PLL0 */
36     scif_pll_enable(SCIF_PLL0);

37     /* Wait for PLL0 locked */
38     scif_wait_for_pll_locked(SCIF_PLL0) ;
39 }
40
41 static void pwm_start_gc(void)
42 {
43     scif_gc_setup(AVR32_SCIF_GCLK_PWM,
44                   SCIF_GCCTRL_PLL0,
45                   AVR32_SCIF_GC_NO_DIV_CLOCK,
46                   0);
47     scif_gc_enable(AVR32_SCIF_GCLK_PWM);
48 }
49
50 void Analogue_Comparator_Init()
51 {
52     static const gpio_map_t ACIFA_GPIO_MAP =
53     {
54         {POTO_AC1AP1_PIN, POTO_AC1AP1_FUNCTION},
55         {POT1_AC1BP1_PIN, POT1_AC1BP1_FUNCTION},
56         {SENSEO_AC1AN1_PIN, SENSEO_AC1AN1_FUNCTION},
57         {SENSE1_AC1BN1_PIN, SENSE1_AC1BN1_FUNCTION},
58     };
59
60     gpio_enable_module(ACIFA_GPIO_MAP, sizeof(ACIFA_GPIO_MAP) / sizeof(
61         ACIFA_GPIO_MAP[0]));
62 }
```

```

55 //Make it an interrupt
56 Disable_global_interrupt();

58 acifa_configure_hysteresis(&AVR32_ACIFA1, ACIFA_COMP_SELA, 2);
59 acifa_configure(&AVR32_ACIFA1,
60 ACIFA_COMP_SELA,
61 POTO_AC1AP1_INPUT,
62 SENSEO_AC1AN1_INPUT,
63 FOSCO);

65 acifa_configure_hysteresis(&AVR32_ACIFA1, ACIFA_COMP_SELB, 2);
66 acifa_configure(&AVR32_ACIFA1,
67 ACIFA_COMP_SELB,
68 POT1_AC1BP1_INPUT,
69 SENSE1_AC1BN1_INPUT,
70 FOSCO);

72 // acifa_enable_interrupt(&AVR32_ACIFA1, (1 << AVR32_ACIFA_ACBINT )| (1 <<
73 AVR32_ACIFA_ACAINT));//Enable ACBINT and ACAINT
74 // AVR32_ACIFA1.iер = 3; //enable interrupts
75 // acifa_enable_interrupt_toggle(&AVR32_ACIFA1, ACIFA_COMP_SELA);
76 // acifa_enable_interrupt_toggle(&AVR32_ACIFA1, ACIFA_COMP_SELB);
77 // acifa_enable_interrupt_inp_lower(&AVR32_ACIFA1, ACIFA_COMP_SELA);
78 // acifa_enable_interrupt_inp_lower(&AVR32_ACIFA1, ACIFA_COMP_SELB);
79 acifa_start(&AVR32_ACIFA1, (ACIFA_COMP_SELA|ACIFA_COMP_SELB));

80 // INTC_register_interrupt(&ACInterruptHandler,AVR32_ACIFA1_IRQ ,
81 AVR32_INTC_INTO);

82 Enable_global_interrupt();
83 }

84 void Motor_Init()
85 {
86 //Turn boths motors off
87 ML_STANDBY;
88 MR_STANDBY;

89 ML_IN1_CLR;
90 ML_IN2_CLR;

91 MR_IN1_CLR;
92 MR_IN2_CLR;

93 Motor_Control.Left_Count = 0;
94 Motor_Control.Right_Count = 0;
95 Motor_Control.Left_State = STOP;
96 Motor_Control.Right_State = STOP;

97 avr32_pwm_channel_t pwm_channel = { {0}, // cmr
98                                     {0}, // cdtv
99                                     {0}, // cdtyupd
100                                    {0}, // cprd
101                                    {0}, // cprdupd
102                                    {0}, // ccnt
103                                    {0}, // dt
104                                    {0}}; // dtupd ; One channel config.

105 /* unsigned int channel_id;*/

```

```

111 // Start PLL for PWM
112 local_start_highfreq_clock();
113 // Start Enable Generic Clock with PLL as source clock
114 pwm_start_gc();
115 gpio_enable_module_pin(ML_PWM_H_PIN, ML_PWM_H_FUNCTION);
116 gpio_enable_module_pin(MR_PWM_H_PIN, MR_PWM_H_FUNCTION);
117 // PWM controller configuration.
118 pwm_opt.diva = AVR32_PWM_DIVA_CLK_OFF;
119 pwm_opt.divb = AVR32_PWM_DIVB_CLK_OFF;
120 pwm_opt.prea = AVR32_PWM_PREA_CCK;
121 pwm_opt.preb = AVR32_PWM_PREB_CCK;
122 pwm_opt.fault_detection_activated = false;
123 pwm_opt.sync_channel_activated = true;
124 pwm_opt.sync_update_channel_mode =
    PWM_SYNC_UPDATE_MANUAL_WRITE_MANUAL_UPDATE;
125 pwm_opt.sync_channel_select[0] = false;
126 pwm_opt.sync_channel_select[1] = false;
127 pwm_opt.sync_channel_select[2] = false;
128 pwm_opt.sync_channel_select[3] = false;
129 pwm_opt.cksel = PWM_CKSEL_GCLK;
130 pwm_init(&pwm_opt);
131 // Update the period
132 pwm_update_period_value(10);
133 // Channel configuration
134 pwm_channel.CMR.dte = 0; // Enable Deadtime for complementary
    Mode
135 pwm_channel.CMR.dthi = 0; // Deadtime Inverted on PWMH
136 pwm_channel.CMR.dtli = 0; // Deadtime Not Inverted on PWML
137 pwm_channel.CMR.ces = 0; // 0/1 Channel Event at the End of
    PWM Period
138 pwm_channel.CMR.calg = PWM_MODE_LEFT_ALIGNED; // Channel mode.
139 pwm_channel.CMR.cpol = PWM_POLARITY_HIGH; // Channel polarity.
140 pwm_channel.CMR.cpre = AVR32_PWM_CPRE_CCK; // Channel prescaler.
141 pwm_channel.cdtv = 50; // Channel duty cycle, should be <
    CPRD.
142 pwm_channel.cprd = 200; // Channel period.

144 pwm_channel_init(ML_PWM_CHANNEL_ID, &pwm_channel); // Set channel
    configuration to channel 0
145 pwm_channel_init(MR_PWM_CHANNEL_ID, &pwm_channel); // Set channel
    configuration to channel 0
146 Analogue_Comparator_Init();
147 }

149 // __attribute__((__interrupt__)) static void ACInterruptHandler(void)
150 // {
151 // }
152 // }

154 void Motor_Start(int Motors)
155 {
156     if(Motors & MOTOR_L)
157     {
158         if(Motor_Control.Left_State == FORWARD)
159         {
160             ML_IN1_SET;
161             ML_IN2_CLR;
162         }

```

```

163     else if (Motor_Control.Left_State == BACKWARD)
164     {
165         ML_IN1_CLR;
166         ML_IN2_SET;
167     }
168     else //Somethings gone wrong
169     {
170         ML_IN1_CLR;
171         ML_IN2_CLR;
172         return; //don't start any pwm channel
173     }
174     ML_GO;
175     pwm_start_channels((1 << MOTOR_L)); //Start PWM Channel on M0 line
176 }

178 if(Motors & MOTOR_R)
179 {
180     if(Motor_Control.Right_State == FORWARD)
181     {
182         MR_IN1_SET;
183         MR_IN2_CLR;
184     }
185     else if (Motor_Control.Right_State == BACKWARD)
186     {
187         MR_IN1_CLR;
188         MR_IN2_SET;
189     }
190     else //Somethings gone wrong
191     {
192         MR_IN1_CLR;
193         MR_IN2_CLR;
194         return; //don't start any pwm channel
195     }
196     MR_GO;
197     pwm_start_channels((1 << MOTOR_R));
198 }
199 }

201 #define HYST_MAX 10
202 #define SAMPLE_TIME 10
203 void Motors_Execute()
204 {
205     int Left_State = acifa_is_acb_inp_higher(&AVR32_ACIFA1);
206     int Right_State = acifa_is_aca_inp_higher(&AVR32_ACIFA1);
207     int Left_Hyst = 0;
208     int Right_Hyst = 0;
209     bool Left_OnTab = false;
210     bool Right_OnTab = false;

212     while(Motors_Moving())
213     {
214         /////////////////////////////////
215         // LEFT MOTOR ///////////////////
216         /////////////////////////////////
217         Left_OnTab = acifa_is_acb_inp_higher(&AVR32_ACIFA1); //Read the status of
the comparator
218
219         if(Left_State == 0) //State Not on Tab

```

```
220     {
221         LED5_CLR;
222         if(Left_OnTab == true)
223         {
224             Left_Hyst++;
225             if(Left_Hyst == HYST_MAX) //reached threshold, change state
226             {
227                 Left_State = 1;
228                 Motor_Control.Left_Count--; //Decrement the global counter
229                 Left_Hyst = 0;
230                 print_dbg("\n\rLeft Count Decrement");
231             }
232         }
233         else //Reset counter
234         {
235             Left_Hyst = 0;
236         }
237     }
238     else //State On Tab
239     {
240         LED5_SET;
241         if(Left_OnTab == true)//still on a tab
242         {
243             Left_Hyst = 0; //Reset counter
244         }
245         else
246         {
247             Left_Hyst++;
248             if(Left_Hyst == HYST_MAX) //Reached Threshold. Change state
249             {
250                 Left_State = 0;
251                 Left_Hyst = 0;
252             }
253         }
254     }
255     ///////////////////////////////
256 // RIGHT MOTOR //////////////////
257 ///////////////////////////////
258 Right_OnTab = acifa_is_aca_inp_higher(&AVR32_ACIFA1); //Read the status of
the comparator

260     if(Right_State == 0) //State Not on Tab
261     {
262         LED6_CLR;
263         if(Right_OnTab == true)
264         {
265             Right_Hyst++;
266             if(Right_Hyst == HYST_MAX) //reached threshold, change state
267             {
268                 Right_State = 1;
269                 Motor_Control.Right_Count--; //Decrement the global counter
270                 Right_Hyst = 0;
271                 print_dbg("\n\rRight Count Decrement");
272             }
273         }
274         else //Reset counter
275         {
276             Right_Hyst = 0;
```

```
277     }
278 }
279 else //State On Tab
280 {
281     LED6_SET;
282     if(Right_OnTab == true)//still on a tab
283     {
284         Right_Hyst = 0;//Reset counter
285     }
286     else
287     {
288         Right_Hyst++;
289         if(Right_Hyst == HYST_MAX)//Reached Threshold. Change state
290         {
291             Right_State = 0;
292             Right_Hyst = 0;
293         }
294     }
295 }
296 int temp = 0;
297 if(Motor_Control.Left_Count <= 0) //if we have reached the end of the
movement on left wheel
298     temp |= MOTOR_L;

300 if(Motor_Control.Right_Count <= 0)
301     temp |= MOTOR_R;
302 if(temp != 0)
303     Motor_Stop(temp); //Stop the Motor

305 //Delay to keep a low sample time
306 delay_ms(SAMPLE_TIME);
307 }
308 }
309 void Motor_Stop(int Motors)
310 {
311     if(Motors & MOTOR_L)
312     {
313         ML_STANDBY;
314         Motor_Control.Left_State = STOP;
315         pwm_stop_channels((1 << MOTOR_L)); //Start PWM Channel on M0 line
316     }

318     if(Motors & MOTOR_R)
319     {
320         MR_STANDBY;
321         Motor_Control.Right_State = STOP;
322         pwm_stop_channels((1 << MOTOR_R));
323     }
324 }
325 int Motors_Move(int millimetres_fwd)//Move this amount forward in centimeters
326 {
327     //Calculate number of interrupts of each wheel
328     int number_interrupts;
329     int distance_moved;
330     if(millimetres_fwd > 0)
331     {
332         Motor_Control.Left_State = FORWARD;
333         Motor_Control.Right_State = FORWARD;
```

```
334     }
335     else
336     {
337         millimetres_fwd = Abs(millimetres_fwd);
338         Motor_Control.Left_State = BACKWARD;
339         Motor_Control.Right_State = BACKWARD;
340     }
341     number_interrupts = (millimetres_fwd * (int)GAMMA) / (int)
342             CIRCUMFERENCE_WHEEL_MM;
343     distance_moved = number_interrupts * MIN_DISTANCE_RESOLUTION;
344     print_dbg("\n\rNumber of interrupts to move = ");
345     print_dbg_ulong(number_interrupts);

346     Motor_Control.Left_Count = number_interrupts;
347     Motor_Control.Right_Count = number_interrupts;
348     Motor_Start(MOTOR_L | MOTOR_R);
349     Motors_Execute();
350     return distance_moved;
351 }

353 void Motors_Reset(void)
354 {
355     Motor_Control.Left_State = FORWARD;
356     Motor_Control.Left_Count = 1;
357     Motor_Control.Right_State = FORWARD;
358     Motor_Control.Right_Count = 1;
359     Motor_Start(MOTOR_L | MOTOR_R);
360     Motors_Execute();
361 }

363 bool Motors_Moving()
364 {
365 //    if(Motor_Control.Left_State != STOP)
366 //    {
367 //        if(Motor_Control.Right_State != STOP)
368 //        {
369 //            return true;
370 //        }
371 //    else
372 //        return false;
373 //    }
374 //    else
375 //    {
376 //        return false;
377 //    }
378     if(Motor_Control.Left_State != STOP) //Left is moving
379     {
380         return true;
381     }
382     else if (Motor_Control.Right_State != STOP) //Right is moving
383     {
384         return true;
385     }
386     else
387     {
388         return false;
389     }
390 }
```

```
393 int Motors_Rotate(int angle_degs)
394 {
395     int interrupts_to_move = 0;
396     int angle_rotated;
397     //calculate interrupts to move
398     interrupts_to_move = angle_degs * ROTATION_CONST;
399     angle_rotated = interrupts_to_move * ROTATION_CONST_INV;
400     // if(Pivot_Type == LEFT_SPOT)
401     //{
402     //    //Right wheel moves
403     //    Motor_Control.Left_Count = 0;
404     //    Motor_Control.Left_State = STOP;
405     //    if(interrupts_to_move > 0)
406     //{
407     //        Motor_Control.Right_State = FORWARD;
408     //}
409     //    else
410     //{
411     //        Motor_Control.Right_State = BACKWARD;
412     //}
413     //    Motor_Control.Right_Count = Abs(interrupts_to_move);
414     //}
415     // else if (Pivot_Type == RIGHT_SPOT)
416     //{
417     //    //Left Wheel Moves
418     //    Motor_Control.Right_Count = 0;
419     //    Motor_Control.Right_State = STOP;
420     //    if(interrupts_to_move > 0)
421     //{
422     //        Motor_Control.Left_State = FORWARD;
423     //}
424     //    else
425     //{
426     //        Motor_Control.Left_State = BACKWARD;
427     //}
428     //    Motor_Control.Left_Count = Abs(interrupts_to_move);
429     //}
430     // else if (Pivot_Type == SPOT_PIVOT)
431     //{
432     //Both Wheels Move
433     if(interrupts_to_move > 0)
434     {
435         Motor_Control.Left_State = FORWARD;
436         Motor_Control.Right_State = BACKWARD;
437     }
438     else
439     {
440         Motor_Control.Right_State = FORWARD;
441         Motor_Control.Left_State = BACKWARD;
442     }
443     Motor_Control.Left_Count = Abs(interrupts_to_move);
444     Motor_Control.Right_Count = Abs(interrupts_to_move);
445     Motor_Start(MOTOR_L | MOTOR_R);
446     Motors_Execute();
447     return angle_rotated;
448 }
```

449 }

H.1.1.8 OV7670.h

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/OV7670.h

```
1  /*
2  *  OV7670.h
3  *
4  *  *  Created: 15/02/2013 13:12:00
5  *  *  Author: hslovett
6  */
7
8  #ifndef OV7670_H_
9  #define OV7670_H_
10 #include <asf.h>
11 ///////////////////////////////////////////////////////////////////
12 //  Constants
13 ///////////////////////////////////////////////////////////////////
14 #define HEIGHT          240
15 #define WIDTH           320
16 #define PIXELSIZE       2
17 #define SETTINGS_LENGTH 167
18 #define OV7670_ADDR     0x21
19
20 #define CAMERA_LEFT      1
21 #define CAMERA_RIGHT     2
22
23 #define CAMERA_LEFT_ERR   0x10
24 #define CAMERA_RIGHT_ERR  0x20
25
26 #define BMPHEADERSIZE    14
27 #define DIBHEADERSIZE    124 //v5
28 #define FILESIZE         153738
29 ///////////////////////////////////////////////////////////////////
30 //  Globals
31 ///////////////////////////////////////////////////////////////////
32 const char default_settings[SETTINGS_LENGTH][2];
33 const uint8_t DIBHead[DIBHEADERSIZE];
34 const uint8_t BMPHeader[BMPHEADERSIZE];
35
36 typedef struct {
37     uint8_t Status;
38     bool Camera_0_Found;
39     bool Camera_1_Found;
40     bool Camera_0_Error;
41     bool Camera_1_Error;
42     uint8_t VSYNCO_State;
43     uint8_t VSYNC1_State;
44 } OV7670_t ;
45
46 OV7670_t OV7670_Status;
47
48 #define IDLE          0
```

```

49 #define TAKE_PHOTO 1
50 #define TAKING_PHOTO 2
51 #define TAKEN_PHOTO 3
52 #define CAMERAS_BUSY 4

54 #define Image0Name "Image_L_%d.bmp"
55 #define Image1Name "Image_R_%d.bmp"
56 ///////////////////////////////////////////////////////////////////
57 // Methods
58 ///////////////////////////////////////////////////////////////////
59 void OV7670_Init(void); //Initialises Camera
60 void FIFO_Init();
61 int TakePhoto(uint8_t Cameras);
62 bool Photos_Ready(void);
63 void Store_Image_0();
64 void Store_Image_1();
65 void FIFO_Reset(uint8_t CameraID);
66 bool Store_Both_Images();
67 //void FIFO_Reset(uint8_t CameraID);
68 ///////////////////////////////////////////////////////////////////
69 // Pins & Macros
70 ///////////////////////////////////////////////////////////////////
71 #define FIFO_0_RCLK AVR32_PIN_PA19
72 #define FIFO_0_nRRST AVR32_PIN_PA15
73 #define FIFO_0_WEN AVR32_PIN_PA20
74 #define FIFO_0_WRST AVR32_PIN_PA21
75 #define FIFO_0_nOE AVR32_PIN_PA28
76 #define FIFO_0_VSYNC AVR32_PIN_PA29

78 #define FIFO_1_RCLK AVR32_PIN_PA23
79 #define FIFO_1_nRRST AVR32_PIN_PA22
80 #define FIFO_1_WEN AVR32_PIN_PA24
81 #define FIFO_1_WRST AVR32_PIN_PA25
82 #define FIFO_1_nOE AVR32_PIN_PA27

84 #define VSYNC_1_PIN AVR32_EIC_EXTINT_1_2_PIN
85 #define VSYNC_1_FUNCTION AVR32_EIC_EXTINT_1_2_FUNCTION
86 #define VSYNC_1_LINE 1
87 #define VSYNC_1_ENABLE_INTERRUPT {eic_enable_interrupt_line(&AVR32_EIC,
     VSYNC_1_LINE);}
88 #define VSYNC_1_DISABLE_INTERRUPT {eic_disable_interrupt_line(&AVR32_EIC,
     VSYNC_1_LINE);}

90 #define VSYNC_0_PIN AVR32_EIC_EXTINT_4_0_PIN
91 #define VSYNC_0_FUNCTION AVR32_EIC_EXTINT_4_0_FUNCTION
92 #define VSYNC_0_LINE 4
93 #define VSYNC_0_ENABLE_INTERRUPT {eic_enable_interrupt_line(&AVR32_EIC,
     VSYNC_0_LINE);}
94 #define VSYNC_0_DISABLE_INTERRUPT {eic_disable_interrupt_line(&AVR32_EIC,
     VSYNC_0_LINE);}

97 #define FIFO_0_RCLK_SET {gpio_set_gpio_pin(FIFO_0_RCLK);}
98 #define FIFO_0_nRRST_SET {gpio_set_gpio_pin(FIFO_0_nRRST);}
99 #define FIFO_0_WEN_SET {gpio_set_gpio_pin(FIFO_0_WEN);}
100 #define FIFO_0_WRST_SET {gpio_set_gpio_pin(FIFO_0_WRST);}
101 #define FIFO_0_nOE_SET {gpio_set_gpio_pin(FIFO_0_nOE);}

```

```

103 #define FIFO_0_RCLK_CLR      {gpio_clr_gpio_pin(FIFO_0_RCLK);}
104 #define FIFO_0_nRRST_CLR    {gpio_clr_gpio_pin(FIFO_0_nRRST);}
105 #define FIFO_0_WEN_CLR       {gpio_clr_gpio_pin(FIFO_0_WEN);}
106 #define FIFO_0_WRST_CLR      {gpio_clr_gpio_pin(FIFO_0_WRST);}
107 #define FIFO_0_nOE_CLR       {gpio_clr_gpio_pin(FIFO_0_nOE);}

111 #define FIFO_1_RCLK_SET      {gpio_set_gpio_pin(FIFO_1_RCLK);}
112 #define FIFO_1_nRRST_SET    {gpio_set_gpio_pin(FIFO_1_nRRST);}
113 #define FIFO_1_WEN_SET       {gpio_set_gpio_pin(FIFO_1_WEN);}
114 #define FIFO_1_WRST_SET      {gpio_set_gpio_pin(FIFO_1_WRST);}
115 #define FIFO_1_nOE_SET       {gpio_set_gpio_pin(FIFO_1_nOE);}

117 #define FIFO_1_RCLK_CLR      {gpio_clr_gpio_pin(FIFO_1_RCLK);}
118 #define FIFO_1_nRRST_CLR    {gpio_clr_gpio_pin(FIFO_1_nRRST);}
119 #define FIFO_1_WEN_CLR       {gpio_clr_gpio_pin(FIFO_1_WEN);}
120 #define FIFO_1_WRST_CLR      {gpio_clr_gpio_pin(FIFO_1_WRST);}
121 #define FIFO_1_nOE_CLR       {gpio_clr_gpio_pin(FIFO_1_nOE);}

124 #define CAMERA_INPUT  {(uint8_t)((AVR32_GPIO.port[1].pvr) & 0xFF);}
125 ///////////////////////////////////////////////////////////////////
126 //Camera Register Address definitions
127 ///////////////////////////////////////////////////////////////////
128 #define OV_GAIN          0x00 //Gain Control Setting - ACG[7:0]
129 #define OV_BLUE          0x01 //Blue Channel Gain
130 #define OV_RED           0x02 //Red Channel Gain
131 #define OV_VREF          0x03 //Vertical Frame Control & ACG[9:8]
132 #define OV_COM1          0x04 //CCIR656 enable, AEC low bits (AECHH, AECH)
133 #define OV_BAVE          0x05 //U/B Average level - AUTO UPDATED
134 #define OV_GbAVE         0x06 //Y/Gb Average Level - AUTO UPDATED
135 #define OV_AECHH         0x07 //Exposure value [15:10] (AECH, COM1)
136 #define OV_RAVE           0x08 //V/R Average level - AUTO UPDATED
137 #define OV_COM2          0x09 //Soft Sleep, Output drive capability
138 #define OV_PID            0x0A //Product ID MSB Read only
139 #define OV_VER            0x0B //Product ID LSB Read Only
140 #define OV_COM3          0x0C //Output data MSB/LSB swap + other stuff
141 #define OV_COM4          0x0D //Average values - MUST BE SAME AS COM17
142 #define OV_COM5          0x0E //RESERVED
143 #define OV_COM6          0x0F //COM6
144 #define OV_AECH           0x10 //Exposure value [9:2] (see AECHH, COM1)
145 #define OV_CLKRC          0x11 //Internal Clock options
146 #define OV_COM7          0x12 //RESET, Output format
147 #define OV_COM8          0x13 //Common control 8
148 #define OV_COM9          0x14 //Automatic Gain Ceiling
149 #define OV_COM10         0x15 //PCLK, HREF and VSYNC options
150 #define OV_RSVD           0x16 //RESERVED
151 #define OV_HSTART         0x17 //Output format Horizontal Frame start
152 #define OV_HSTOP          0x18 //Output format Horizontal Frame end
153 #define OV_VSTRT          0x19 //Output format Vertical Frame start
154 #define OV_VSTOP           0x1A //Output format Vertical Frame Stop
155 #define OV_PSHFT          0x1B //Pixel Delay Select
156 #define OV_MIDH           0x1C //Manufacturer ID MSB - READ ONLY
157 #define OV_MIDL           0x1D //Manufacturer ID LSB - READ ONLY
158 #define OV_MVFP            0x1E //Mirror / Vflip Enable
159 #define OV_LAEC           0x1F //RESERVED
160 #define OV_ADCCTRO        0x20 //ADC Control

```

```

161 #define OV_ADCCTR1    0x21 //RESERVED
162 #define OV_ADCCTR2    0x22 //RESERVED
163 #define OV_ADCCTR3    0x23 //RESERVED
164 #define OV_AEW        0x24 //ACG/AEC Stable Operating Region Upper Limit
165 #define OV_AEB        0x25 //ACG/AEC Stable Operation Region Lower Limit
166 #define OV_VPT        0x26 //ACG/AEC Fast Mode Operation Region
167 #define OV_BBIAS       0x27 //B Channel Signal Output Bias
168 #define OV_GbBIAS      0x28 //Gb Channel Output Bias
169 #define OV_RSVD1       0x29 //RESERVED
170 #define OV_EXHCH       0x2A //Dummy Pixel Insert MSB
171 #define OV_EXHCL       0x2B //Dummy Pixel Insert LSB
172 #define OV_RBIAS       0x2C //R Channel Signal Output Bias
173 #define OV_ADVFL       0x2D //LSB of insert dummy line in vertical direction
174 #define OV_ADVFH       0x2E //MSB of insert dummy line in vertical direction
175 #define OV_YAVE        0x2F //Y/G Channel Average Value
176 #define OV_HSYST       0x30 //HSYNC Rising Edge Delay (low 8 bits)
177 #define OV_HSYEN       0x31 //HSYNCE Falling Edge Delay (low 8 bits)
178 #define OV_HREF        0x32 //HREF Control
179 #define OV_CHLF        0x33 //Array Current Control - RESERVED
180 #define OV_ARBLM       0x34 //Array Reference Control - RESERVED
181 #define OV_RSVD2       0x35 //RESERVED
182 #define OV_RSVD3       0x36 //RESERVED
183 #define OV_ADCCTRL      0x37 //ADC Control - RESERVED
184 #define OV_ACOM         0x38 //ADC and Analog Common Mode Control - RESERVED
185 #define OV_OFON         0x39 //ADC Offset Control
186 #define OV_TSLB         0x3A //Line Buffer Test Option
187 #define OV_COM11        0x3B //COM11
188 #define OV_COM12        0x3C //COM12
189 #define OV_COM13        0x3D //COM13
190 #define OV_COM14        0x3E //COM14
191 #define OV_EDGE          0x3F //Edge Detection Adjustment
192 #define OV_COM15        0x40 //COM15
193 #define OV_COM16        0x41 //COM16
194 #define OV_COM17        0x42 //COM17
195 #define OV_AWBC1         0x43
196 #define OV_AWBC2         0x44
197 #define OV_AWBC3         0x45
198 #define OV_AWBC4         0x46
199 #define OV_AWBC5         0x47
200 #define OV_AWBC6         0x48
201 #define OV_RSVD4         0x49
202 #define OV_RSVD5         0x40
203 #define OV_RSVD6         0x4A
204 #define OV_REG4B         0x4B
205 #define OV_DNSTH         0x4C
206 #define OV_RSVD7         0x4D
207 #define OV_RSVD8         0x4E
208 #define OV_MTX1          0x4F
209 #define OV_MTX2          0x50
210 #define OV_MTX3          0x51
211 #define OV_MTX4          0x52
212 #define OV_MTX5          0x53
213 #define OV_MTX6          0x54
214 #define OV_BRIGHT         0x55
215 #define OV_CONTRAS        0x56
216 #define OV_CONTRASCNTR   0x57
217 #define OV_MTXS          0x58
218 #define OV_RSVD9         0x59

```

```
219 #define OV_RSVD9_1      0x5A
220 #define OV_RSVD9_2      0x5B
221 #define OV_RSVD9_3      0x5C
222 #define OV_RSVD9_4      0x5D
223 #define OV_RSVD9_5      0x5E
224 #define OV_RSVD9_6      0x5F
225 #define OV_RSVD10     0x60
226 #define OV_RSVD11     0x61
227 #define OV_LCC1       0x62
228 #define OV_LCC2       0x63
229 #define OV_LCC3       0x64
230 #define OV_LCC4       0x65
231 #define OV_LCC5       0x66
232 #define OV_MANU      0x67
233 #define OV_MANV      0x68
234 #define OV_GFIX      0x69
235 #define OV_GGAIN     0x6A
236 #define OV_DBLV      0x6B
237 #define OV_AWBCTR3   0x6C
238 #define OV_AWBCTR2   0x6D
239 #define OV_AWBCTR1   0x6E
240 #define OV_AWBCTR0   0x6F
241 #define OV_SCALING_XSC 0x70
242 #define OV_SCALING_YSC 0x71
243 #define OV_SCALING_DCWCTR 0x72
244 #define OV_SCALING_PCLK_DIV 0x73
245 #define OV_REG74      0x74
246 #define OV_REG75      0x75
247 #define OV_REG76      0x76
248 #define OV_REG77      0x77
249 #define OV_RSVD12     0x78
250 #define OV_RSVD13     0x79
251 #define OV_GAM1       0x7A
252 #define OV_GAM2       0x7B
253 #define OV_GAM3       0x7C
254 #define OV_GAM4       0x7D
255 #define OV_GAM5       0x7E
256 #define OV_GAM6       0x7F
257 #define OV_GAM7       0x80
258 #define OV_GAM8       0x81
259 #define OV_GAM9       0x82
260 #define OV_GAM10      0x83
261 #define OV_GAM11      0x84
262 #define OV_GAM12      0x85
263 #define OV_GAM13      0x86
264 #define OV_GAM14      0x87
265 #define OV_GAM15      0x88
266 #define OV_GAM16      0x89
267 #define OV_RSVD14     0x8A
268 #define OV_RSVD15     0x8B
269 #define OV_RSVD16     0x8C
270 #define OV_RSVD17     0x8D
271 #define OV_RSVD18     0x8E
272 #define OV_RSVD19     0x8F
273 #define OV_RSVD20     0x90
274 #define OV_RSVD21     0x91
275 #define OV_DM_LNL    0x92
276 #define OV_DM_LNH    0x93
```

```
277 #define OV_LCC6      0x94
278 #define OV_LCC7      0x95
279 #define OV_RSVD22    0x96
280 #define OV_RSVD23    0x97
281 #define OV_RSVD24    0x98
282 #define OV_RSVD25    0x99
283 #define OV_RSVD26    0x9A
284 #define OV_RSVD27    0x9B
285 #define OV_RSVD28    0x9C
286 #define OV_BD50ST    0x9D
287 #define OV_BD60ST    0x9E
288 #define OV_HIST0     0x9F
289 #define OV_HIST1     0xA0
290 #define OV_HIST2     0xA1
291 #define OV_HIST3     0xA2
292 #define OV_HIST4     0xA3
293 #define OV_HIST5     0xA4
294 #define OV_HIST6     0xA5
295 #define OV_HIST7     0xA6
296 #define OV_HIST8     0xA7
297 #define OV_HIST9     0xA8
298 #define OV_HIST10    0xA9
299 #define OV_HIST11    0xAA
300 #define OV_HIST12    0xAB
301 #define OV_STR_OPT    0xAC
302 #define OV_STR_R      0xAD
303 #define OV_STR_G      0xAE
304 #define OV_STR_B      0xAF
305 #define OV_RSVD28_1   0xB0
306 #define OV_RSVD29    0xB1
307 #define OV_RSVD30    0xB2
308 #define OV_THL_ST     0xB3
309 #define OV_RSVD31    0xB4
310 #define OV_THL_DLT    0xB5
311 #define OV_RSVD32    0xB6
312 #define OV_RSVD33    0xB7
313 #define OV_RSVD34    0xB8
314 #define OV_RSVD35    0xB9
315 #define OV_RSVD36    0xBA
316 #define OV_RSVD37    0xBB
317 #define OV_RSVD38    0xBC
318 #define OV_RSVD39    0xBD
319 #define OV_AD_CHB    0xBE
320 #define OV_AD_CHR     0xBF
321 #define OV_AD_CHGb   0xC0
322 #define OV_AD_CHGr   0xC1
323 #define OV_RSVD40    0xC2
324 #define OV_RSVD41    0xC3
325 #define OV_RSVD42    0xC4
326 #define OV_RSVD43    0xC5
327 #define OV_RSVD44    0xC6
328 #define OV_RSVD45    0xC7
329 #define OV_RSVD46    0xC8
330 #define OV_SATCTR   0xC9

334 #endif /* OV7670_H_ */
```

H.1.1.9 OV7670.c

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/OV7670.c

```
1  /*
2   *  OV7670.c
3   *
4   *  Created: 15/02/2013 13:12:12
5   *  Author: hslovett
6   */
7
8
9 #include <asf.h>
10 #include "CustomDevices/CustomDevices.h"
11 #include "stdio.h"
12 #include "delay.h"
13 // Camera
14 // #include "CustomDevices/OV7670.h"
15 // I2C Mux
16 // #include "CustomDevices/PCA9542A.h"
17 // MotorDriver
18 // /*#include "CustomDevices/MotorDriver.h"*/
19 // SDCard
20 // #include "CustomDevices/SD_Card.h"
21
22 __attribute__((__interrupt__)) static void VSYNC0_Handler (void)
23 {
24     //print_dbg("\n\rVSYNC0 Detected!");
25     eic_clear_interrupt_line(&AVR32_EIC, VSYNC_0_LINE);
26     //VSYNC_0_DISABLE_INTERRUPT;
27     switch(OV7670_Status.VSYNC0_State)
28     {
29         case(TAKE_PHOTO):
30             FIFO_0_WEN_SET;
31             OV7670_Status.VSYNC0_State = TAKING_PHOTO;
32             break;
33
34         case(TAKING_PHOTO):
35             FIFO_0_WEN_CLR;
36             OV7670_Status.VSYNC0_State = TAKEN_PHOTO;
37             break;
38
39         case (TAKEN_PHOTO):
40             FIFO_0_WEN_CLR;
41             break;
42
43         case(IDLE):
44             default:
45                 VSYNC_0_DISABLE_INTERRUPT;
46                 FIFO_0_WEN_CLR;
47                 OV7670_Status.VSYNC0_State = IDLE;
48                 break;
49 }
```

```
49     }
50 }

52 _attribute_((_interrupt_)) static void VSYNC1_Handler (void)
53 {
54     //print_dbg("\n\rVSYNC1 Detected!");
55     eic_clear_interrupt_line(&AVR32_EIC, VSYNC_1_LINE);
56     //VSYNC_1_DISABLE_INTERRUPT;
57     switch(OV7670_Status.VSYNC1_State)
58     {
59         case(TAKE_PHOTO):
60             FIFO_1_WEN_SET;
61             OV7670_Status.VSYNC1_State = TAKING_PHOTO;
62             //print_dbg("\n\rCase: Take Photo;");
63             break;
64
65         case(TAKING_PHOTO):
66             FIFO_1_WEN_CLR;
67             OV7670_Status.VSYNC1_State = TAKEN_PHOTO;
68             //print_dbg("\n\rCase: Taking Photo;");
69             break;
70
71         case (TAKEN_PHOTO):
72             FIFO_1_WEN_CLR;
73             //print_dbg("\n\rCase: Taken Photo;");
74             break;
75
76         case(IDLE):
77         default:
78             VSYNC_1_DISABLE_INTERRUPT;
79             FIFO_1_WEN_CLR;
80             OV7670_Status.VSYNC1_State = IDLE;
81             //print_dbg("\n\rCase: Idle;");
82             break;
83     }
84 }

85 unsigned char Write_Reg(unsigned char Register, unsigned char Data)
86 {
87     /* I2C Traffic Generated:
88      * S | OV_7670 + W | A | RegID | A | Data | A | P |
89      */
90     uint8_t Buff[2] = {Register, Data};
91     int status = twim_write(&AVR32_TWIMO, &Buff, 2, OV7670_ADDR, false);
92     return status;
93 }

94 unsigned char Read_Reg(unsigned char Register, unsigned char *Data)
95 {
96     /* I2C Traffic Generated:
97      * S | OV_ADDR + W | A | RegID | A | P |
98      * S | OV_ADDR + R | A | Data | ~A | P |
99      */
100    unsigned char Buff[2] = {Register, 0};
101    int status = twim_write(&AVR32_TWIMO, &Buff, 1, OV7670_ADDR, false);
102    if(status != STATUS_OK)
103        return status;

105    status = twim_read(&AVR32_TWIMO, &Buff, 1, OV7670_ADDR, false);
106    *Data = Buff[0];
```

```
108     return status;
109 }
110 void OV7670_Init()
111 {
112
114 //Check Cameras Exist
115 PCA9542A_Chан_Sel(I2C_CHANNEL_0);
116 if (twim_probe(&AVR32_TWIMO, OV7670_ADDR) == STATUS_OK)
117     OV7670_Status.Camera_0_Found = true;
118 else
119     OV7670_Status.Camera_0_Found = false;
120
121 PCA9542A_Chан_Sel(I2C_CHANNEL_1);
122 if (twim_probe(&AVR32_TWIMO, OV7670_ADDR) == STATUS_OK)
123     OV7670_Status.Camera_1_Found = true;
124 else
125     OV7670_Status.Camera_1_Found = false;
126
128 //Initialise Cameras
129 if(OV7670_Status.Camera_0_Found)
130 {
131     PCA9542A_Chан_Sel(I2C_CHANNEL_0);
132 //Reset Camera
133 if(STATUS_OK != Write_Reg(OV_COM7, 0x80))
134 {
135     print_dbg("\n\rCamera Reset Fail");
136     OV7670_Status.Camera_0_Error = true;
137     OV7670_Status.Status = ERR_DEVICE;
138     //return FAIL;
139 }
140 delay_ms(10); //wait for Camera to reset
141 for (int i = 0; i < SETTINGS_LENGTH; i++)
142 {
143     if(STATUS_OK != Write_Reg(default_settings[i][0], default_settings[i]
144 [1]))
145     {
146         print_dbg("\n\rCamera Initialise Fail");
147         //return FAIL;
148         OV7670_Status.Camera_0_Error = true;
149         OV7670_Status.Status = ERR_DEVICE;
150         break;
151     }
152     delay_ms(1);
153 }
154 if(OV7670_Status.Camera_1_Found)
155 {
156     PCA9542A_Chан_Sel(I2C_CHANNEL_1);
157
158 //Reset Camera
159 if(STATUS_OK != Write_Reg(OV_COM7, 0x80))
160 {
161     print_dbg("\n\rCamera Reset Fail");
162     OV7670_Status.Camera_1_Error = true;
163     OV7670_Status.Status = ERR_DEVICE;
```

```

164     //return FAIL;
165 }
166 delay_ms(10); //wait for Camera to reset
167 for (int i = 0; i < SETTINGS_LENGTH; i++)
168 {
169     if(STATUS_OK != Write_Reg(default_settings[i][0], default_settings[i]
170     ][1]))
171     {
172         print_dbg("\n\rCamera Initialise Fail");
173         //return FAIL;
174         OV7670_Status.Camera_1_Error = true;
175         OV7670_Status.Status = ERR_DEVICE;
176         break;
177     }
178 }
179 }
180 PCA9542A_Chан_Sel(NO_SELECT);

182 //Initialise VSYNC Interrupts
183 eic_options_t eic_options;
184 eic_options.eic_mode = EIC_MODE_EDGE_TRIGGERED;
185 eic_options.eic_edge = EIC_EDGE_FALLING_EDGE;
186 eic_options.eic_async = EIC_SYNCH_MODE;
187 eic_options.eic_line = VSYNC_1_LINE;
188 //eic_options.eic_line = VSYNC_0_LINE;

190 Disable_global_interrupt();
191 gpio_enable_module_pin(VSYNC_1_PIN, VSYNC_1_FUNCTION);
192 gpio_enable_module_pin(VSYNC_0_PIN, VSYNC_0_FUNCTION);

194 gpio_enable_pin_pull_up(VSYNC_1_PIN); //Enable pull up as it is a low level
195     interrupt
196 gpio_enable_pin_pull_up(VSYNC_0_PIN);
197 //Initialise EIC
198 eic_init(&AVR32_EIC, &eic_options, 1);
199 eic_options.eic_line = VSYNC_0_LINE;
eic_init(&AVR32_EIC, &eic_options, 1);

201 INTC_register_interrupt(&VSYNC1_Handler, AVR32_EIC_IRQ_1, AVR32_INTC_INTO);
202 INTC_register_interrupt(&VSYNCO_Handler, AVR32_EIC_IRQ_4, AVR32_INTC_INTO);
203 //Enable interrupt on VSYNC1
204 eic_enable_line(&AVR32_EIC, VSYNC_1_LINE);
205 eic_enable_line(&AVR32_EIC, (VSYNC_0_LINE));
206 VSYNC_1_ENABLE_INTERRUPT;
207 VSYNC_0_ENABLE_INTERRUPT;

209 FIFO_Init();
210 Enable_global_interrupt();

212 }
213 void FIFO_Init()
214 {
215     //Disable both outputs
216     FIFO_0_nOE_SET
217     FIFO_1_nOE_SET

219 //Reset Buffer 0

```

```
220     FIFO_0_WRST_CLR;
221     FIFO_0_RCLK_CLR;
222     FIFO_0_nRRST_SET;
223     FIFO_0_WEN_CLR;
224     delay_us(10);
225     FIFO_0_RCLK_SET;
226     delay_us(10);
227     FIFO_0_RCLK_CLR;
228     FIFO_0_nRRST_CLR;
229     delay_us(10);
230     FIFO_0_RCLK_SET;
231     delay_us(10);
232     FIFO_0_RCLK_CLR;
233     FIFO_0_nRRST_SET;
234     delay_us(10);
235     FIFO_0_WRST_SET;

237 //Reset Buffer 1
238 FIFO_1_WRST_CLR;
239 FIFO_1_RCLK_CLR;
240 FIFO_1_nRRST_SET;
241 FIFO_1_WEN_CLR;
242 delay_us(10);
243 FIFO_1_RCLK_SET;
244 delay_us(10);
245 FIFO_0_RCLK_CLR;
246 FIFO_1_nRRST_CLR;
247 delay_us(10);
248 FIFO_1_RCLK_SET;
249 delay_us(10);
250 FIFO_1_RCLK_CLR;
251 FIFO_1_nRRST_SET;
252 delay_us(10);
253 FIFO_1_WRST_SET;
254 }

256 void FIFO_Reset(uint8_t CameraID)
257 {
258     FIFO_0_nOE_SET;
259     FIFO_1_nOE_SET;
260     if(CameraID & CAMERA_LEFT)
261     {
262         FIFO_0_WRST_CLR;
263         FIFO_0_nRRST_CLR;
264         FIFO_0_RCLK_SET;
265         delay_us(10);
266         FIFO_0_RCLK_CLR;
267         FIFO_0_nRRST_SET;
268         FIFO_0_WRST_SET;
269     }
270     if(CameraID & CAMERA_RIGHT)
271     {
272         FIFO_1_WRST_CLR;
273         FIFO_1_nRRST_CLR;
274         FIFO_1_RCLK_SET;
275         delay_us(10);
276         FIFO_1_RCLK_CLR;
277         FIFO_1_nRRST_SET;
```

```
278     FIFO_1_WRST_SET;
279 }
281 }
283 int TakePhoto(uint8_t Cameras)
284 {
286     //Only want to take pictures on cameras found
287     if(((OV7670_Status.VSYNC0_State != IDLE) || !OV7670_Status.Camera_0_Found)
288         && ((OV7670_Status.VSYNC1_State != IDLE) || !OV7670_Status.Camera_1_Found))
289     )
290     return CAMERAS_BUSY; //wait for cameras to be idle if they are found
291
292     if(Cameras & CAMERA_LEFT)
293         OV7670_Status.VSYNC0_State = TAKE_PHOTO;
294
295     if(Cameras & CAMERA_RIGHT)
296         OV7670_Status.VSYNC1_State = TAKE_PHOTO;
297     eic_clear_interrupt_line(&AVR32_EIC, VSYNC_1_LINE);
298     eic_clear_interrupt_line(&AVR32_EIC, VSYNC_0_LINE);
299     VSYNC_0_ENABLE_INTERRUPT;
300     VSYNC_1_ENABLE_INTERRUPT;
301
302     return TAKING_PHOTO;
303 }
304
305 bool Photos_Ready(void)
306 {
307     int status = 0;
308     if(OV7670_Status.Camera_0_Found == true) //If camera is there
309     {
310         if(OV7670_Status.Camera_0_Error == false)//and has no errors
311         {
312             if(OV7670_Status.VSYNC0_State == TAKEN_PHOTO)
313             {
314                 status |= 1; //camera0 has taken photo
315             }
316             else
317                 status |= 1;
318         }
319         else
320             status |= 1;
321
322         if(OV7670_Status.Camera_1_Found == true) //If camera is there
323         {
324             if(OV7670_Status.Camera_1_Error == false)//and has no errors
325             {
326                 if(OV7670_Status.VSYNC1_State == TAKEN_PHOTO)
327                 {
328                     status |= 1; //camera0 has taken photo
329                 }
330             else
331                 status |= 1;
332         }
333     }
```

```
334     else
335         status |= 1;
336
337     if(status)
338         return true;
339     else
340         return false;
341 }
342
343
344
345 bool Store_Both_Images()
346 {
347     if(Photos_Ready() == false)
348         return false;
349
350     Store_Image_1();
351     FIFO_Reset(CAMERA_RIGHT);
352
353     Store_Image_0();
354     FIFO_Reset(CAMERA_LEFT);
355
356     OV7670_Status.VSYNC0_State = IDLE;
357     OV7670_Status.VSYNC1_State = IDLE;
358     return true;
359 }
360 // void Store_Image_0()
361 // {
362 //     int i,j;
363 //     //Image0
364 //     //make file
365 //     //delete file if it exists already
366 //     char Filename_buff[15];
367 //     i = 0;
368 //     while(1)
369 //     {
370 //         nav_filelist_reset();
371 //         sprintf(&Filename_buff, Image0Name, i++);
372 //         if(nav_filelist_findname((FS_STRING)Filename_buff, false))
373 //         {
374 //             //nav_setcwd((FS_STRING)Image0Name, true, false);
375 //             // print_dbg("\n\r File Exists");
376 //             // print_dbg(&Filename_buff);
377 //             //nav_file_del(false);
378 //         }
379 //         else
380 //         {
381 //             break;
382 //         }
383 //     }
384 //     nav_file_create((FS_STRING)Filename_buff); //create file
385 //
386 //     file_open(FOPEN_MODE_W);
387 //     //write bitmap headers
388 //     file_write_buf(BMPHeader, BMPHEADERSIZE);
389 //     file_write_buf(DIBHead, DIBHEADERSIZE);
390 //
391 //     // //read and write image data
```

```
392 //  //Image0
393 //  //reset read pointer
394 //  FIFO_0_nRRST_CLR;
395 //  FIFO_0_RCLK_SET;
396 //
397 //  FIFO_0_RCLK_CLR;
398 //  FIFO_0_nRRST_SET;
399 //  delay_us(10);
400 //  //enable output
401 //  FIFO_0_nOE_CLR;
402 //  uint8_t buffer[WIDTH * 2];
403 //
404 //  for(j = 0; j < HEIGHT; j++)
405 //  {
406 //    for(i = 0; i < WIDTH*2; i+=2)
407 //    {
408 //      FIFO_0_RCLK_SET;
409 //      delay_us(10);
410 //      buffer[i+1] = ((AVR32_GPIO.port[1].pvr) & 0xFF); //CAMERA_INPUT;
411 //      delay_us(10);
412 //      FIFO_0_RCLK_CLR;
413 //      delay_us(10);
414 //      FIFO_0_RCLK_SET;
415 //      delay_us(10);
416 //      buffer[i] = ((AVR32_GPIO.port[1].pvr) & 0xFF); //CAMERA_INPUT;
417 //      delay_us(10);
418 //      FIFO_0_RCLK_CLR;
419 //      delay_us(10);
420 //    }
421 //    file_write_buf(&buffer, WIDTH * 2);
422 //  }
423 //  FIFO_0_nOE_SET;
424 //  file_close();
425 //
426 //
427 // }

428 // void Store_Image_1()
429 // {
430 //   int i, j;
431 //   uint8_t buffer[WIDTH * 2];
432 //   char Filename_buff[15];
433 //   //uint8_t *Buffer_ram;
434 //   //Buffer_ram = mspace_malloc(sdram_msp, WIDTH * 2);
435 //   //if(Buffer_ram == NULL)
436 //   //{
437 //   //   print_dbg("\n\rBuffer allocation fail.\n\r");
438 //   //   return;
439 //   //}
440 //   i = 0;
441 //   //make file
442 //   //delete file if it exists already
443 //   nav_filelist_reset();
444 //   while(1)
445 //   {
446 //     sprintf(&Filename_buff, Image1Name, i++);
447 //     if(nav_filelist_findname((FS_STRING)Filename_buff, false))
448 //     {
449 //       {
```

```
450 //      //nav_setcwd((FS_STRING)Image1Name, true, false);
451 //      //print_dbg("\n\rImage1.bmp File Exists");
452 //      //nav_file_del(false);
453 //    }
454 //  else
455 //  {
456 //    break;
457 //  }
458 //}
459 //  nav_file_create((FS_STRING)Filename_buff); //create file
460 //  file_open(FOPEN_MODE_W);
461 //  //write bitmap headers
462 //  file_write_buf(BMPHeader, BMPHEADERSIZE);
463 //  file_write_buf(DIBHead, DIBHEADERSIZE);
464 //  //Image1
465 //  //reset read pointer
466 //  FIFO_1_nRRST_CLR;
467 //
468 //  FIFO_1_RCLK_SET;
469 //  delay_us(10);
470 //  FIFO_1_RCLK_CLR;
471 //  FIFO_1_nRRST_SET;
472 //
473 //  //enable output
474 //  FIFO_1_nOE_CLR;
475 //  // uint8_t buffer[WIDTH * 2];
476 //
477 //  for(j = 0; j < HEIGHT; j++)
478 //
479 //    for(i = 0; i < WIDTH*2; i+=2)
480 //
481 //      FIFO_1_RCLK_SET;
482 //      delay_us(10);
483 //      buffer[i+1] = ((AVR32_GPIO.port[1].pvr) & 0xFF); //CAMERA_INPUT;
484 //      delay_us(10);
485 //      FIFO_1_RCLK_CLR;
486 //      delay_us(10);
487 //      FIFO_1_RCLK_SET;
488 //      delay_us(10);
489 //      buffer[i] = ((AVR32_GPIO.port[1].pvr) & 0xFF); //CAMERA_INPUT;
490 //      delay_us(10);
491 //      FIFO_1_RCLK_CLR;
492 //      delay_us(10);
493 //
494 //    file_write_buf(&buffer, WIDTH * 2);
495 //
496 //
497 //  FIFO_1_nOE_SET; //disable output
498 //  file_close();
499 //  //mspace_free(sdram_msp, Buffer_ram);
500 //  /* mspace_free(sdram_msp, Buffer_ram); */
501 //

503 void Store_Image_1()
504 {
505   int i, j;
506   //uint8_t buffer[WIDTH * 2];
507   char Filename_buff[15];
```

```

508     uint8_t *Buffer_ram;
509     Buffer_ram = mspace_malloc(sdram_msp, HEIGHT * WIDTH * 2);
510     i = 0;
511     //make file
512     //delete file if it exists already
513     nav_filelist_reset();
514     while(1)
515     {
516         sprintf(&Filename_buff, Image1Name, i++);
517         if(nav_filelist_findname((FS_STRING)Filename_buff, false))
518         {
519             ;
520         }
521         else
522         {
523             break;
524         }
525     }

527     //Image1
528     //reset read pointer
529     FIFO_1_nRRST_CLR;

531     FIFO_1_RCLK_SET;
532     delay_us(10);
533     FIFO_1_RCLK_CLR;
534     FIFO_1_nRRST_SET;

536     //enable output
537     FIFO_1_nOE_CLR;
538     // uint8_t buffer[WIDTH * 2];

540     for(j = 0; j < HEIGHT * WIDTH * 2; j+= 2)
541     {
542         FIFO_1_RCLK_SET;
543         delay_us(10);
544         Buffer_ram[j+1] = ((AVR32_GPIO.port[1].pvr) & 0xFF); //CAMERA_INPUT;
545         delay_us(10);
546         FIFO_1_RCLK_CLR;
547         delay_us(10);
548         FIFO_1_RCLK_SET;
549         delay_us(10);
550         Buffer_ram[j] = ((AVR32_GPIO.port[1].pvr) & 0xFF); //CAMERA_INPUT;
551         delay_us(10);
552         FIFO_1_RCLK_CLR;
553         delay_us(10);
554     }

556     FIFO_1_nOE_SET;//disable output
557     /* file_close(); */
558     SaveBitmap(Buffer_ram, WIDTH, HEIGHT, Filename_buff);
559     mspace_free(sdram_msp, Buffer_ram);
560 }

562 void Store_Image_0()
563 {
564     int i, j;
565     //uint8_t buffer[WIDTH * 2];

```

```
566     char Filename_buff[15];
567     uint16_t *Buffer_ram;
568     Buffer_ram = mspace_malloc(sdram_msp, HEIGHT * WIDTH );
569     i = 0;
570     //make file
571     //delete file if it exists already
572     nav_filelist_reset();
573     while(1)
574     {
575         sprintf(&Filename_buff, Image0Name, i++);
576         if(nav_filelist_findname((FS_STRING)Filename_buff, false))
577         {
578             ;
579         }
580         else
581         {
582             break;
583         }
584     }

586     //Image1
587     //reset read pointer
588     FIFO_0_nRRST_CLR;

589     FIFO_0_RCLK_SET;
590     delay_us(10);
591     FIFO_0_RCLK_CLR;
592     FIFO_0_nRRST_SET;

595     //enable output
596     FIFO_0_nOE_CLR;
597     //  uint8_t buffer[WIDTH * 2];

599     for(j = 0; j < HEIGHT * WIDTH; j++)
600     {
601         FIFO_0_RCLK_SET;
602         delay_us(10);
603         Buffer_ram[j] = (((AVR32_GPIO.port[1].pvr) & 0xFF); //CAMERA_INPUT;
604         delay_us(10);
605         FIFO_0_RCLK_CLR;
606         delay_us(10);
607         FIFO_0_RCLK_SET;
608         delay_us(10);
609         Buffer_ram[j] |= (((AVR32_GPIO.port[1].pvr) & 0xFF) << 8); //CAMERA_INPUT;
610         delay_us(10);
611         FIFO_0_RCLK_CLR;
612         delay_us(10);
613     }

615     FIFO_0_nOE_SET; //disable output
616 /*   file_close(); */
617     SaveBitmap(Buffer_ram, WIDTH, HEIGHT, Filename_buff);
618     mspace_free(sdram_msp, Buffer_ram);
619 }
```

H.1.1.10 OV7670.c

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/OV7670_Setup.c

```
1  /*
2   *  OV7670_Setup.c
3   *
4   *  * Created: 15/02/2013 13:14:09
5   *  * Author: hslovett
6   */
7
8 #include "CustomDevices/CustomDevices.h"
9
10 const char default_settings[SETTINGS_LENGTH][2]=
11 {
12 {OV_TSLB, 0x04},
13 {OV_COM15, 0xd0}, //RGB565 / RGB555
14 {OV_COM7, 0x14},
15 {OV_HREF, 0x80},
16 {OV_HSTART, 0x16},
17 {OV_HSTOP, 0x04},
18 {OV_VSTRT, 0x02},
19 {OV_VSTOP, 0x7b}, //0x7a,
20 {OV_VREF, 0x06}, //0xa,
21 {OV_COM3, 0x00}, //MSB and LSB swapped
22 {OV_COM14, 0x00}, //
23 {OV_SCALING_XSC, 0x00},
24 {OV_SCALING_YSC, 0x00},
25 {OV_SCALING_DCWCTR, 0x11},
26 {OV_SCALING_PCLK_DIV, 0x00}, //
27 {0xa2, 0x02},
28 {OV_CLKRC, 0x01},
29 {OV_GAM1, 0x20},
30 {OV_GAM2, 0x1c},
31 {OV_GAM3, 0x28},
32 {OV_GAM4, 0x3c},
33 {OV_GAM5, 0x55},
34 {OV_GAM6, 0x68},
35 {OV_GAM7, 0x76},
36 {OV_GAM8, 0x80},
37 {OV_GAM9, 0x88},
38 {OV_GAM10, 0x8f},
39 {OV_GAM11, 0x96},
40 {OV_GAM12, 0xa3},
41 {OV_GAM13, 0xaf},
42 {OV_GAM14, 0xc4},
43 {OV_GAM15, 0xd7},
44 {OV_GAM16, 0xe8},
45 {OV_COM8, 0xe0},
46 {OV_GAIN, 0x00}, //AGC
47 {OV_AECH, 0x00},
48 {OV_COM4, 0x00},
49 {OV_COM9, 0x20}, //0x38, limit the max gain
50 {OV_HIST6, 0x05},
51 {OV_HIST12, 0x07},
52 {OV_AEW, 0x75},
53 {OV_AEB, 0x63},
```

```
54 {OV_VPT, 0xA5},
55 {OV_HIST0, 0x78},
56 {OV_HIST1, 0x68},
57 {OV_HIST2, 0x03}, //0x0b,
58 {OV_HIST7, 0xdff}, //0xd8,
59 {OV_HIST8, 0xdff}, //0xd8,
60 {OV_HIST9, 0xf0},
61 {OV_HIST10, 0x90},
62 {OV_HIST11, 0x94},
63 {OV_COM8, 0xe5},
64 {OV_COM5, 0x61},
65 {OV_COM6, 0x4b},
66 {0x16, 0x02},
67 {OV_MVFP, 0x27}, //0x37,
68 {0x21, 0x02},
69 {0x22, 0x91},
70 {0x29, 0x07},
71 {0x33, 0x0b},
72 {0x35, 0x0b},
73 {0x37, 0x1d},
74 {0x38, 0x71},
75 {OV_OFON, 0x2a}, //
76 {OV_COM12, 0x78},
77 {0x4d, 0x40},
78 {0x4e, 0x20},
79 {OV_GFIX, 0x0c}, ///////////////////////////////
80 {OV_DBLV, 0x60}, //PLL
81 {OV_REG74, 0x19},
82 {0x8d, 0x4f},
83 {0x8e, 0x00},
84 {0x8f, 0x00},
85 {0x90, 0x00},
86 {0x91, 0x00},
87 {OV_DM_LNL, 0x00}, //0x19 ,//0x66
88 {0x96, 0x00},
89 {0x9a, 0x80},
90 {0xb0, 0x84},
91 {0xb1, 0x0c},
92 {0xb2, 0x0e},
93 {OV_THL_ST, 0x82},
94 {0xb8, 0xa},
95 {OV_AWBC1, 0x14},
96 {OV_AWBC2, 0xf0},
97 {OV_AWBC3, 0x34},
98 {OV_AWBC4, 0x58},
99 {OV_AWBC5, 0x28},
100 {OV_AWBC6, 0x3a},
101 {0x59, 0x88},
102 {0x5a, 0x88},
103 {0x5b, 0x44},
104 {0x5c, 0x67},
105 {0x5d, 0x49},
106 {0x5e, 0x0e},
107 {OV_LCC3, 0x04},
108 {OV_LCC4, 0x20},
109 {OV_LCC5, 0x05},
110 {OV_LCC6, 0x04},
111 {OV_LCC7, 0x08},
```

```
112 {OV_AWBCTR3, 0x0a},  
113 {OV_AWBCTR2, 0x55},  
114 {OV_AWBCTR1, 0x11},  
115 {OV_AWBCTR0, 0x9f}, //0x9e for advance AWB  
116 {OV_GGAIN, 0x40},  
117 {OV_BLUE, 0x40},  
118 {OV_RED, 0x40},  
119 {OV_COM8, 0xe7},  
120 {OV_COM10, 0x02}, //VSYNC negative  
121 {OV_MTX1, 0x80},  
122 {OV_MTX2, 0x80},  
123 {OV_MTX3, 0x00},  
124 {OV_MTX4, 0x22},  
125 {OV_MTX5, 0x5e},  
126 {OV_MTX6, 0x80},  
127 {OV_MT XS, 0x9e},  
128 {OV_COM16, 0x08},  
129 {OV_EDGE, 0x00},  
130 {OV_REG75, 0x05},  
131 {OV_REG76, 0xe1},  
132 {OV_DNSTH, 0x00},  
133 {OV_REG77, 0x01},  
134 {OV_COM13, 0xc2}, //0xc0,  
135 {OV_REG4B, 0x09},  
136 {OV_SATCTR, 0x60},  
137 {OV_COM16, 0x38},  
138 {OV CONTRAS, 0x40},  
139 {0x34, 0x11},  
140 {OV_COM11, 0x02}, //0x00, //0x02,  
141 {OV_HIST5, 0x89}, //0x88,  
142 {0x96, 0x00},  
143 {0x97, 0x30},  
144 {0x98, 0x20},  
145 {0x99, 0x30},  
146 {0x9a, 0x84},  
147 {0x9b, 0x29},  
148 {0x9c, 0x03},  
149 {OV_BD50ST, 0x4c},  
150 {OV_BD60ST, 0x3f},  
151 {0x78, 0x04},  
152 {0x79, 0x01}, //Some weird thing with reserved registers.  
153 {0xc8, 0xf0},  
154 {0x79, 0x0f},  
155 {0xc8, 0x00},  
156 {0x79, 0x10},  
157 {0xc8, 0x7e},  
158 {0x79, 0xa},  
159 {0xc8, 0x80},  
160 {0x79, 0xb},  
161 {0xc8, 0x01},  
162 {0x79, 0x0c},  
163 {0xc8, 0x0f},  
164 {0x79, 0xd},  
165 {0xc8, 0x20},  
166 {0x79, 0x09},  
167 {0xc8, 0x80},  
168 {0x79, 0x02},  
169 {0xc8, 0xc0},
```

```
170 {0x79, 0x03},  
171 {0xc8, 0x40},  
172 {0x79, 0x05},  
173 {0xc8, 0x30},  
174 {0x79, 0x26},  
175 {OV_COM2, 0x03},  
176 {OV_BRIGHT, 0x00},  
177 {OV_CONTRAS, 0x40},  
178 {OV_COM11, 0x42}, //0x82, //0xc0, //0xc2, //night mode  
  
180 };
```

H.1.1.11 PCA9542A.h

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/PCA9542A.h

```
1 /*  
2  * PCA9542A.h  
3  *  
4  * Created: 15/02/2013 12:21:46  
5  * Author: hslovett  
6  */  
  
9 #ifndef PCA9542A_H_  
10 #define PCA9542A_H_  
  
12 #define A0 0  
13 #define A1 0  
14 #define A2 1  
15 #define PCA9542A_ADDR (0x70 | (A2 << 2) | (A1 << 1) | A0)  
  
17 #define NO_SELECT 0x00  
18 //#define ERROR 0x01  
19 #define I2C_CHANNEL_0 0x04  
20 #define I2C_CHANNEL_1 0x05  
  
22 //Status Codes  
23 #define SUCCESS 0  
24 #define DEVICE_NOT_FOUND 2  
  
26 typedef struct {  
27     uint8_t Status;  
28     uint8_t ChannelSelected;  
29 } PCA9542A_t;  
  
31 PCA9542A_t PCA9542A;  
32 int PCA9542A_Init();  
33 //void PCA9542A_Channel_Select(uint8_t Channel);  
34 void PCA9542A_Chан_Sel(unsigned char Channel);  
35 #endif /* PCA9542A_H_ */
```

H.1.1.12 PCA9542A.c

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/PCA9542A.c

```

1  /*
2   *  PCA9542A.c
3   *
4   *  Created: 15/02/2013 12:21:36
5   *  Author: hslovett
6   */
7
8 #include <asf.h>
9 #include "CustomDevices/CustomDevices.h"
10 //Camera
11 /*#include "CustomDevices/0V7670.h"*/
12 //I2C Mux
13 /*#include "CustomDevices/PCA9542A.h"*/
14 //MotorDriver
15 /*#include "CustomDevices/MotorDriver.h"*/
16 //SDCard
17 /*#include "CustomDevices/SD_Card.h"*/
18
19 int PCA9542A_Init()
20 {
21     int status = twim_probe(&AVR32_TWIMO, PCA9542A_ADDR);
22     if (status != STATUS_OK)
23     {
24         PCA9542A.Status = DEVICE_NOT_FOUND;
25         return DEVICE_NOT_FOUND;
26     }
27     char buff[2] = {NO_SELECT, 0};
28     status = twim_write(&AVR32_TWIMO, &buff, 1, PCA9542A_ADDR, false);
29     PCA9542A.Status = STATUS_OK;
30     PCA9542A.ChannelSelected = NO_SELECT;
31     return status;
32 }
33
34 void PCA9542A_ChangeSel(unsigned char Channel)
35 {
36     int status = 0;
37     char buff[2] = {Channel, 0};
38     status = twim_write(&AVR32_TWIMO, &buff, 1, PCA9542A_ADDR, false);
39     if(status == STATUS_OK)
40     {
41         PCA9542A.ChannelSelected = Channel;
42     }
43     else
44     {
45         PCA9542A.Status = ERR_PROTOCOL;
46     }
47 }
```

H.1.1.13 SD_Card.h

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/SD_Card.h

```

1  /*
2   * SD_Card.h
3   *
4   * Created: 10/02/2013 17:11:51
5   * Author: hslovett
6   */
7
8
9 #ifndef SD_CARD_H_
10#define SD_CARD_H_
11#include "ImageProcessor.h"
12#define SIGNAL_FILE "signal.bin"
13#define TWOD_SIGNAL_FILE "signal2d.bin"
14
15typedef struct {
16    uint8_t Status;
17    uint32_t Memory_size;
18} SD_Status_t;
19SD_Status_t SD_Status;
20
21void local_pdca_init(void);
22void sd_mmc_resources_init(void);
23static void pdca_int_handler(void);
24void wait();
25void Log_Write_ulong(unsigned long n);
26void Log_Write(char *buff, int length);
27void SaveBuff( int * WorkingBuffer , int size);
28int Read2DSignal( int * WorkingBuffer );
29int ReadSignal( int * WorkingBuffer );
30void SaveBitmap(uint16_t *Image , int width , int height , char *FileName);
31//void ReadBitmap(char *Filename);
32void ReadBitmap(char *Filename , Image_t *image);
33void SaveBuff_CSV(char *Filename , int *WorkingBuffer , int size);
34void SaveCBuff_CSV(char *Filename , dsp16_complex_t *ComplexBuffer , int size);
35void Read_CSV(char *Filename , int *WorkingBuffer , int size);
36#endif /* SD_CARD_H_ */

```

H.1.1.14 SD_Card.c

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/SD_Card.c

```

1 /*
2  * SD_Card.c
3  *
4  * Created: 10/02/2013 17:11:58
5  * Author: hslovett
6  */
7 //Camera
8 //##include "CustomDevices/OV7670.h"*/
9 //I2C Mux
10//##include "CustomDevices/PCA9542A.h"*/
11//MotorDriver

```

```
12  /*#include "CustomDevices/MotorDriver.h"*/
13  //SDCard
14  /*#include "CustomDevices/SD_Card.h"*/
15  #include "CustomDevices/CustomDevices.h"
16  #include "conf_sd_mmc_spi.h"
17  #include <asf.h>
18  #include "stdlib.h"
19  #include "stdio.h"
20  // Dummy char table
21  const char dummy_data[] =
22  #include "dummy.h"
23  ;

26  // PDCA Channel pointer
27  volatile avr32_pdca_channel_t* pdca_channelrx ;
28  volatile avr32_pdca_channel_t* pdca_channeltx ;
29  // Used to indicate the end of PDCA transfer
30  volatile bool end_of_transfer;
31  // Local RAM buffer for the example to store data received from the SD/MMC
32  // card
33  volatile char ram_buffer[1000];

35  void wait()
36  {
37      volatile int i;
38      for(i = 0 ; i < 5000; i++);
39  }
40  /* interrupt handler to notify if the Data reception from flash is
41   * over, in this case lunch the Memory(ram_buffer) to USART transfer and
42   * disable interrupt*/
43
44  static void pdca_int_handler(void)
45  {
46      // Disable all interrupts.
47      Disable_global_interrupt();
48
49      // Disable interrupt channel.
50      pdca_disable_interrupt_transfer_complete(AVR32_PDCA_CHANNEL_SPI_RX);
51
52      sd_mmc_spi_read_close_PDCA(); //unselects the SD/MMC memory.
53      wait();
54      // Disable unnecessary channel
55      pdca_disable(AVR32_PDCA_CHANNEL_SPI_TX);
56      pdca_disable(AVR32_PDCA_CHANNEL_SPI_RX);
57
58      // Enable all interrupts.
59      Enable_global_interrupt();
60
61      end_of_transfer = true;
62  }

64  /*! \brief Initializes SD/MMC resources: GPIO, SPI and SD/MMC.
65   */
66  void sd_mmc_resources_init(void)
67  {
68      // GPIO pins used for SD/MMC interface
```

```

69     static const gpio_map_t SD_MMC_SPI_GPIO_MAP =
70 {
71     {SD_MMC_SPI_SCK_PIN, SD_MMC_SPI_SCK_FUNCTION }, // SPI Clock.
72     {SD_MMC_SPI_MISO_PIN, SD_MMC_SPI_MISO_FUNCTION}, // MISO.
73     {SD_MMC_SPI_MOSI_PIN, SD_MMC_SPI_MOSI_FUNCTION}, // MOSI.
74     {SD_MMC_SPI_NPCS_PIN, SD_MMC_SPI_NPCS_FUNCTION} // Chip Select NPCS.
75 };

76
77 // SPI options.
78 spi_options_t spiOptions =
79 {
80     .reg          = SD_MMC_SPI_NPCS,
81     .baudrate    = SD_MMC_SPI_MASTER_SPEED, // Defined in conf_sd_mmc_spi.h.
82     .bits         = SD_MMC_SPI_BITS,           // Defined in conf_sd_mmc_spi.h.
83     .spck_delay   = 0,
84     .trans_delay  = 0,
85     .stay_act     = 1,
86     .spi_mode     = 0,
87     .modfdis     = 1
88 };

89 // Assign I/Os to SPI.
90 gpio_enable_module(SD_MMC_SPI_GPIO_MAP,
91                     sizeof(SD_MMC_SPI_GPIO_MAP) / sizeof(SD_MMC_SPI_GPIO_MAP
92 [0]));
93
94 // Initialize as master.
95 spi_initMaster(SD_MMC_SPI, &spiOptions);
96
97 // Set SPI selection mode: variable_ps, pcs_decode, delay.
98 spi_selectionMode(SD_MMC_SPI, 0, 0, 0);
99
100 // Enable SPI module.
101 spi_enable(SD_MMC_SPI);
102
103 // Initialize SD/MMC driver with SPI clock (PBA).
104 sd_mmc_spi_init(spiOptions, PBA_HZ);
105 }

106 /*! \brief Initialize PDCA (Peripheral DMA Controller A) resources for the SPI
107      transfer and start a dummy transfer
108 */
109 void local_pdca_init(void)
110 {
111     // this PDCA channel is used for data reception from the SPI
112     pdca_channel_options_t pdca_options_SPI_RX ={ // pdca channel options
113
114     .addr = ram_buffer,
115     // memory address. We take here the address of the string dummy_data. This
116     // string is located in the file dummy.h
117
118     .size = 512,                                // transfer counter: here the
119     // size of the string
120     .r_addr = NULL,                             // next memory address after 1st
121     // transfer complete
122     .r_size = 0,                                // next transfer counter not
123     // used here

```

```

120     .pid = AVR32_PDCA_CHANNEL_USED_RX,           // select peripheral ID - data
121     are on reception from SPI1 RX line
122     .transfer_size = PDCA_TRANSFER_SIZE_BYT   // select size of the transfer:
123     8,16,32 bits
124   };
125
126   // this channel is used to activate the clock of the SPI by sending a dummy
127   // variables
128   pdca_channel_options_t pdca_options_SPI_TX ={ // pdca channel options
129
130     .addr = (void *)&dummy_data,                // memory address.
131                               // We take here the address of
132     the string dummy_data.                      // This string is located in the
133                               // file dummy.h
134     .size = 512,                                // transfer counter: here the
135     size of the string
136     .r_addr = NULL,                             // next memory address after 1st
137     transfer complete
138     .r_size = 0,                                // next transfer counter not
139     used here
140     .pid = AVR32_PDCA_CHANNEL_USED_TX,           // select peripheral ID - data
141     are on reception from SPI1 RX line
142     .transfer_size = PDCA_TRANSFER_SIZE_BYT   // select size of the transfer:
143     8,16,32 bits
144   };
145
146   // Init PDCA transmission channel
147   pdca_init_channel(AVR32_PDCA_CHANNEL_SPI_TX, &pdca_options_SPI_TX);
148
149   // Init PDCA Reception channel
150   pdca_init_channel(AVR32_PDCA_CHANNEL_SPI_RX, &pdca_options_SPI_RX);
151
152   //!\ brief Enable pdca transfer interrupt when completed
153   INTC_register_interrupt(&pdca_int_handler, AVR32_PDCA_IRQ_0, AVR32_INTC_INT1
154   ); // pdca_channel_spi1_RX = 0
155
156 }
157
158 #define BUFFER_FILENAME "Buffer.bin"
159 #define BUFFERCSV_FILENAME "Buffer.csv"
160 void SaveBuff( int * WorkingBuffer , int size)
161 {
162   //If the file exists, delete it
163   if(nav_filelist_findname((FS_STRING)BUFFER_FILENAME, false))
164   {
165     nav_setcwd((FS_STRING)BUFFER_FILENAME, false, false);
166     nav_file_del(false);
167   }
168   nav_file_create((FS_STRING)BUFFER_FILENAME);
169   nav_setcwd((FS_STRING)BUFFER_FILENAME, false, true);
170   file_open(FOPEN_MODE_APPEND);
171   file_write_buf(WorkingBuffer, size * sizeof(WorkingBuffer));
172   file_close();
173 }
174 void SaveBuff_CSV(char *Filename, int *WorkingBuffer, int size)
175 {
176   int i, j;

```

```
167     char Buff[16];
168     //If the file exists, delete it
169     nav_filelist_reset();
170     if(nav_filelist_findname((FS_STRING)Filename, false))
171     {
172         nav_setcwd((FS_STRING)Filename, false, false);
173         nav_file_del(false);
174     }
175     nav_file_create((FS_STRING)Filename);
176     nav_setcwd((FS_STRING)Filename, false, true);
177     file_open(FOPEN_MODE_W);
178     for(i = 0; i < size; i++)
179     {
180         sprintf(Buff, "%d,", WorkingBuffer[i]);
181         //itoa(WorkingBuffer[i], Buff, 10);
182         j = 0;
183         while(Buff[j++] != 0); //count the size of data to be written
184         atoi(Buff);
185         file_write_buf(Buff, j-1);
186         //file_write_buf(",", 1);
187     }

188     file_close();
189 }
190 void SaveCBuff_CSV(char *Filename, dsp16_complex_t *ComplexBuffer, int size)
191 {
192     int i, j;
193     char Buff[16];
194     //If the file exists, delete it
195     nav_filelist_reset();
196     if(nav_filelist_findname((FS_STRING)Filename, false))
197     {
198         nav_setcwd((FS_STRING)Filename, false, false);
199         nav_file_del(false);
200     }
201     nav_file_create((FS_STRING)Filename);
202     nav_setcwd((FS_STRING)Filename, false, true);
203     file_open(FOPEN_MODE_W);
204     for(i = 0; i < size; i++)
205     {
206         if(ComplexBuffer[i].imag >= 0)
207             sprintf(Buff, "%d%dj,", ComplexBuffer[i].real, ComplexBuffer[i].imag);
208         else
209             sprintf(Buff, "%d%dj,", ComplexBuffer[i].real, ComplexBuffer[i].imag);
210         //itoa(WorkingBuffer[i], Buff, 10);
211         j = 0;
212         while(Buff[j++] != 0); //count the size of data to be written
213         atoi(Buff);
214         file_write_buf(Buff, j-1);
215         //file_write_buf(",", 1);
216     }

217     file_close();
218 }
219 void Read_CSV(char *Filename, int *WorkingBuffer, int size)
220 {
221     char Buff[32];
222     int i, j;
```

```

225     char c;
226     nav_filelist_reset();
227     if(WorkingBuffer == NULL){
228         print_dbg("\n\rRead_CSV: Buffer not initialised");
229         return;
230     }
231     //Check file Exists
232     if(nav_filelist_findname((FS_STRING)Filename, false) == false){
233         print_dbg("\n\rRead_CSV : File doesn't exist;");
234         return;
235     }
236     nav_setcwd((FS_STRING)Filename, false, true);
237     file_open(FOPEN_MODE_R);
238     for(i = 0; i < size; i++)
239     {
240         if(file_eof())
241             break;
242         c = 0;
243         //j = 0;
244         for(j = 0; j < 32; j++)
245             Buff[j] = 0; //clear the buffer
246         j = 0;
247         while(c != ',',)
248         {
249             if(file_eof())
250                 break;
251             c = file_getc();
252             if(c == ',')
253                 break;
254             Buff[j++] = c; //load string into buffer
255         }
256         WorkingBuffer[i] = atoi(Buff); //Convert to int and put into buffer
257     }
258     file_close();
259     return;
260 }
261 void Log_Write(char *buff, int length)
262 {
263     nav_setcwd((FS_STRING)LOG_FILE, true, false);
264     file_open(FOPEN_MODE_APPEND);
265     if(length == -1)
266         length = sizeof(buff);
267     file_write_buf(buff, length);
268     file_close();
269 }
270 void Log_Write_ulong(unsigned long n)
271 {
272     char tmp[11];
273     int i = sizeof(tmp) - 1;

275     // Convert the given number to an ASCII decimal representation.
276     tmp[i] = '\0';
277     do
278     {
279         tmp[--i] = '0' + n % 10;
280         n /= 10;
281     } while (n);

```

```
283     // Transmit the resulting string with the given USART.
284     Log_Write(tmp + i, -1);
285 }

287 int ReadSignal( int * WorkingBuffer )
288 {
289     bool status_b;
290     int Status, temp;
291     char c = 0;
292     if(Columbus_Status.SD_Card->Status != STATUS_OK)
293         return ERR_IO_ERROR;
294     nav_filelist_reset();
295     nav_setcwd((FS_STRING)SIGNAL_FILE, false, false);
296     status_b = file_open(FOPEN_MODE_R);
297     if(status_b == false)
298     {
299         print_dbg("File Open Error");
300         return ERR_IO_ERROR;
301     }

304     //Status = file_read_buf(WorkingBuffer, 16);
305     for(Status = 0; Status < FFT_SIZE; Status++)
306     {
307         //    print_dbg("\n\r Read from file: ");
308         c = 0;
309         temp = 0;
310         temp |= file_getc() << 24;
311         temp |= file_getc() << 16;
312         temp |= file_getc() << 8;
313         temp |= file_getc();

315     //    print_dbg_char(c);

317     WorkingBuffer[Status] = temp;
318     //    print_dbg(" Working Buff = ");
319     //    print_dbg_char(WorkingBuffer[Status]);
320     }
321     file_close();
322     return STATUS_OK;
323 }

325 int Read2DSignal( int * WorkingBuffer )
326 {
327     bool status_b;
328     int Status, temp;
329     char c = 0;
330     if(Columbus_Status.SD_Card->Status != STATUS_OK)
331         return ERR_IO_ERROR;
332     nav_filelist_reset();
333     nav_setcwd((FS_STRING)TWOD_SIGNAL_FILE, false, false);
334     status_b = file_open(FOPEN_MODE_R);
335     if(status_b == false)
336     {
337         print_dbg("File Open Error");
338         return ERR_IO_ERROR;
339     }
```

```
342 //Status = file_read_buf(WorkingBuffer, 16);
343 for(Status = 0; Status < FFT_SIZE * FFT_SIZE; Status++)
344 {
345     //    print_dbg("\n\r Read from file: ");
346     c = 0;
347     temp = 0;
348     temp |= file_getc() << 24;
349     temp |= file_getc() << 16;
350     temp |= file_getc() << 8;
351     temp |= file_getc();
352
353     //    print_dbg_char(c);
354
355     WorkingBuffer[Status] = temp;
356     //    print_dbg(" Working Buff = ");
357     //    print_dbg_char(WorkingBuffer[Status]);
358 }
359 file_close();
360 return STATUS_OK;
361 }

363 void SaveBitmap(uint16_t *Image, int width, int height, char *FileName)
364 {
365     int i, j, k;
366     uint8_t *Buffer;

368     nav_filelist_reset();
369     if(nav_filelist_findname((FS_STRING)FileName, false))
370     {
371         nav_setcwd((FS_STRING)FileName, true, false);
372         nav_file_del(false);
373     }
374     nav_file_create((FS_STRING)FileName);
375     file_open(FOPEN_MODE_W);
376     //write a modified bitmap header
377     //Calculate which is the biggest:
378     i = width * 2;
379     if(height > i)
380         i = height;
381     if(DIBHEADERSIZE > i)
382         i = DIBHEADERSIZE;

384     Buffer = malloc(i);

386     for(i = 0; i < BMPHEADERSIZE; i++)//copy all the header
387     {
388         Buffer[i] = BMPHeader[i];
389     }
390     //edit the size field
391     j = width * height * 2 + BMPHEADERSIZE + DIBHEADERSIZE;
392     for(i = 0; i < 4; i++)
393     {
394         Buffer[i + 2] = (uint8_t)(j >> 8*i);
395     }

397     file_write_buf(Buffer, BMPHEADERSIZE);
```

```
399     //DIB Header
400     for(i = 0; i < DIBHEADERSIZE; i++)
401     {
402         Buffer[i] = DIBHead[i];
403     }
404     Buffer[4] = (uint8_t)(width & 0xFF);
405     Buffer[5] = (uint8_t)((width >> 8) & 0xFF);
406     Buffer[6] = (uint8_t)((width >> 16) & 0xFF);
407     Buffer[7] = (uint8_t)((width >> 24) & 0xFF);

409     Buffer[8] = (uint8_t)(height & 0xFF);
410     Buffer[9] = (uint8_t)((height >> 8) & 0xFF);
411     Buffer[10] = (uint8_t)((height >> 16) & 0xFF);
412     Buffer[11] = (uint8_t)((height >> 24) & 0xFF);

414     file_write_buf(Buffer, DIBHEADERSIZE);

416     for(i = 0; i < height ; i++ )
417     {
418         for(j = 0; j < width ; j++)
419         {
420             //Copy the data across.

422             /*Buffer[j] = Image[i*width + j];*/
423             Buffer[(2 * j) + 1] = (uint8_t)(Image[i*width + j]);
424             Buffer[(2 * j)] = (uint8_t)(Image[i*width + j] >> 8);
425         }
426         if(file_write_buf(Buffer, width * 2) != (width * 2))
427         {
428             print_dbg("\n\rFile write error.");
429         }

431         //      j = width % 4;
432         //      if(j != 0)
433         //          {//Padding is needed to make things 4 byte aligned
434         //              file_write_buf(Buffer, j);
435         //          }
436     }

440     free(Buffer);
441     file_close();
442 }

444 #define BMP_HEADER_FILESIZE_OFFSET      2
445 #define BMP_HEADER_OFFSETTOARRAY_OFFSET 10
446 #define DIB_V5_WIDTH_OFFSET            4
447 #define DIB_V5_HEIGHT_OFFSET           8
448 #define DIB_V5_BITCOUNT_OFFSET         14
449 #define DIB_V5_IMAGESIZE_OFFSET        20

451 int ReadBigEndian(uint8_t *Buffer, int Offset, uint size)
452 {
453     int retVal, i;
454     retVal = 0; //initialise value
455     for(i = 0; i < size; i++)
456     {
```

```

457     retVal |= Buffer[Offset + i] << (i * 8);
458 }
459 return (Buffer[Offset]) | (Buffer[Offset + 1] << 8) | (Buffer[Offset + 2] <<
460     16) | (Buffer[Offset + 3] << 24);
461 }
462 void ReadBitmap(char *Filename, Image_t *image)
463 {
464 //  Image_t image;
465     int i, j, FileSize, OffsetToArray, temp, BitCount, ImageSize;
466     uint8_t Buffer[128];
467     nav_filelist_reset();
468     if(nav_filelist_findname((FS_STRING)Filename, false) == false)//if the file
469         doesn't exist
470     {
471         print_dbg("\n\rFile ");
472         print_dbg(Filename);
473         print_dbg("\n\r does not exist;");
474         return;
475     }
476     nav_setcwd((FS_STRING)Filename, false, false);
477     file_open(FOPEN_MODE_R);
478 //Read Header
479     file_read_buf(Buffer, BMPHEADERSIZE);
480 //Check for BM to confirm it is a Bitmap
481     if((Buffer[0] != 'B') || (Buffer[1] != 'M'))
482     {
483         print_dbg("\n\rBitmap Parse Fail 'BM'");
484         return;
485     }
486 //Extract file size and offset to pixel array
487     FileSize = ReadBigEndian(Buffer, BMP_HEADER_FILESIZE_OFFSET, 4);
488     OffsetToArray = ReadBigEndian(Buffer, BMP_HEADER_OFFSETTOARRAY_OFFSET, 4);

489     file_read_buf(Buffer, DIBHEADERSIZE);
490     temp = ReadBigEndian(Buffer, 0, 4);
491     if(temp != 0x7C) //check it is a V5 BMP DIB Header
492     {
493         print_dbg("\n\rBMP Parse: DIB Header not V5");
494         return;
495     }
496     image->Width= ReadBigEndian(Buffer, DIB_V5_WIDTH_OFFSET, 4);
497     image->Height = ReadBigEndian(Buffer, DIB_V5_HEIGHT_OFFSET, 4);
498     BitCount = ReadBigEndian(Buffer, DIB_V5_BITCOUNT_OFFSET, 2);
499     ImageSize = ReadBigEndian(Buffer, DIB_V5_IMAGESIZE_OFFSET, 4);
500     print_dbg("\n\rBitmap Width = ");
501     print_dbg_ulong(image->Width);
502     print_dbg("\n\rBitmap Height = ");
503     print_dbg_ulong(image->Height);
504     print_dbg("\n\rBitmap File Size = ");
505     print_dbg_ulong(FileSize);
506     print_dbg("\n\rBitmap Offset to Array = ");
507     print_dbg_ulong(OffsetToArray);
508     print_dbg("\n\rBitmap Image Bitcount = ");
509     print_dbg_ulong(BitCount);
510     print_dbg("\n\rBitmap Image Size = ");
511     print_dbg_ulong(ImageSize);

512     file_seek(OffsetToArray, FS_SEEK_SET);

```

```

513     j = 0;
514     image->ImagePtr = mspace_malloc(sdram_msp, image->Height * image->Width);
515     for(i = 0; i < ImageSize; i += 2)
516     {
517         image->ImagePtr[j++] = (file_getc()<<8) | (file_getc());
518     }
519     file_close();
520     nav_filelist_reset();
521     return;
522 }
```

H.1.1.15 TWI.c

..../Code/The_Columbus/ColumbusTest/src/CustomDevices/TWI.c

```

1  /*
2   * TWI.c
3   *
4   * Created: 27/02/2013 10:51:19
5   * Author: hslovett
6   */
7
8 #include "CustomDevices/CustomDevices.h"
9 #include <asf.h>
10
11 #define TARGET_ADDRESS          0x0          //!< Target's TWI address
12 #define TARGET_ADDR_LGT          3             //!< Internal Address length
13 #define VIRTUALMEM_ADDR         0x123456    //!< Internal Address
14 #define TWIM_MASTER_SPEED       50000        //!< Speed of TWI
15
16
17 void twim_init (void)
18 {
19     int8_t status;
20     /**
21     * \internal
22     * PIN 2 & 3 in Header J24 can be used in EVK1104
23     * PIN 1 & 2 in Header J44 can be used in UC3C_EK
24     * \endinternal
25     */
26     const gpio_map_t TWIM_GPIO_MAP = {
27     {AVR32_TWIMSO_TWCK_0_0_PIN, AVR32_TWIMSO_TWCK_0_0_FUNCTION},
28     {AVR32_TWIMSO_TWD_0_0_PIN, AVR32_TWIMSO_TWD_0_0_FUNCTION}
29 };
30
31 // Set TWIM options
32 const twi_options_t TWIM_OPTIONS = {
33     .pba_hz = FOSCO,
34     .speed = TWIM_MASTER_SPEED,
35     .chip = TARGET_ADDRESS,
36     .smbus = false,
37 };
38 // TWIM gpio pins configuration
39 gpio_enable_module (TWIM_GPIO_MAP,
```

```
40     sizeof (TWIM_GPIO_MAP) / sizeof (TWIM_GPIO_MAP[0]));  
  
42 // Initialize as master.  
43 status = twim_master_init (&AVR32_TWIMO, &TWIM_OPTIONS);  
45 }
```

References

- Atmel Corporation. *AVR311: TWI Slave*, 2007.
- Atmel Corporation. [Uc3c-ek rev 2 schematic](#), 2009.
- Atmel Corporation. *AT32UC3C0512C Datasheet*, 2012a.
- Atmel Corporation. *ATMega644P Datasheet*, 2012b.
- Atmel Corporation. [Atmel software framework](#), 2012c.
- Atmel Corporation. *ATXMega256A3BU Datasheet*, 2012d.
- PCB Cart. [Pcb manufacturer](#), 2013.
- Creative Robotics Ltd. [Hub-ee powered wheels](#), 2013.
- Electronic Lives Manufacturing. [Fatfs - generic fat file system module](#), 2012.
- Farnell. [Farnell online store](#), 2012.
- Wayne Fulton. [Image file formats - jpg, tif, png, gif. which to use?](#), 2010.
- Patrick Goebel. [Robot cartography: Ros + slam](#), 2012.
- Steve R. Gunn. *Electronics First Year Lab: C9 - Analogue Input*. University of Southampton, 2012.
- I. Haller and S. Nedevschi. Design of interpolation functions for subpixel-accuracy stereo-vision systems. *Image Processing, IEEE Transactions on*, 21(2):889–898, 2012.
- Rostam Affendi Hamzah, Sani Irwan Md Salim, and Hasrul Nisham Rosly. An effective distance detection of obstacles in stereo vision application. *Canadian Journal on Electrical and Electronics Engineering*, 1(3):49–53, 2010.
- Jin Liu and Xiaofeng Lin. Equalization in high-speed communication systems. *Circuits and Systems Magazine, IEEE*, 4(2):4–17, 2004.

- Microsoft. *Xbox 360 kinect*, 2012.
- Jernej Mrovlje and Damir Vrančić. Distance measuring based on stereoscopic pictures. Technical report, University of Ljubljana, 2008.
- Mark Nixon and Alberto S Aguado. *Feature Extraction & Image Processing for Computer Vision*. Academic Press, 2012.
- OmniVision. *OmniVision Serial Camera Control Bus (SCCB) Functional Specification*, 2007.
- Phillips. *PCA9542A : 2-channel I2C-bus multiplexer and interrupt logic*, 2009.
- Phillips. *UM10204 - I2C-bus specification and user manual*, 2012.
- Ashutosh Saxena, Jamie Schulte, and Andrew Y. Ng. *Depth estimation using monocular and stereo cues*, 2007.
- Stephen Se, David Lowe, and Jim Little. Mobile robot localization and mapping with uncertainty using scale-invariant visual landmarks. *The International Journal of Robotics Research*, pages 735–758, 2002.
- Texas Instruments. *Stellaris LM3S9B96 Datasheet*, 2012.
- S. Thrun. Learning occupancy grid maps with forward sensor models. *Autonomous robots*, 15(2):111–127, 2003.
- Edwin Tjandranegara. *Distance estimation algorithm for stereo pair images*, 2005.
- D.M. Tsai and C.T. Lin. *Fast normalized cross correlation for defect detection*, 2003.
- Vishay Semiconductors. *TCRT1000, TCRT1010 Datasheet*, 2012.
- F. Zhao, Q. Huang, and W. Gao. Image matching by normalized cross-correlation. In *Acoustics, Speech and Signal Processing, 2006. ICASSP 2006 Proceedings. 2006 IEEE International Conference on*, volume 2, pages II–II. IEEE, 2006.