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

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Turn off iNotes!

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

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A STEREOSCOPIC VISION ROBOT

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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.

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	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	Seperation 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	$2\pi r_b$

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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

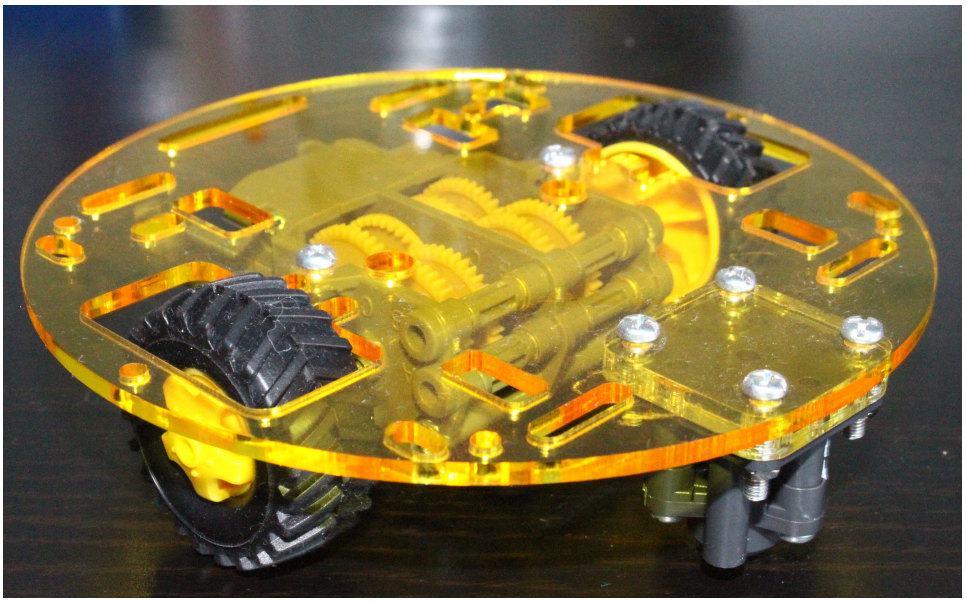


Figure 1.1: The base of the robot

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 Stellaris	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^2C , SSI, MAC, CAN, EPI, USB, USART, 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

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

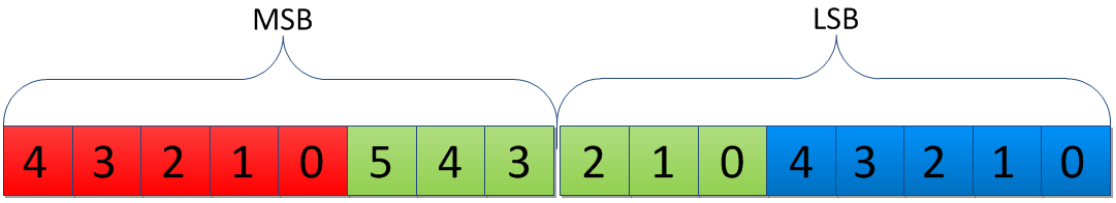


Figure 3.1: RGB565 pixel format

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 used of the built-in interrupt-driven I^2C interface (named TWI in Atmel AVRs)[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.

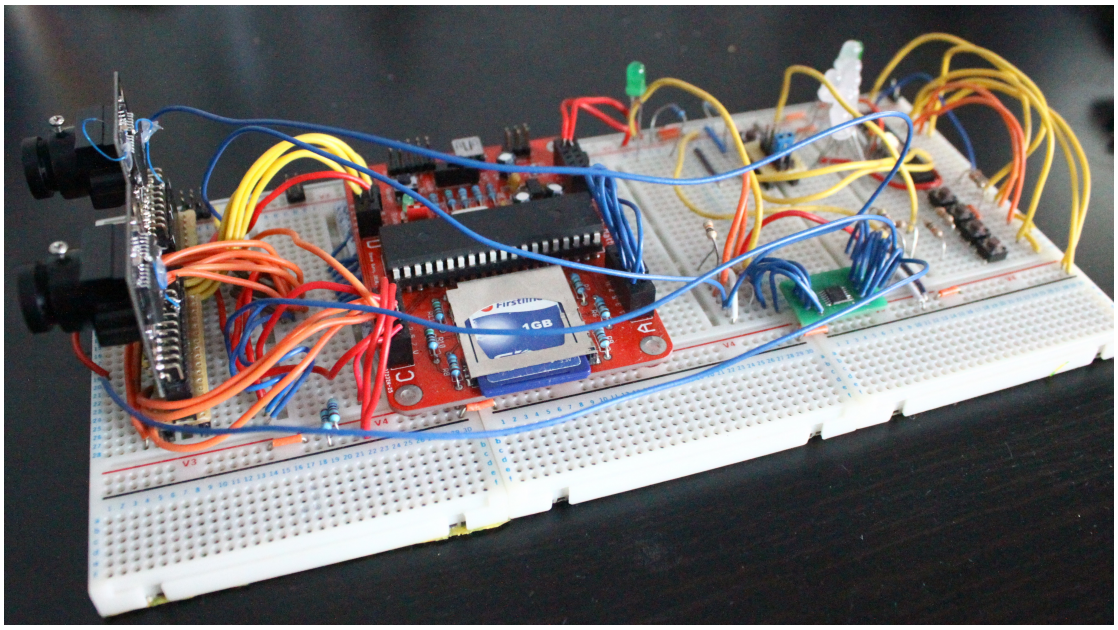


Figure 3.4: Prototype of Dual Camera operation.

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. Another prototype was also made to stream the camera images to a TFT screen. This helped with with testing cameras and focusing them. Figure 3.5 shows the set up during operation.

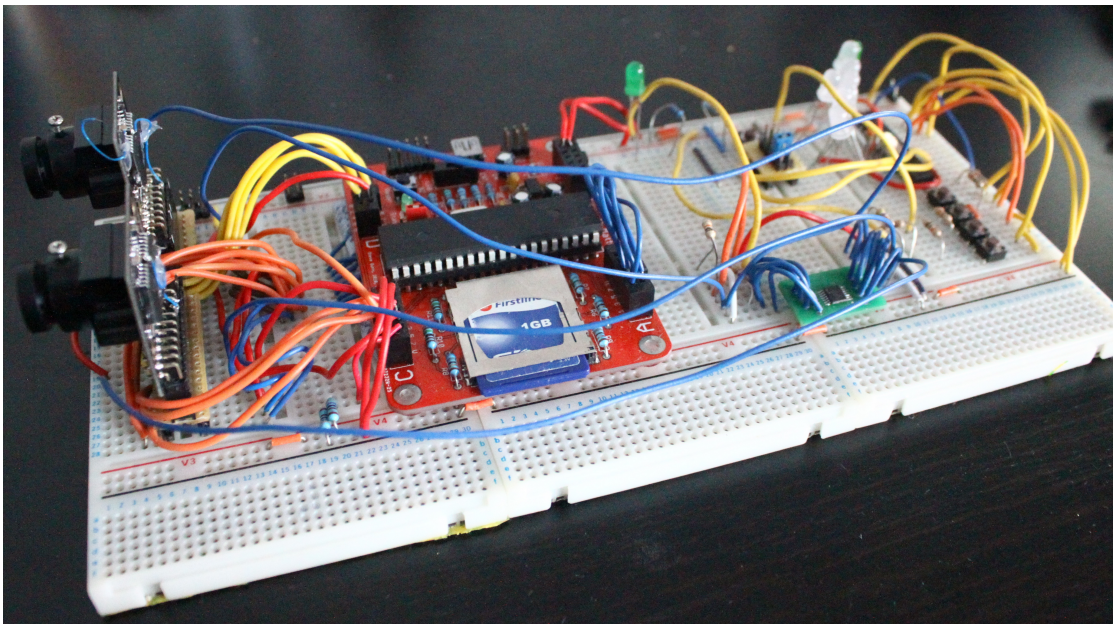


Figure 3.5: Prototype of streaming camera images to TFT screen.

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 3.6 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 3.7 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,

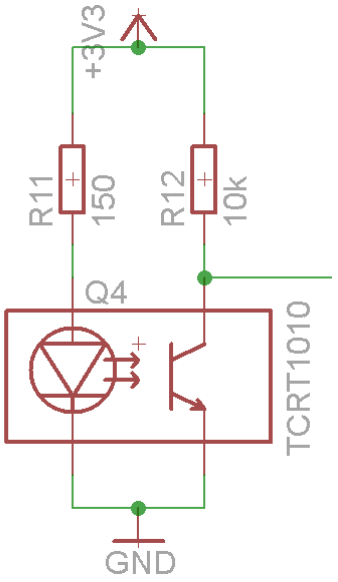


Figure 3.6: Circuit diagram of Optosensor

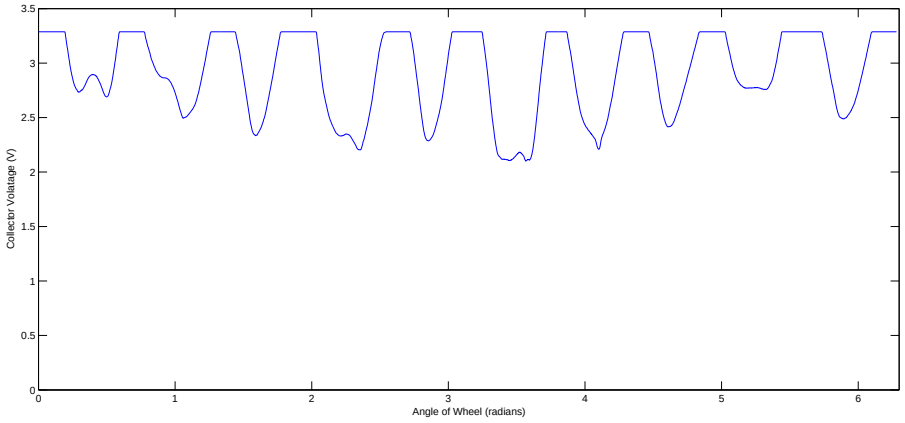


Figure 3.7: Graph of Wheel Angle against the Voltage read by the AVR

and ten dips in the voltage can be seen in figure 3.7. 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.

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.

$$\text{Counts} = \delta \times \frac{\gamma}{C_w} \tag{3.1}$$

For rotation, the radius from the centre of the robot to the wheels needs to be known, see figure 3.9(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.

$$\delta_R = A \times \frac{C_b}{360} \tag{3.2}$$

Combining equations (3.1) and (3.2) gives:

$$Interrupts = A \times \frac{\gamma}{C_w} \times \frac{C_b}{360} \tag{3.3}$$

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 3.9).

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 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 3.8. 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 an 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.

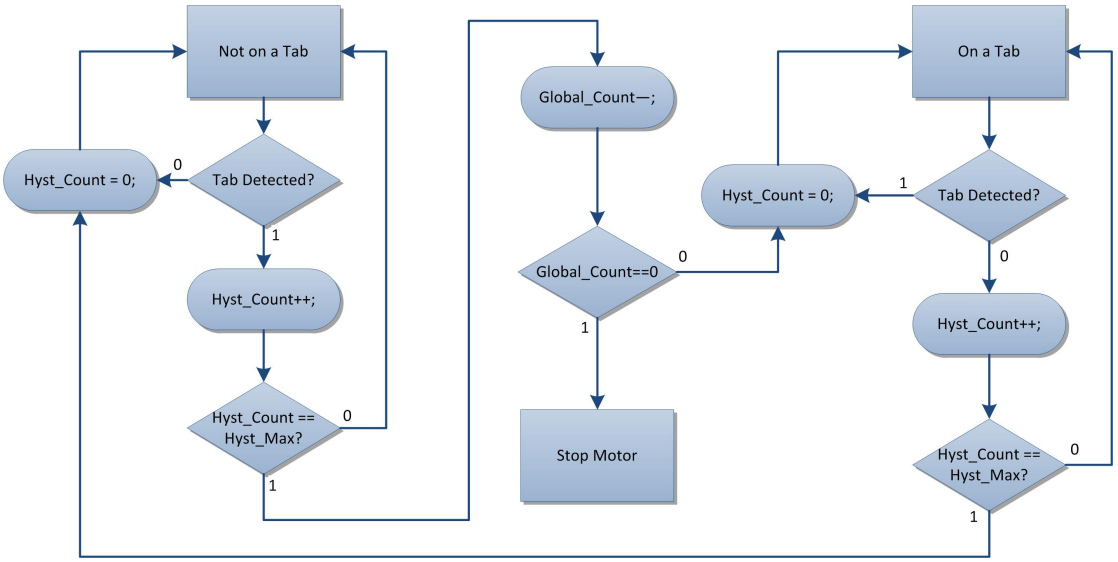


Figure 3.8: A State Machine showing the operation of the *Motor_Execute* method

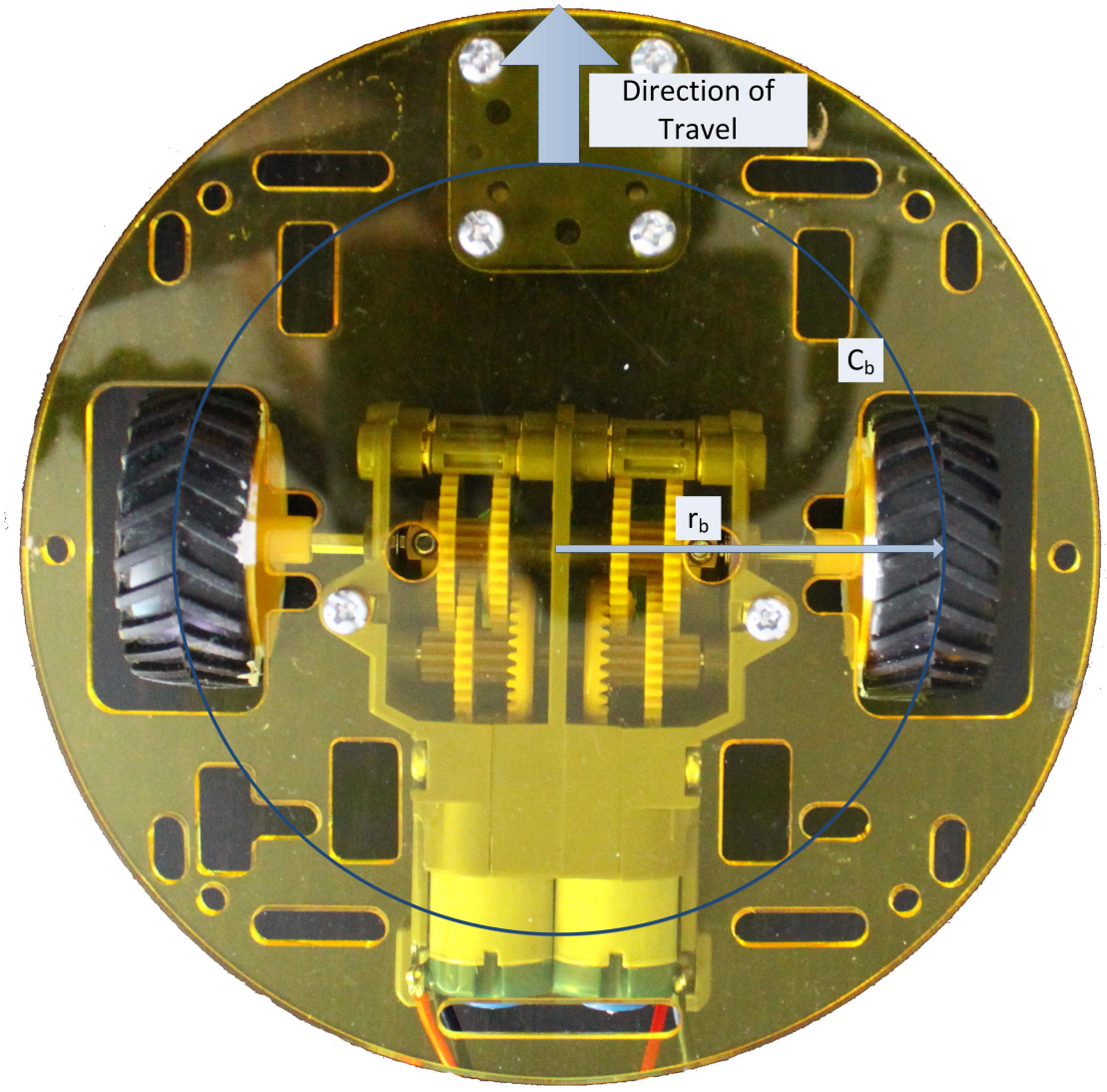
The final code can be seen in appendix H. *Motor_Init* method must be called before operation can occur. This sets up the PWM and analogue comparators. Methods *Motors_Move* and *Motors_Rotate* are the methods that can be called to move in a straight line or rotate on the spot. They both take an input 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

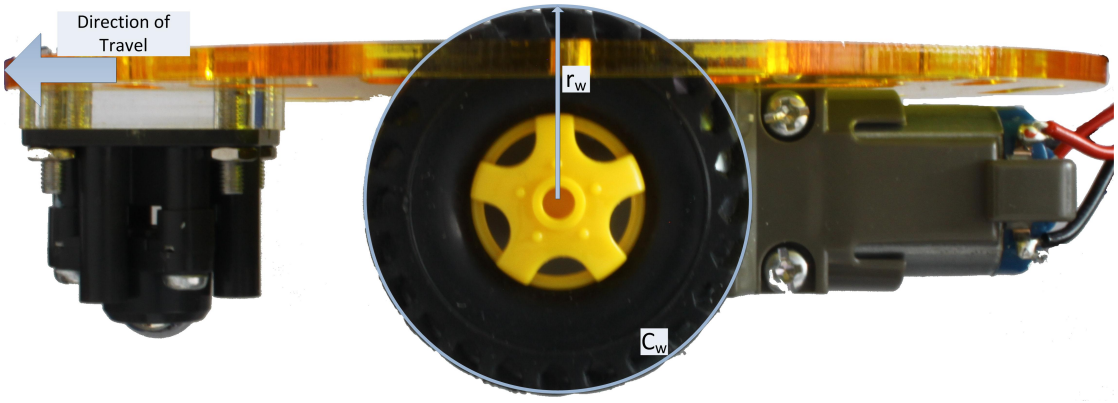
Test Rotation

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 3.10. 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



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



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

Figure 3.9: 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

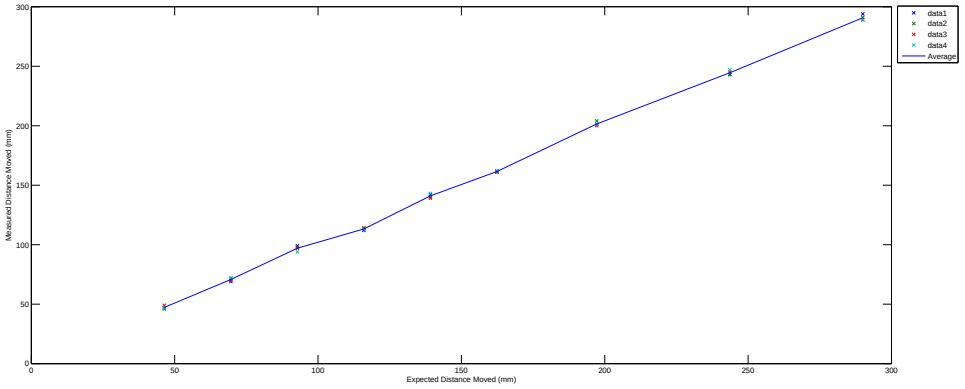


Figure 3.10: A plot of Expected Distance against the measured data. Line indicates the average of the data at each point.

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

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 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.

$$\Delta_\delta = \frac{C_w}{\gamma} = 12mm \tag{3.4}$$

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

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 that 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 3.11 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

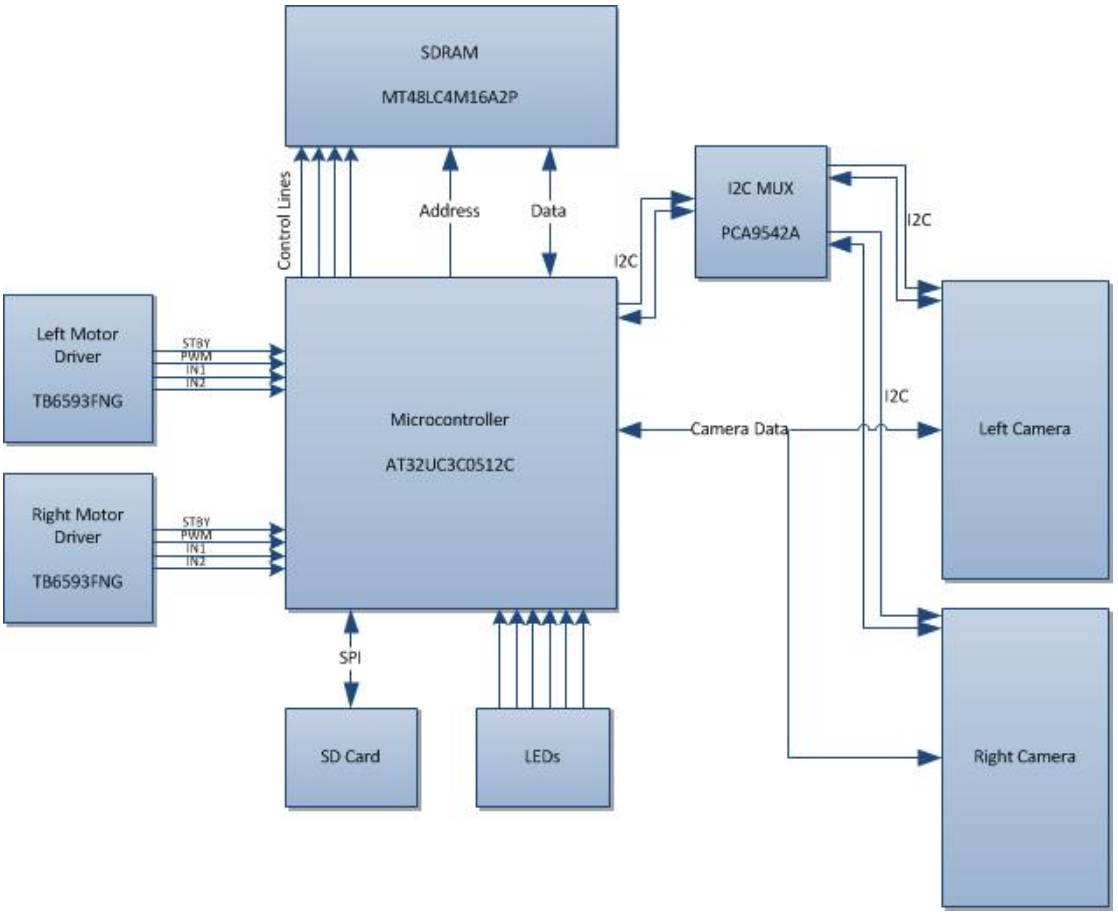


Figure 3.11: A hierarchical diagram of the robot

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

	Port			
Pin	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	-

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.

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 $100mm \times 70mm$. 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 3.12.

Considerations - Power consumption of devices not exceeding VReg

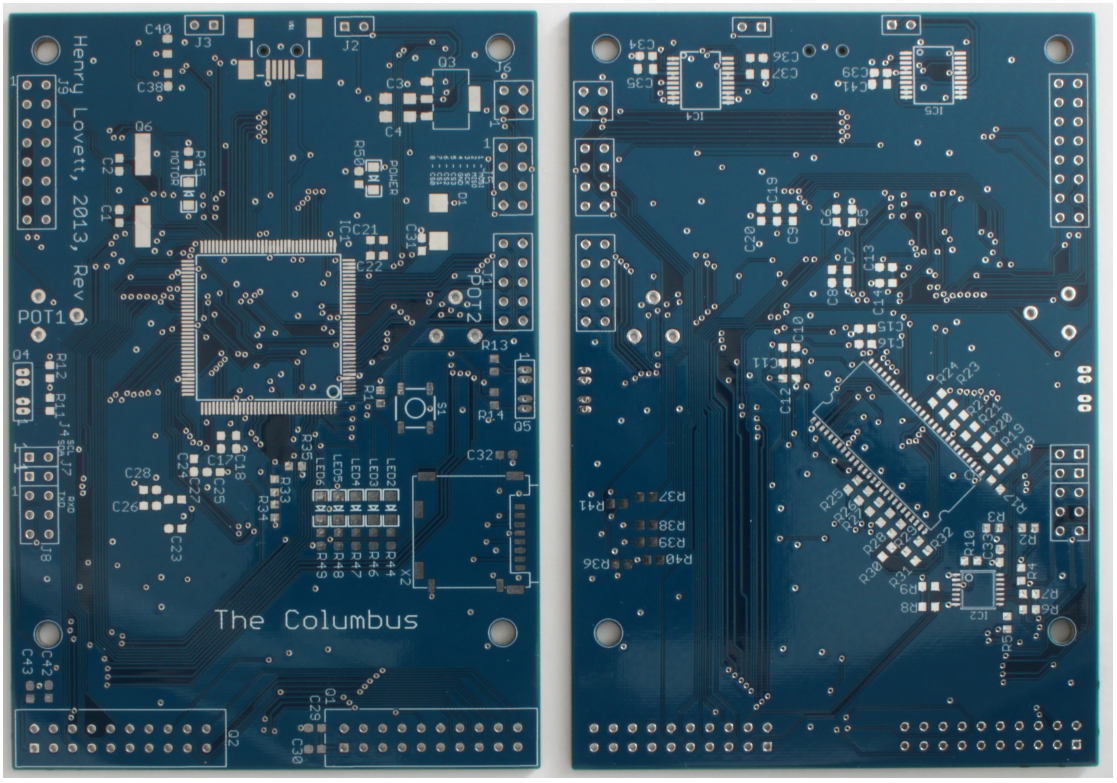


Figure 3.12: PCB with no components. Left: Top View. Right: Bottom View

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
       layer (/SERVICES/MEMORY/CTRL_ACCESS/)
6  if (mem_test_unit_ready(LUN_ID_SD_MMC_SPI_MEM) == CTRL_GOOD)
7  {
8    // Get and display the capacity
9    mem_read_capacity(LUN_ID_SD_MMC_SPI_MEM, &VarTemp);
10   print_dbg("OK:\t");
```

```
11      //printf_ulong((VarTemp + 1) >> (20 - FS_SHIFT_B_TO_SECTOR));
12      i = ((VarTemp + 1) >> (20 - FS_SHIFT_B_TO_SECTOR));
13      print_dbg_ulong(i);
14      print_dbg("MB\r\n");
15      print_dbg("SD Card Okay.\n\r");
16    }
17    else
18    {
19      // Display an error message
20      print_dbg("Not initialized: Check if memory is ready...\r\n");
21    }
22    nav_reset();
23    // Use the last drive available as default.
24    nav_drive_set(nav_drive_nb() - 1);
25    // Mount it.
26    nav_partition_mount();
27    nav_filelist_reset();
28    if(nav_filelist_findname((FS_STRING)LOG_FILE, false))
29    {
30      print_dbg("\n\rLog File Already Exists\n\rAttempting to delete...");
31      nav_setcwd((FS_STRING)LOG_FILE, true, false);
32      nav_file_del(false);

34      if(nav_filelist_findname((FS_STRING)LOG_FILE, false))
35        print_dbg("\n\rLog File Still Exists...");
36      else
37        print_dbg("\n\rLog File Deleted!");
38    }
39    print_dbg("\n\rCreating Log File.");

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;

23    }
24    print_dbg("\rSDRAM filled with test pattern       \r\n");
25    // Recover the test pattern from the SDRAM and verify it.
26    for (i = 0, j = 0; i < sdram_size; i++)
27    {
28      if (i == j * progress_inc)
29      {
30        print_dbg("\rRecovering test pattern from SDRAM: ");
31        print_dbg_ulong(j++);
32        print_dbg("%");
33      }
34      tmp = sdram[i];
35      if (tmp != i)//failed
36      {
37        noErrors++;
38      }
39    }
40    print_dbg("\rSDRAM tested: ");
41    print_dbg_ulong(noErrors);
42    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

```
1   ////////////////////////////////////////////////
2   // TWI Test ////////////////////////////////////
3   ////////////////////////////////////////////////
4   print_dbg("\n\n\rTWI Test:\n\r");
5   Log_Write("\n\n\rTWI Test:\n\r", 14);
6   for(k = 0; tkmp < 3; k++)
7   {
8     if(k == 0){
```

```
9         print_dbg("Scanning all Channels\n\r");
10      }
11      else if (k == 1){
12        //Channel 0
13        PCA9542A_Chan_Sel(I2C_CHANNEL_0);
14        print_dbg("\n\rScanning Channel 0\n\r");
15      }
16      else {
17        //Channel 1
18        PCA9542A_Chan_Sel(I2C_CHANNEL_1);
19        print_dbg("\n\rScanning Channel 1\n\r");
20      }

22      print_dbg("h 0 1 2 3 4 5 6 7 8 9 A B C D E F\n\r");
23      tmp = 0;
24      for(i = 0; i < 8; i++)
25      {
26        print_dbg_ulong(i);
27        print_dbg(" ");
28        for(j = 0; j < 16; j++){
29          int status = twim_probe(TWIM, tmp++);
30          if(status == STATUS_OK){
31            print_dbg("A");
32          }
33          else{
34            print_dbg("-");
35          }
36          print_dbg(" ");
37        }
38        print_dbg("\n\r");
39      }
40    }
41    noErrors = 0;
42    //Check cameras exist
43    PCA9542A_Chan_Sel(I2C_CHANNEL_0);
44    if(twim_probe(TWIM, 0x21) != STATUS_OK)
45      print_dbg("\n\rCamera 0 Not Found;");
46    PCA9542A_Chan_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  {
9    print_dbg("\n\rCamera Initialise Okay!");
10 }
11 else
12   print_dbg("\n\rCamara Initialise Fail.");
13
14 print_dbg("\n\rTaking Photos");
15
16 TakePhoto(CAMERA_LEFT | CAMERA_RIGHT);
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.

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 that usually necessary. Figure 3.13 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

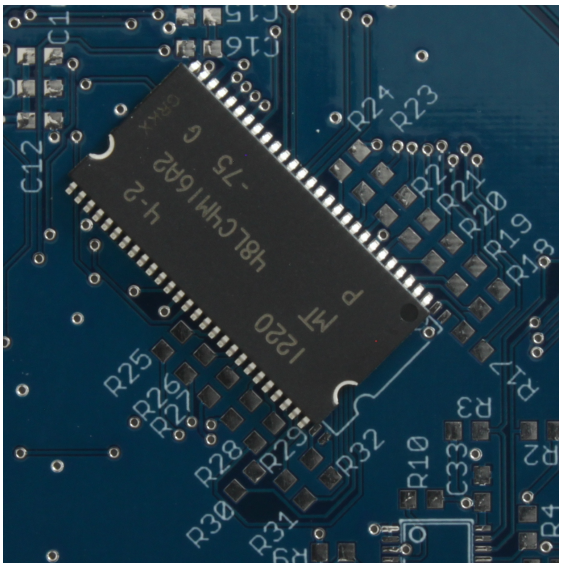


Figure 3.13: SDRAM Chip shown against its footprint.

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 3.15(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 3.15(b).

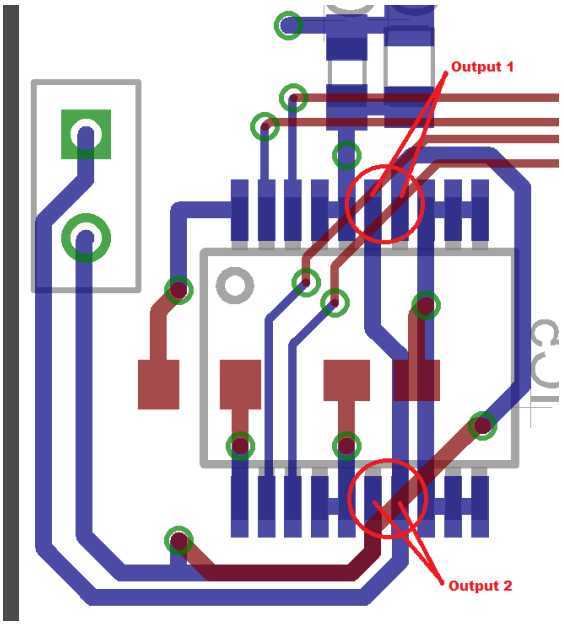


Figure 3.14: Motor Driver error. Outputs incorrectly connected

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 3.14 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
- SDRAM footprint
- SDRAM chip select line

- SDRAM data line resistors
- Camera interrupt line
- Motor driver pinout

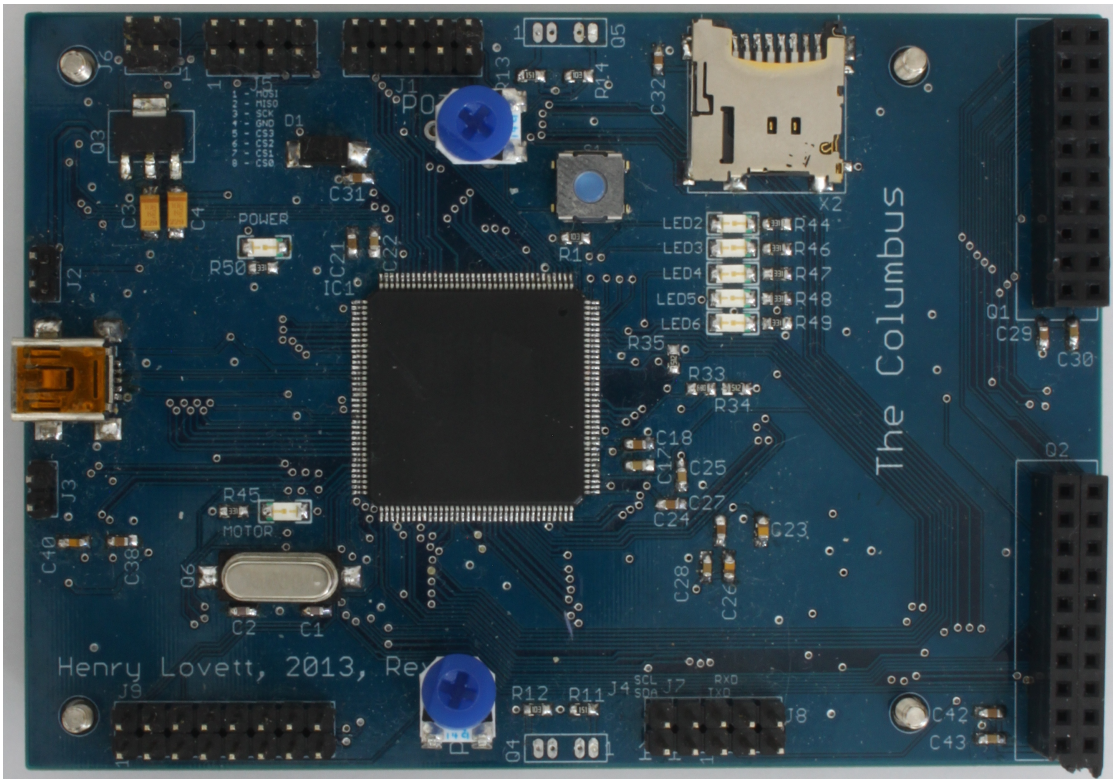
Three of the faults could have been avoided by consulting the datasheet more carefully during the circuit design stage. The footprint error was due to not being experienced in designing footprints and the data line resistors was a mistake due to lack of attention being paid.

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.

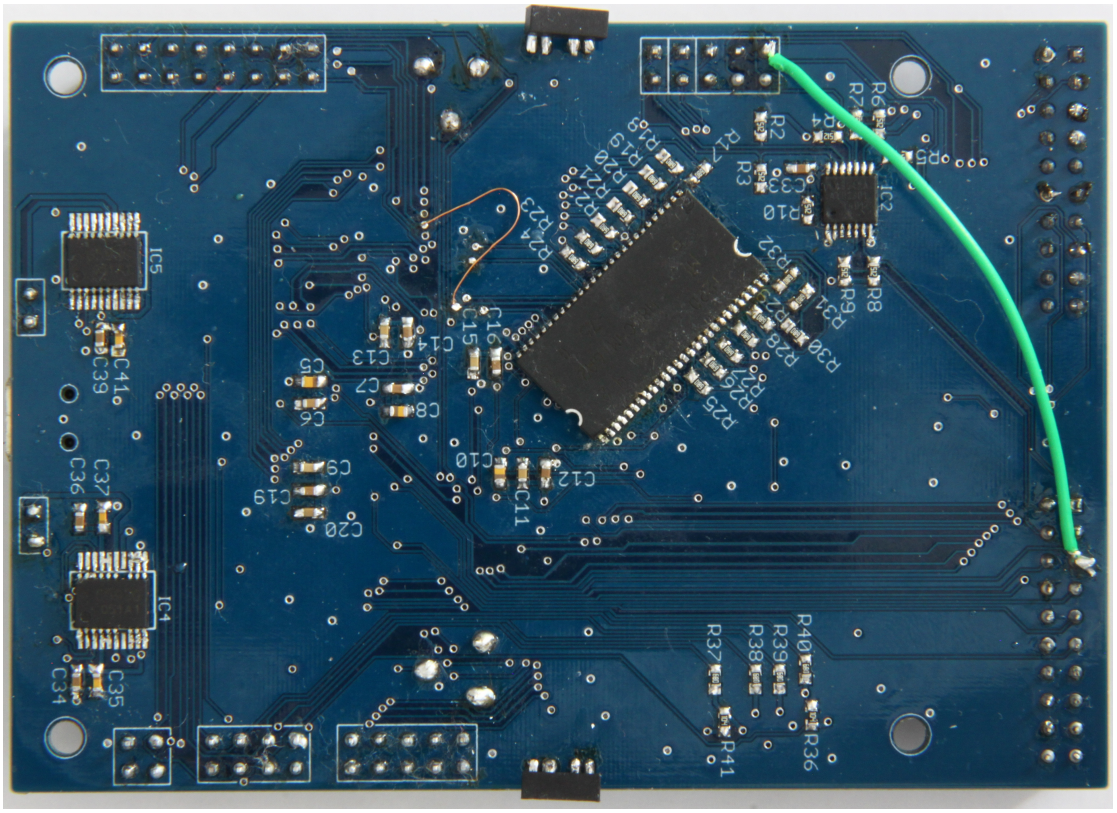
The PCB itself, was a success. It was a complex PCB with many potential things that could have gone wrong. All devices are functional (with a few small modifications) on the PCB so firmware development could continue with all hardware able to be used.

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.



(a) Top view of built PCB



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

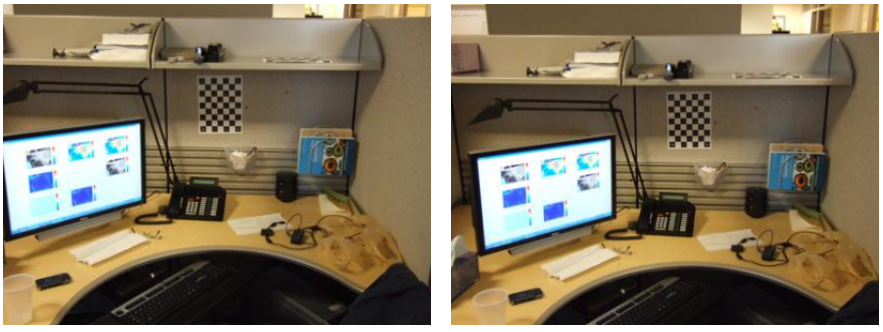
Figure 3.15: Pictures of the built PCB.

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

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

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

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

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

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

Where n is the number of pixels in A and B,
σ is the standard deviation of the image, and
$\bar{A}$ is the a 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 a 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 a 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 operates slowly on a microcontroller without any.

4.1.4 Comparison

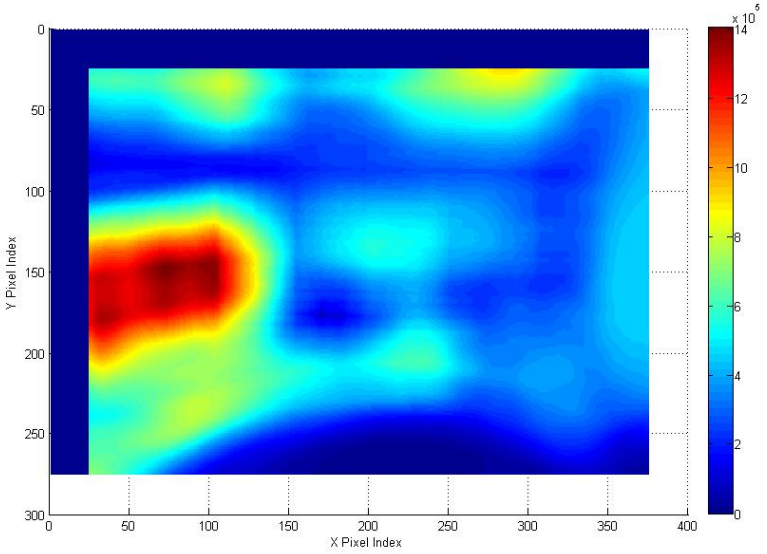
To compare these equations, a 50 by 50 window taken from the right picture was compared with the left image over the entire valid range. The coordinates on the graph give the centre pixel of the calculation.

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).

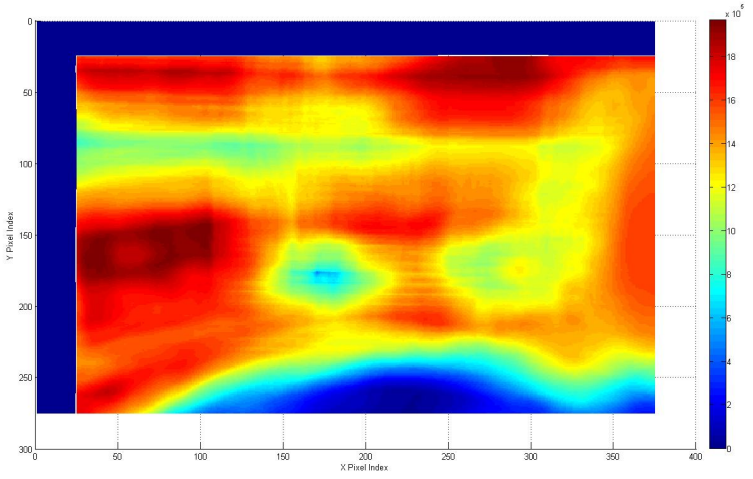
SAD results in figure 4.2(a) show large areas of matching. A minimum occurs around the location expected$(170, 175)$ of a value of 5.66×10^4. However, along the bottom of the image, where a dark area occurs below the desk in the lower part of figures 4.1, the SAD algorithm detects a greater comparison, 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.

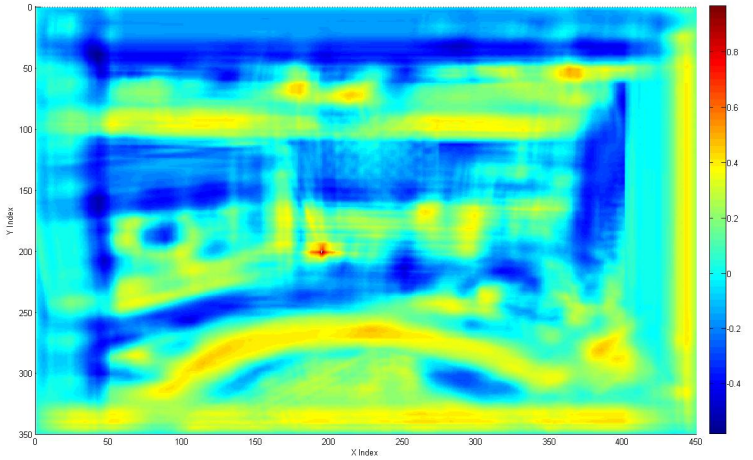
The NCC results are visible in figure 4.2(c). A match can be seen at coordinate $(195, 201)$ with a peak value of 0.9654. The coordinate is different to the previous results because the cross correlation works over the boundary of the image creating more results. The dimensions of the image are 300×400,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

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

Object is to the same side in both images:

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

Object is directly in front of a camera:

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

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

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

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

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.

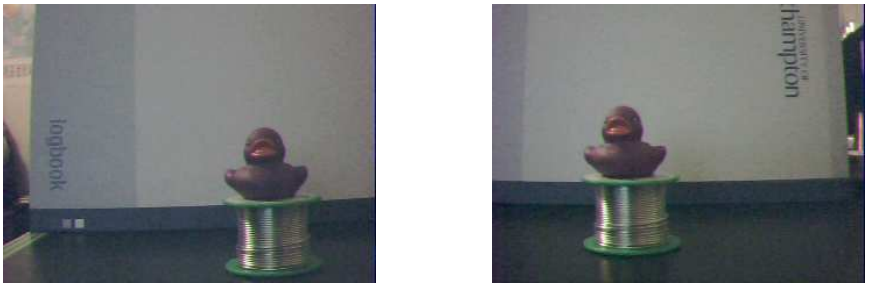


Figure 4.3: Stereo pair of images of a rubber duck on a reel of solder

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 ducks 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 $B = 45mm$, $\varphi_0 = 0.6249^c$, $x_0 = 320$ and x_1 and x_2 are from the matched and chosen x coordinates respectively:

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

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). Figure 4.5 shows that by increasing B will give you

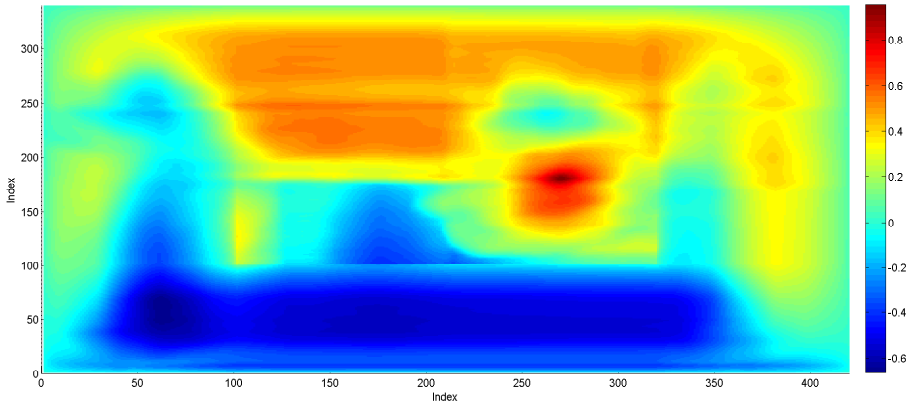


Figure 4.4: NCC results from matching using the ducks head from the right image as the template to the left image

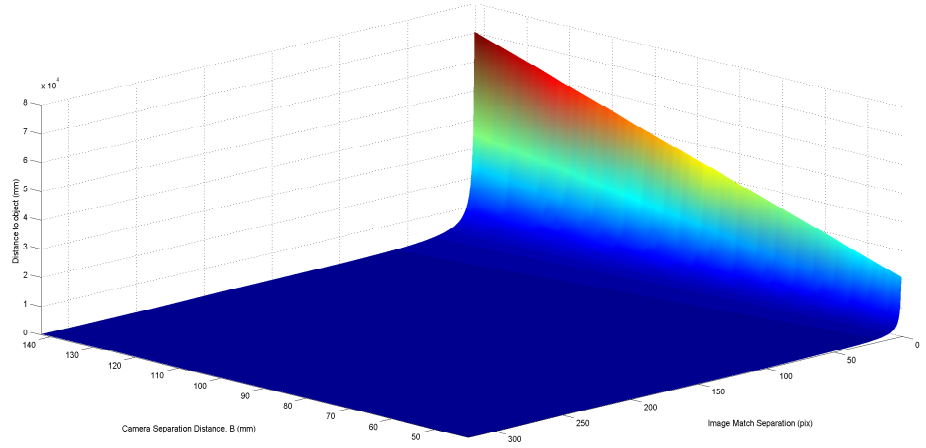


Figure 4.5: 3D Surface plot graph showing range of distances that can be calculated over a range of camera separation, B, values.

a larger range of detectable distances, but at a lower resolution. A separation of more than 100 is about the same calculated distance due to the function being of the form $D = \frac{k}{\Delta_x}$. An external frame could be made for the robot to increase the separation if needed.

The robot was designed to be small, but some accuracy still remained. With a separation of $B = 42mm$, the maximum distance to an object is, theoretically, $20m$. With a higher resolution camera, less error will be introduced into the range finding.

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 4.6 and 4.7.

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-\jmath 2\pi ft}dt \tag{4.10}$$

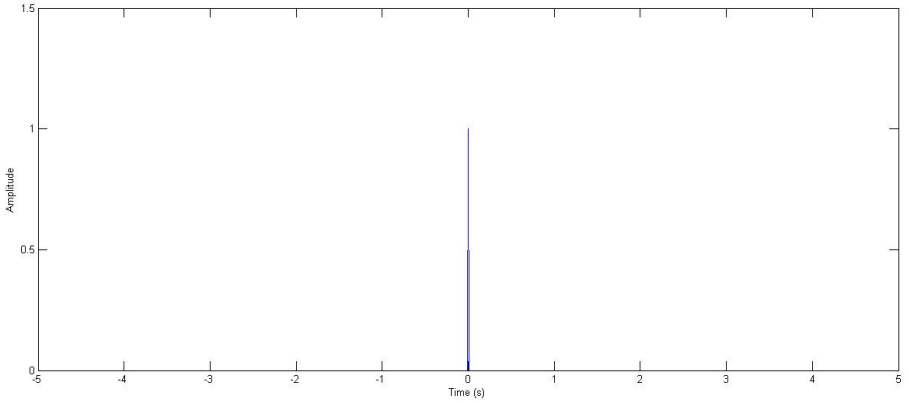
The Fourier transform is used in many areas of signal processing. It is used for filter design, system analysis and image processing as well as many others. It shows the frequency components of a time domain signal.

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, 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.

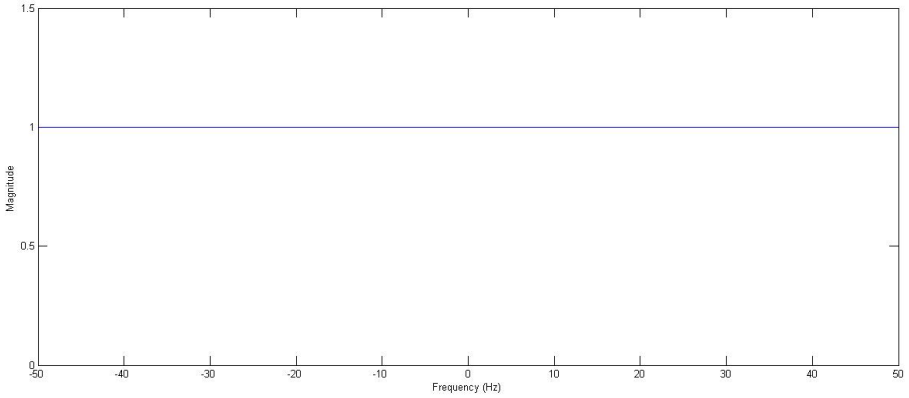
$$X[k] = \sum_{0}^{N-1} x[n]e^{-\jmath\Omega_0 kn} \tag{4.11}$$

Where Ω_0 is the sample frequency

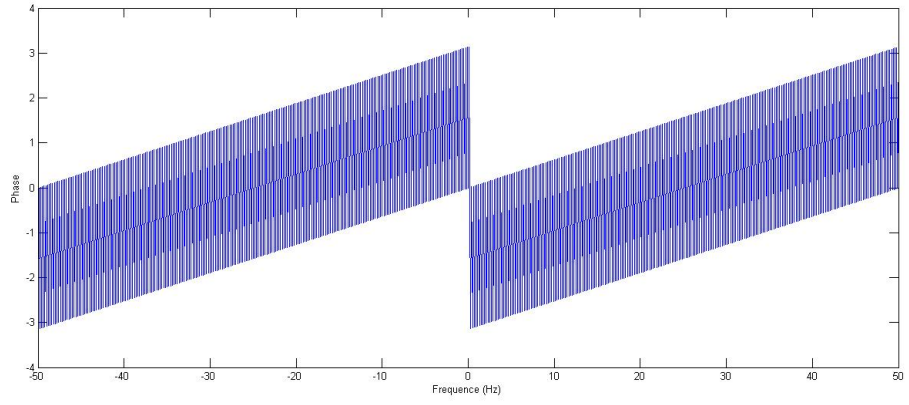
A property of the Fourier Transform of interest is the convolution theorem which states that convolution in time is multiplication in frequency and is defined mathematically in equation (4.12). As discussed in section 4.1.3, cross correlation is very similar to convolution. Cross correlation is defined 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.



(a) A graph showing a Dirac Function

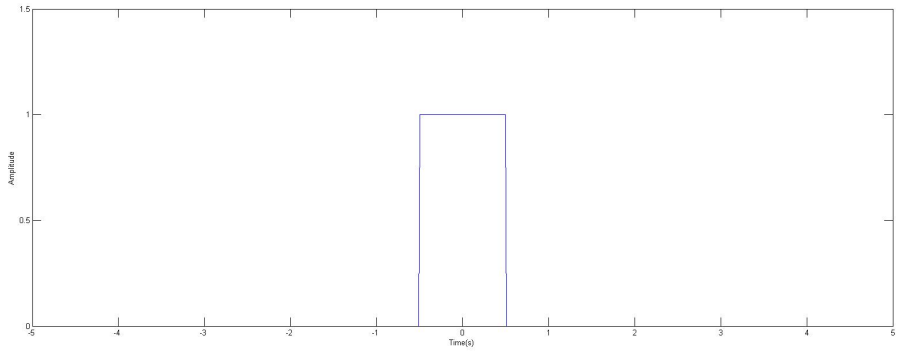


(b) A graph showing the magnitude of the Fourier transform of the Dirac Function

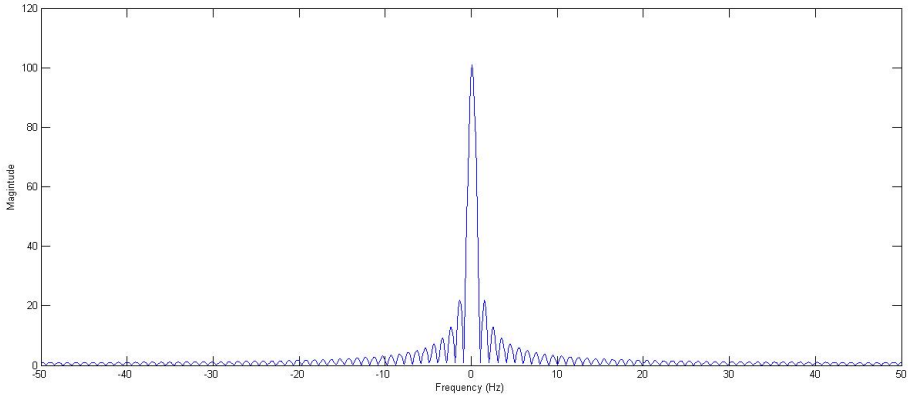


(c) A graph showing the phase of the Fourier transform of the Dirac Function

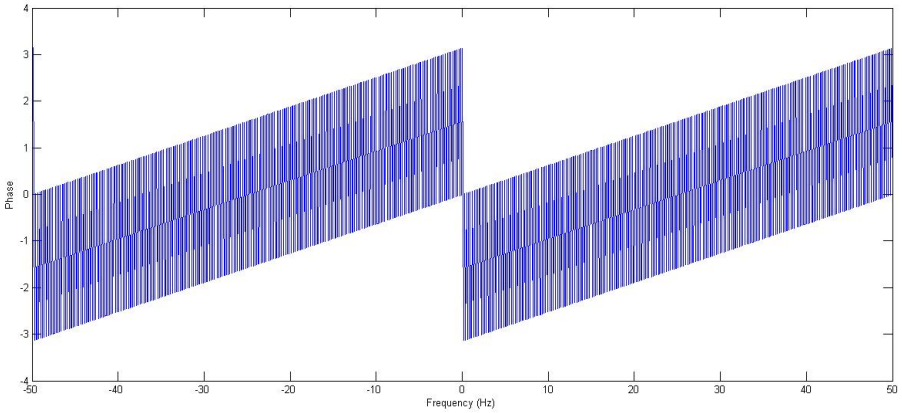
Figure 4.6: A Dirac signal and the phase and magnitude of its Fourier Transform



(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 4.7: A 2D Rectangular pulse and the phase and magnitude of its Fourier Transform

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

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

$$f(t) \star g(t) = f(t) * g(-t) = F(f) \cdot G(-f) \tag{4.14}$$

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)

$$F(u,v) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y)e^{-2\pi\jmath(xu+yv)}dxdy \tag{4.15}$$

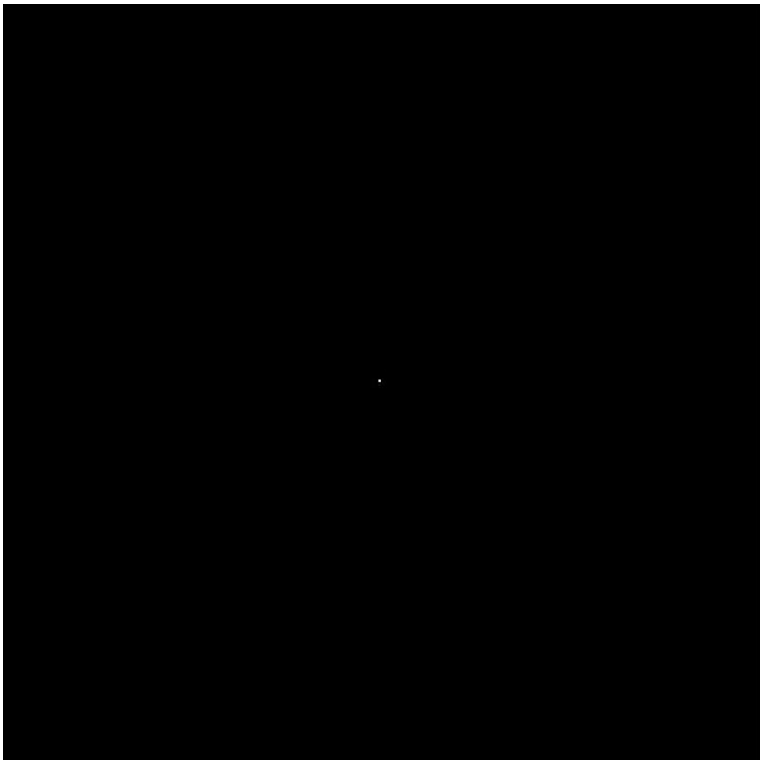
$$F(u,v) = \frac{1}{N} \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} f(x,y)e^{-\frac{2\pi\jmath(xu+yv)}{N}} \qquad x,y,u,v \in \{0 \dots N-1\} \tag{4.16}$$

Figures 4.8 and 4.9 show the two dimensional equivalent test signals of figures 4.6(a) and 4.7(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 4.6(b) and 4.8(b)) are both constant values and the rectangular pulses both have a modulus sinc function magnitude (figures 4.7(a) and 4.9(a)).

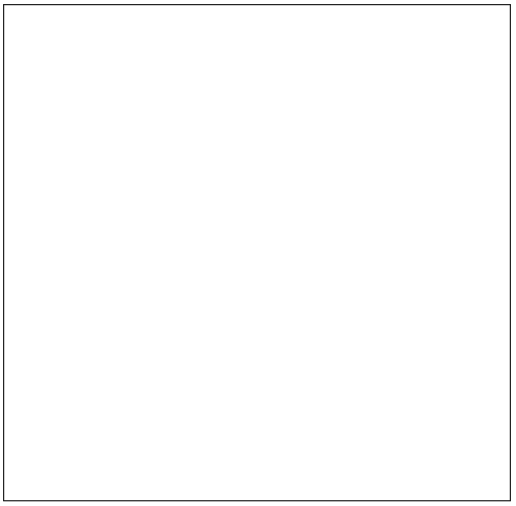
The 2D Fourier transform can also be optimised to a fast Fourier transform algorithm in a similar way as the 1D case. The algorithm, sometimes referred to as the Butterfly transform, is briefly discussed in Nixon and Aguado (2012) where is is explained that the algorithm can be easily applied to images 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:

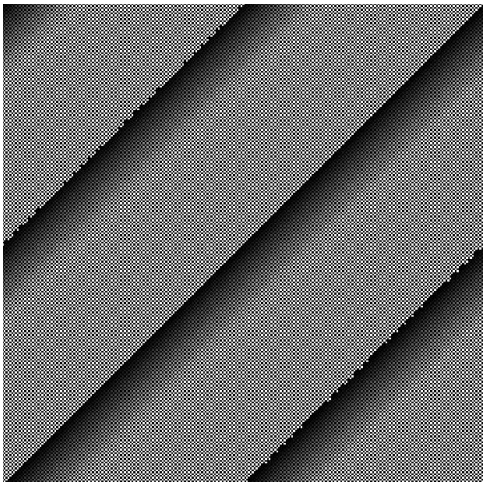
1. Calculate the 1D FFT of each of the rows of the 2D data. (An FFT of data of length n returns an array, also of length n)



(a) An image of a 2D Dirac Function

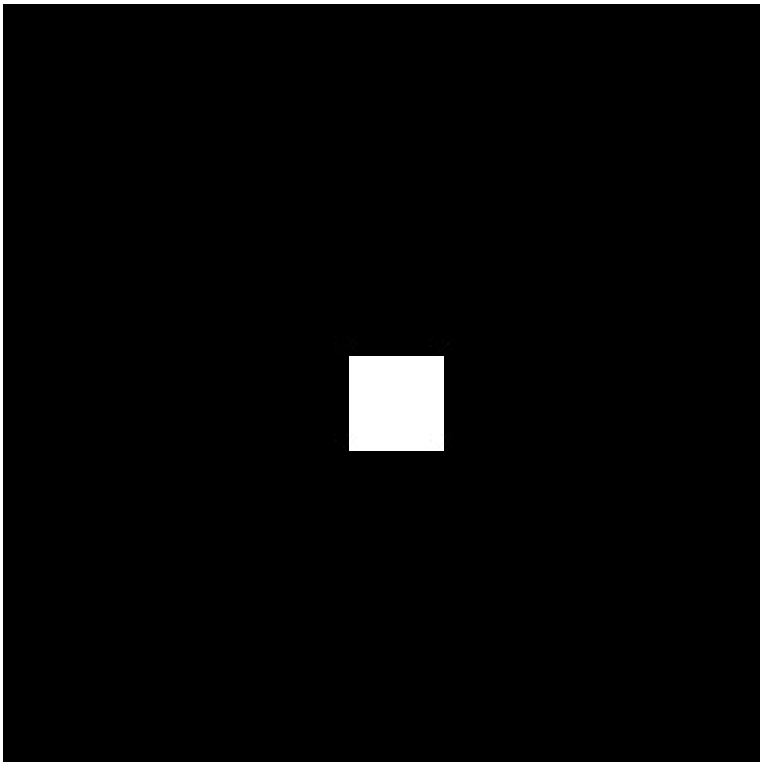


(b) An image of the magnitude of the Fourier transform of the 2D Dirac Function

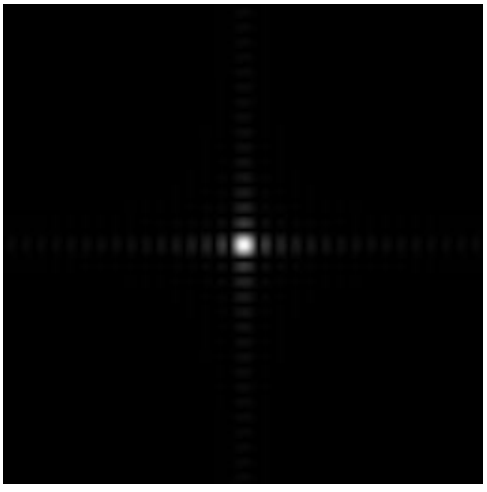


(c) An image of the phase of the Fourier transform of the 2D Dirac Function

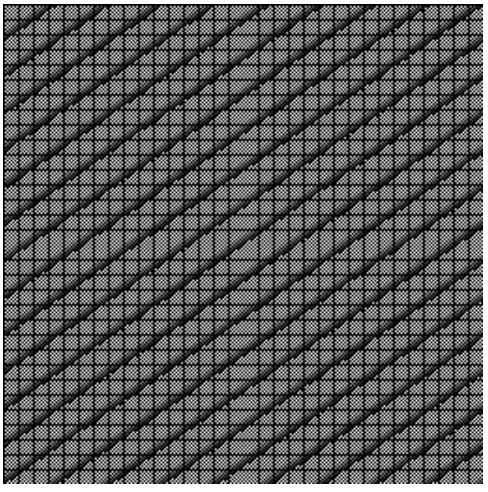
Figure 4.8: A 2D Dirac signal and the phase and magnitude of its Fourier Transform



(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 4.9: A 2D Rectangular Pulse signal and the phase and magnitude of its Fourier transform

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.

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 4.10 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 4.11 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

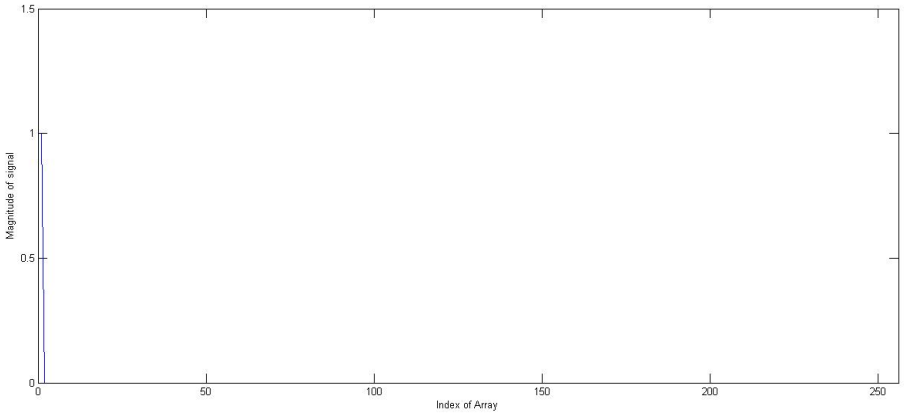


Figure 4.10: Input Dirac Signal for AVR fast Fourier transform

with figure 4.6(b), they are relatively similar. The phase, however, seems to be very different. Figure 4.6(c) shows what was expected, but the two phase results seem not to match. This could due to MATLAB having more accurate algorithms and a more accurate representation that 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 4.12 is obtained. This, though is 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 4.12 is 0.9897 to 4 decimal places giving an overall error of 1.03%.

Figures 4.13, 4.14 and 4.15 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 4.14) is different to the result when the magnitude is calculated on the AVR (figure 4.15). There are also differences in the result from the AVR and the result from MATLAB in figure 4.7, which can, again, be put down to the algorithms.

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 4.8(a) and 4.9(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

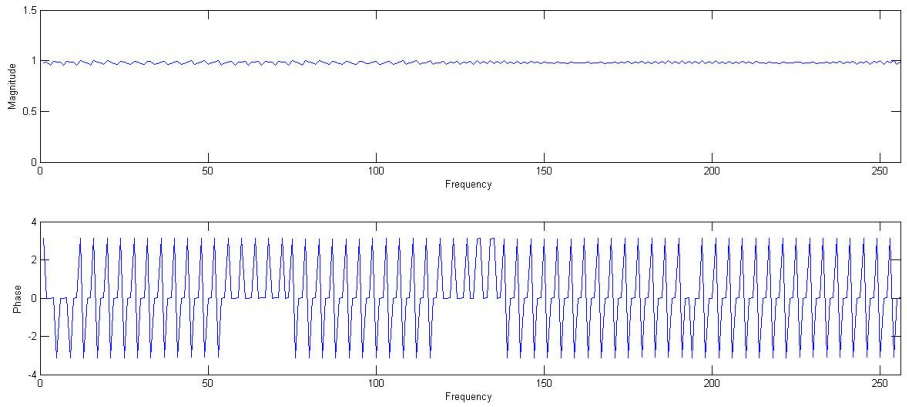


Figure 4.11: Output phase and magnitude of the complex output from AVR fast Fourier transform of a Dirac function

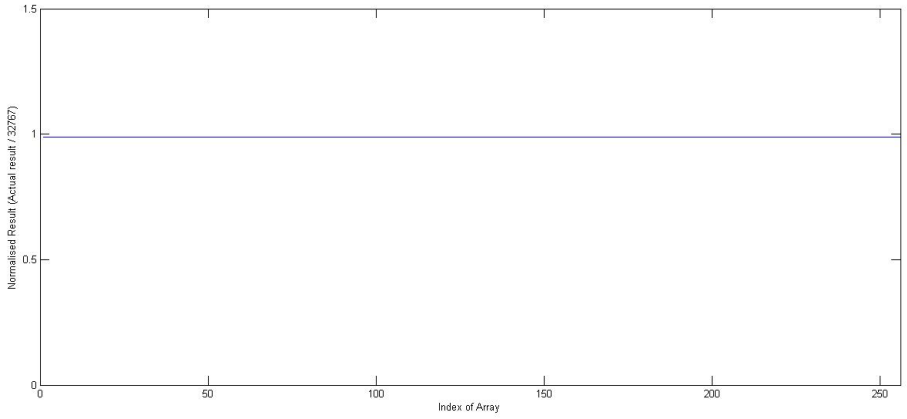


Figure 4.12: Maginitude calculated by the AVR of the Fourier transform of a Dirac function

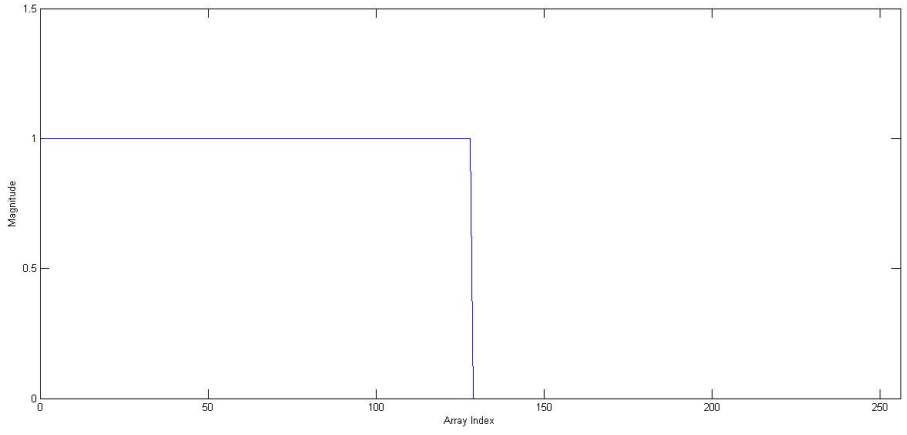


Figure 4.13: Input Rectangular Pulse for AVR fast Fourier transform

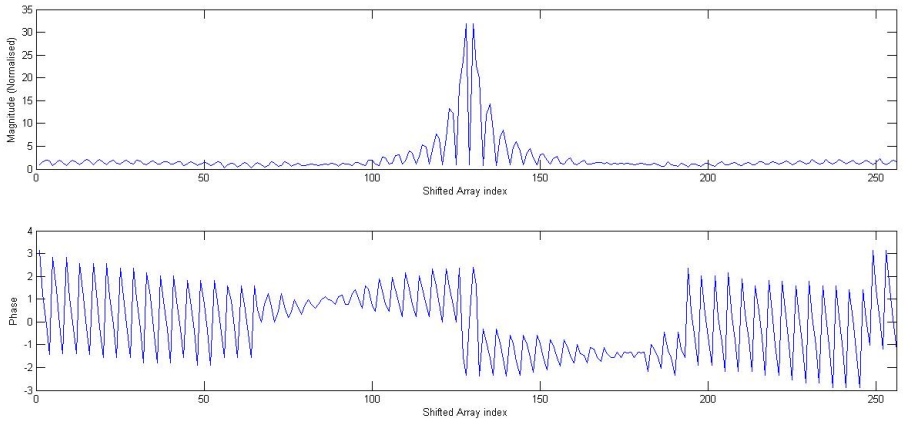


Figure 4.14: Output phase and magnitude of the complex output from AVR fast Fourier transform of a Rectangular Pulse

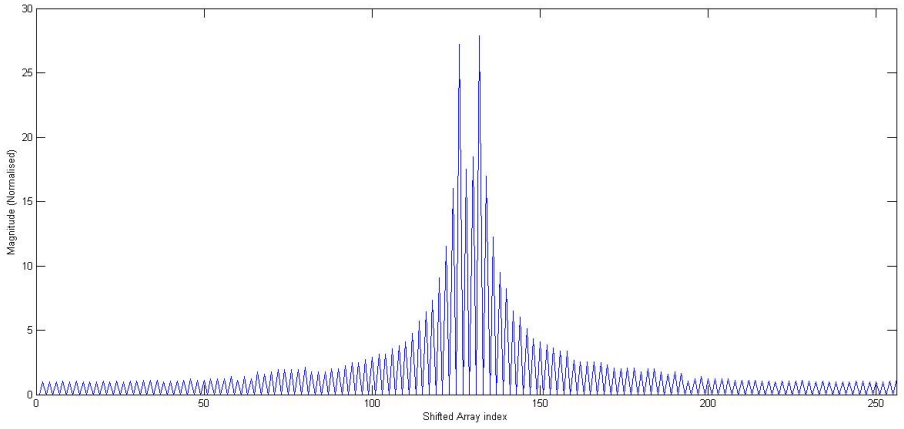


Figure 4.15: Maginitude calculated by the AVR of the Fourier transform of a Rectangular Pulse

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 4.16. 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 4.12. 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 4.17(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,

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

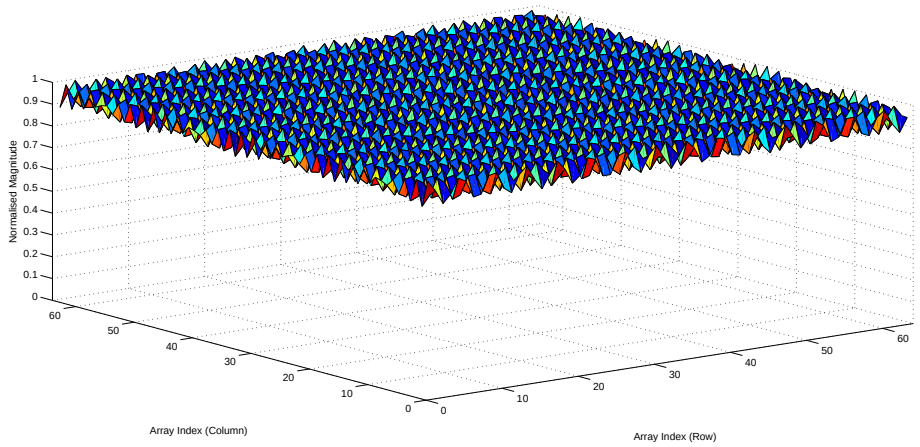
	Size of FFT Data	
	64	256
1D	5019	23599
2D	618168	-

the phase (figure 4.17(b)) seems to differ a lot from the expected result in figure 4.9(c).

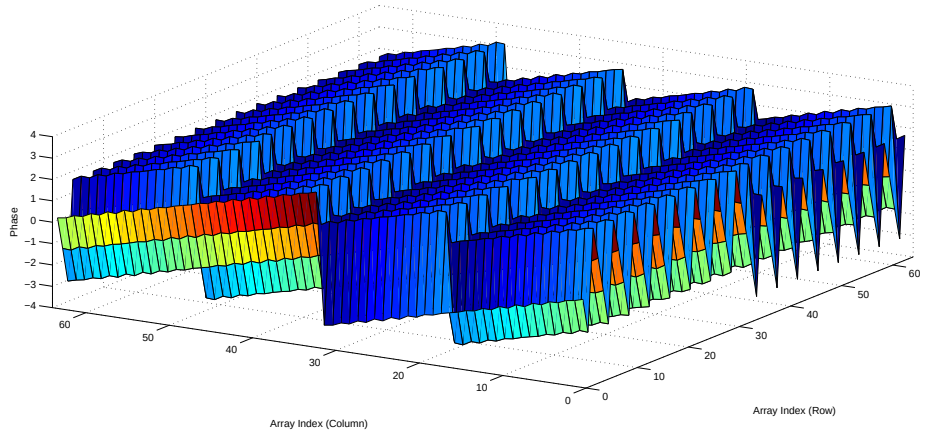
The transforms are calculated in real time with a 16MHz clock source. Table 4.2 shows the number of clock cycles taken to calculate the relevant sized transform. A 64×64 transform takes $39ms$ to compute with a 16MHz clock. This could be reduced by increasing the internal clock speed by using the PLLs 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

Maybe IFFT it too to find total errors in algorithm?

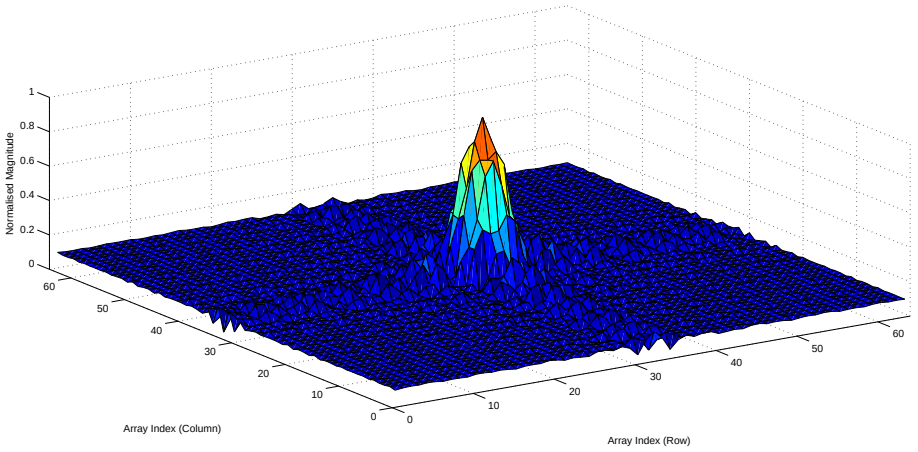


(a) A 3D Plot of the normalised magnitude of the complex data returned by the 2D fast Fourier Transform on the AVR

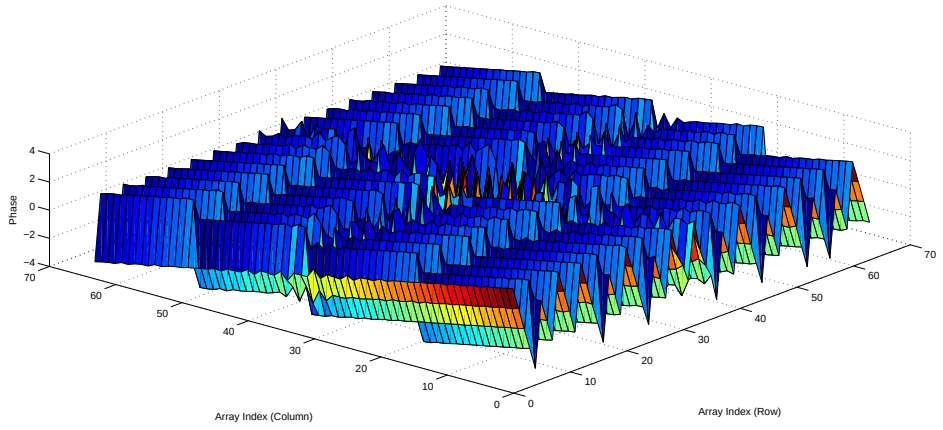


(b) A 3D Plot of the phase of the complex data returned by the 2D fast Fourier Transform on the AVR

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 Dirac Function



(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 4.17: 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

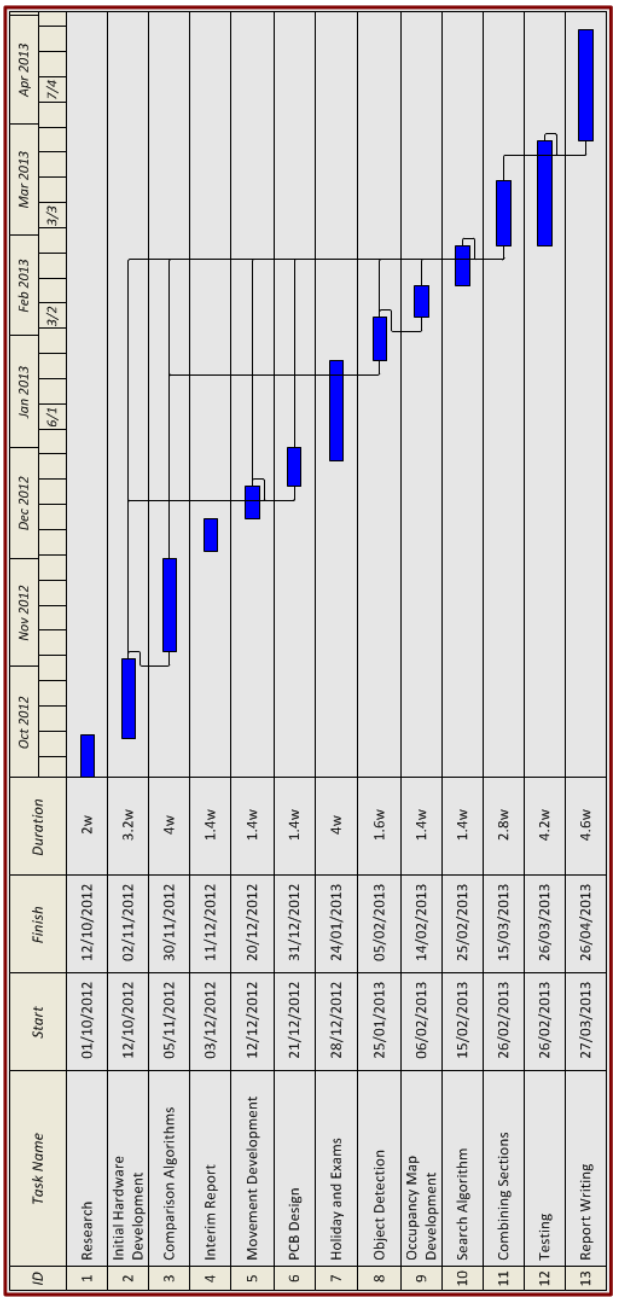


Figure A.1: Gantt Chart of how time will be spent in the areas of the project

Appendix B

Circuit Diagrams

B.1 OV7670 Breakout Board Schematic

B.2 Il Matto and Dual Camera Schematic

B.3 The Columbus Circuit Diagram

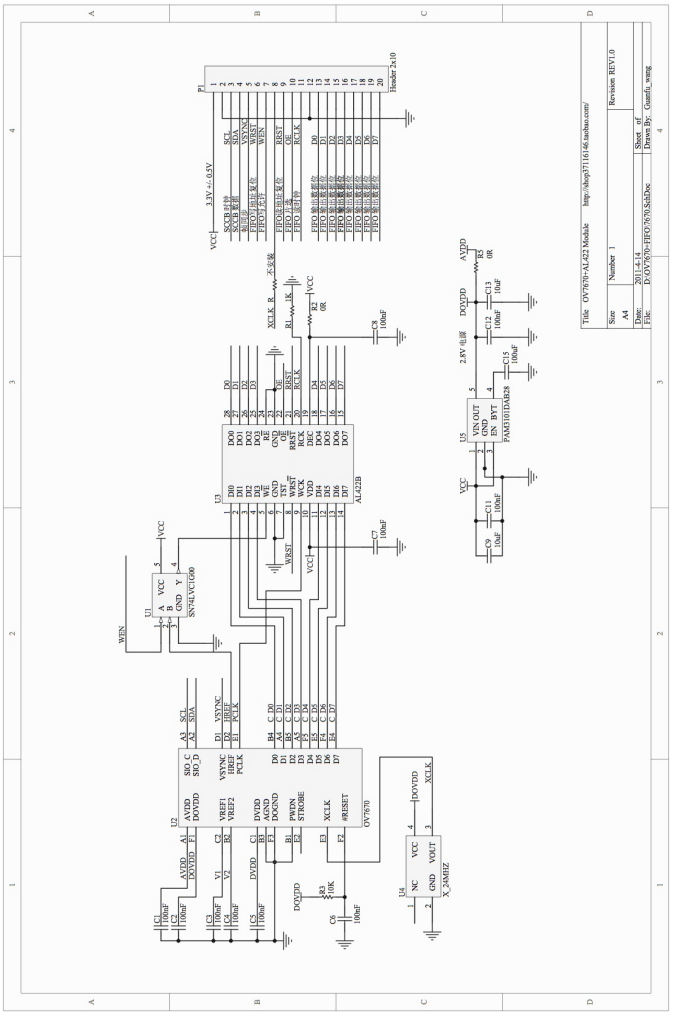


Figure B.1: The circuit diagram for the OV7670 breakout board

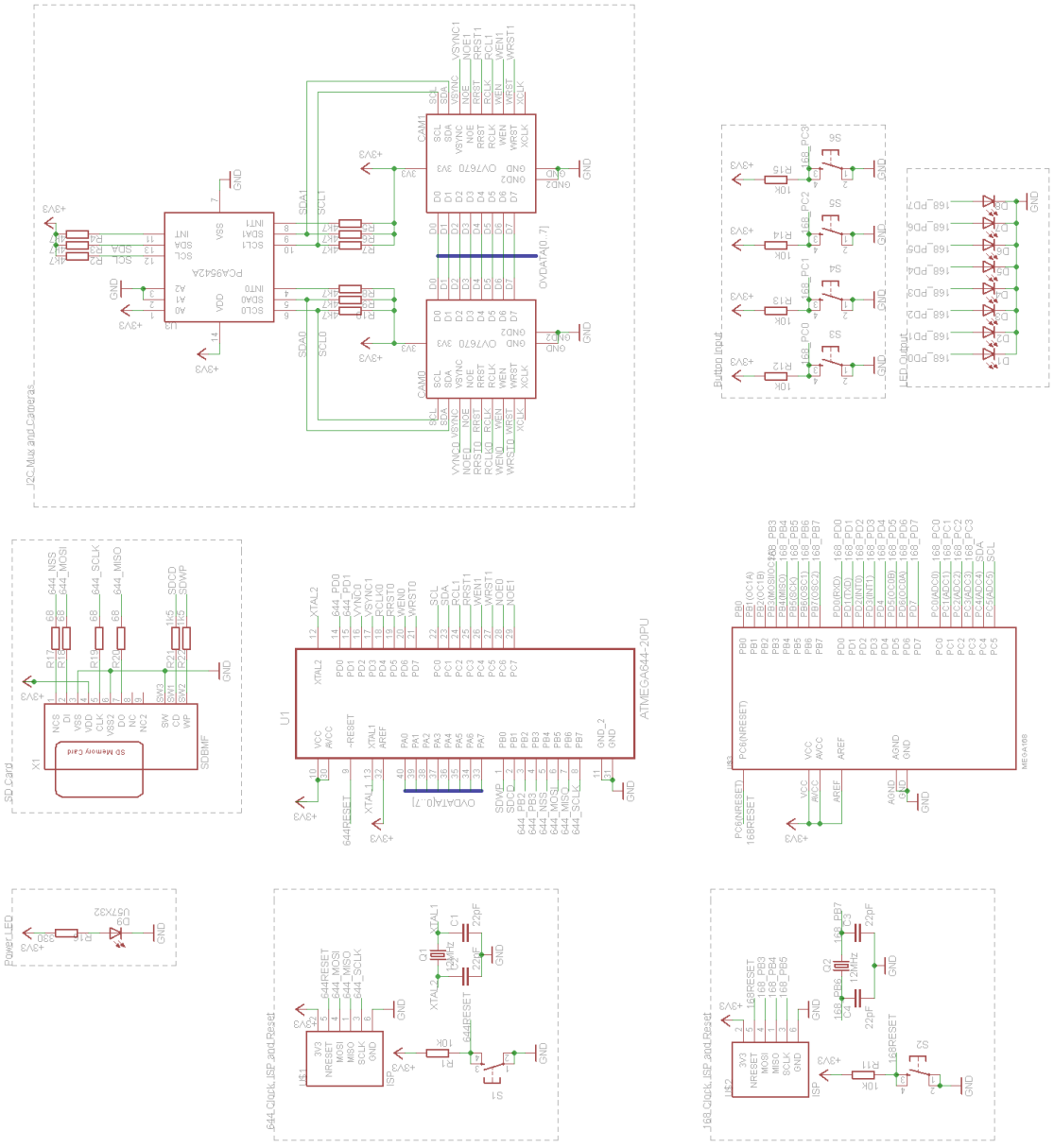


Figure B.2: The circuit diagram for Dual Cameras using the Il Matto Board

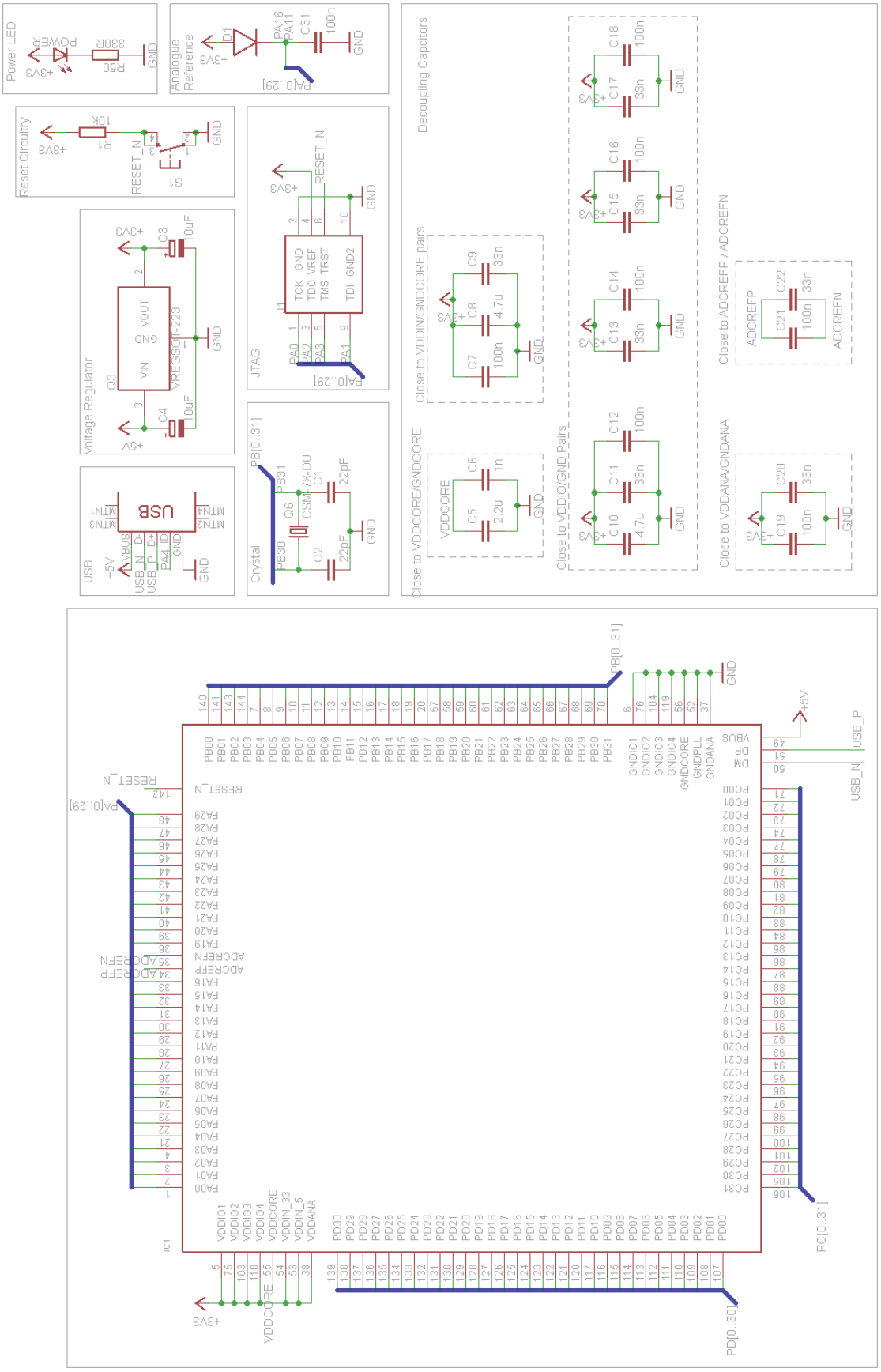


Figure B.3: The Columbus Circuit Diagram Page 1

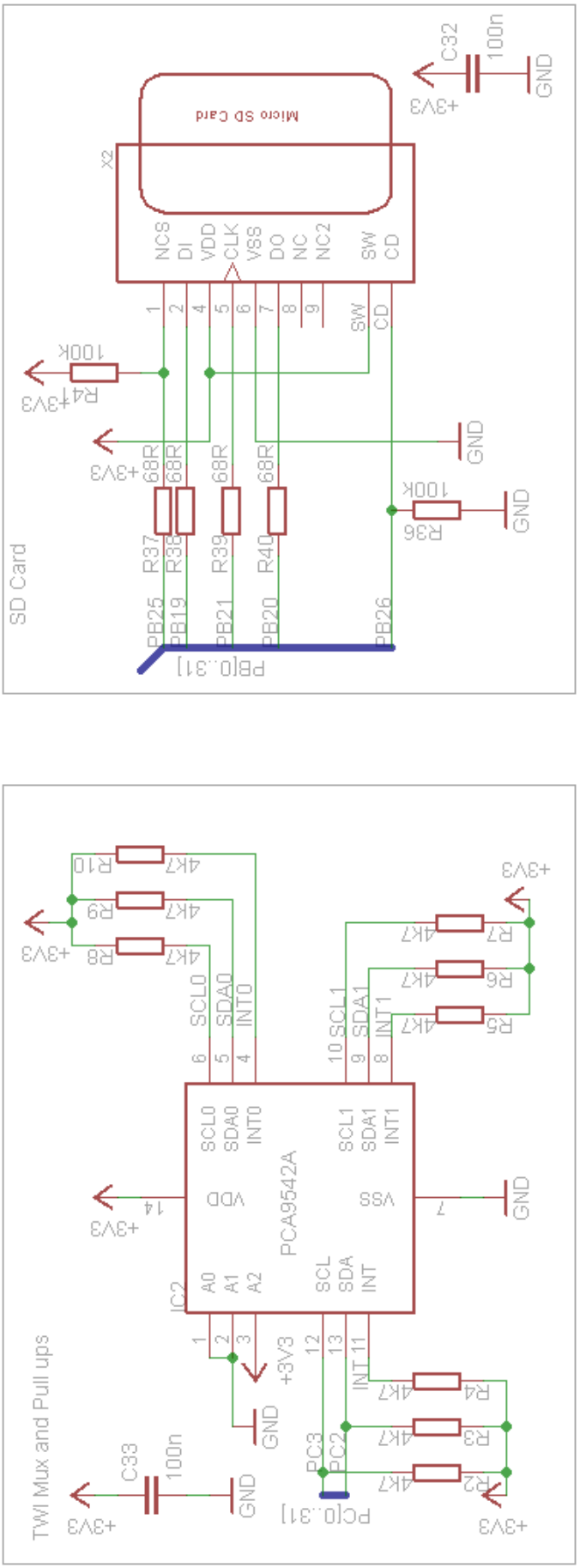


Figure B.4: The Columbus Circuit Diagram Page 2

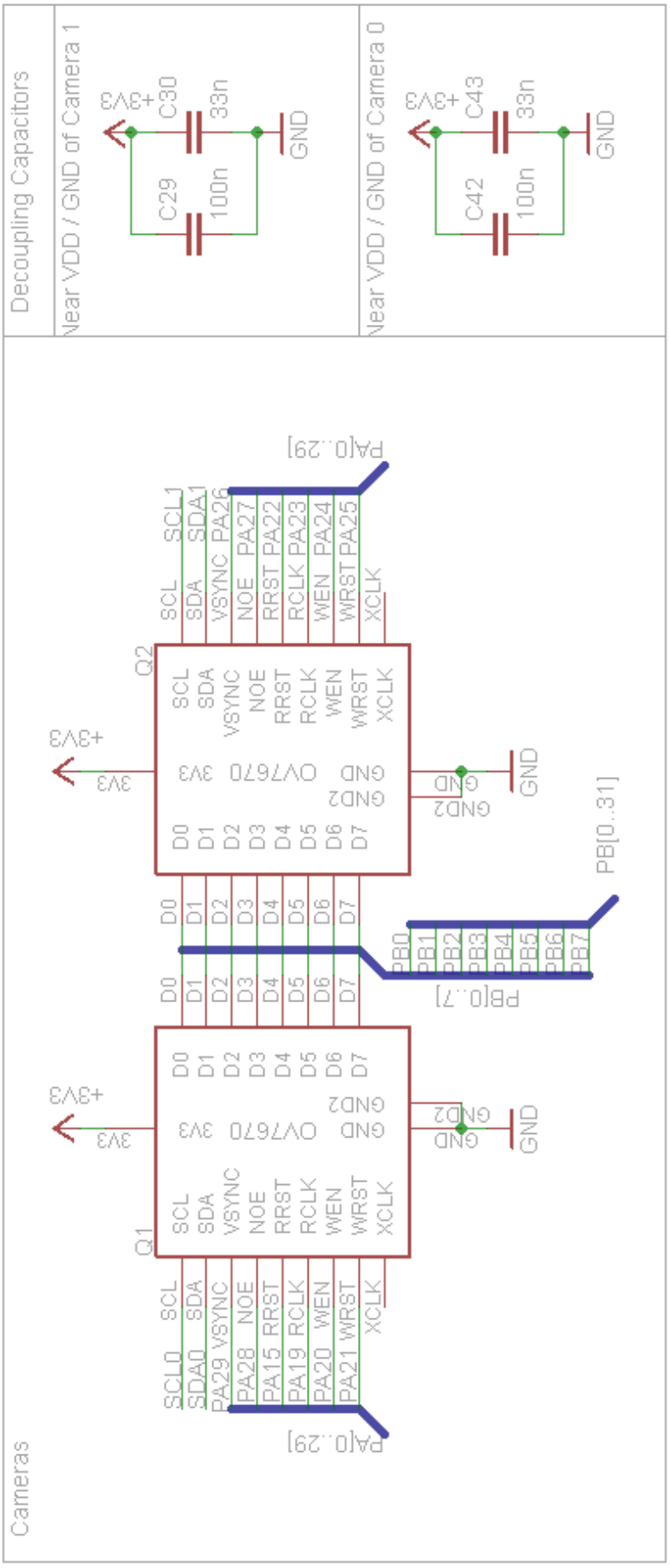


Figure B.5: The Columbus Circuit Diagram Page 3

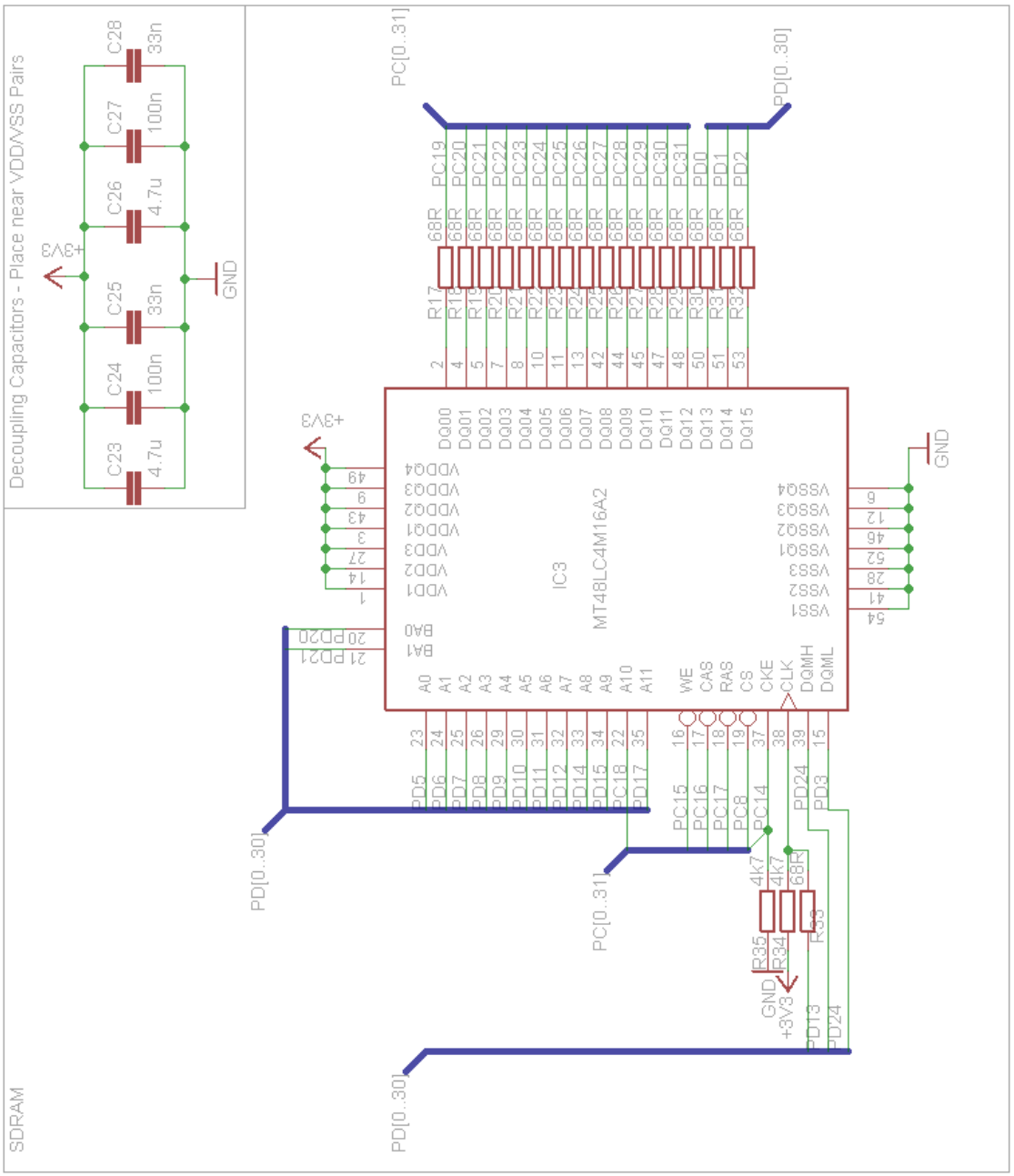


Figure B.6: The Columbus Circuit Diagram Page 4

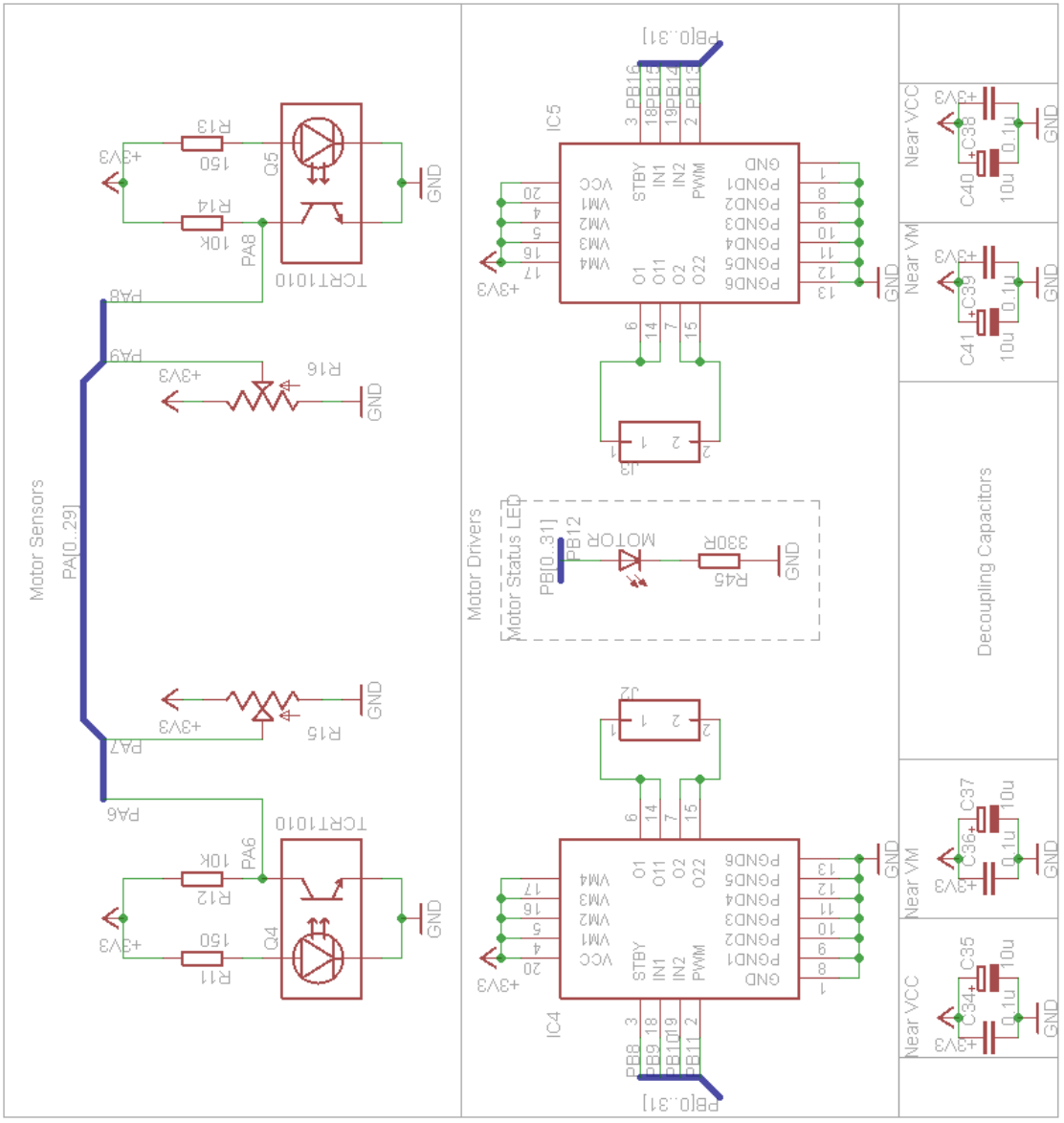


Figure B.7: The Columbus Circuit Diagram Page 5

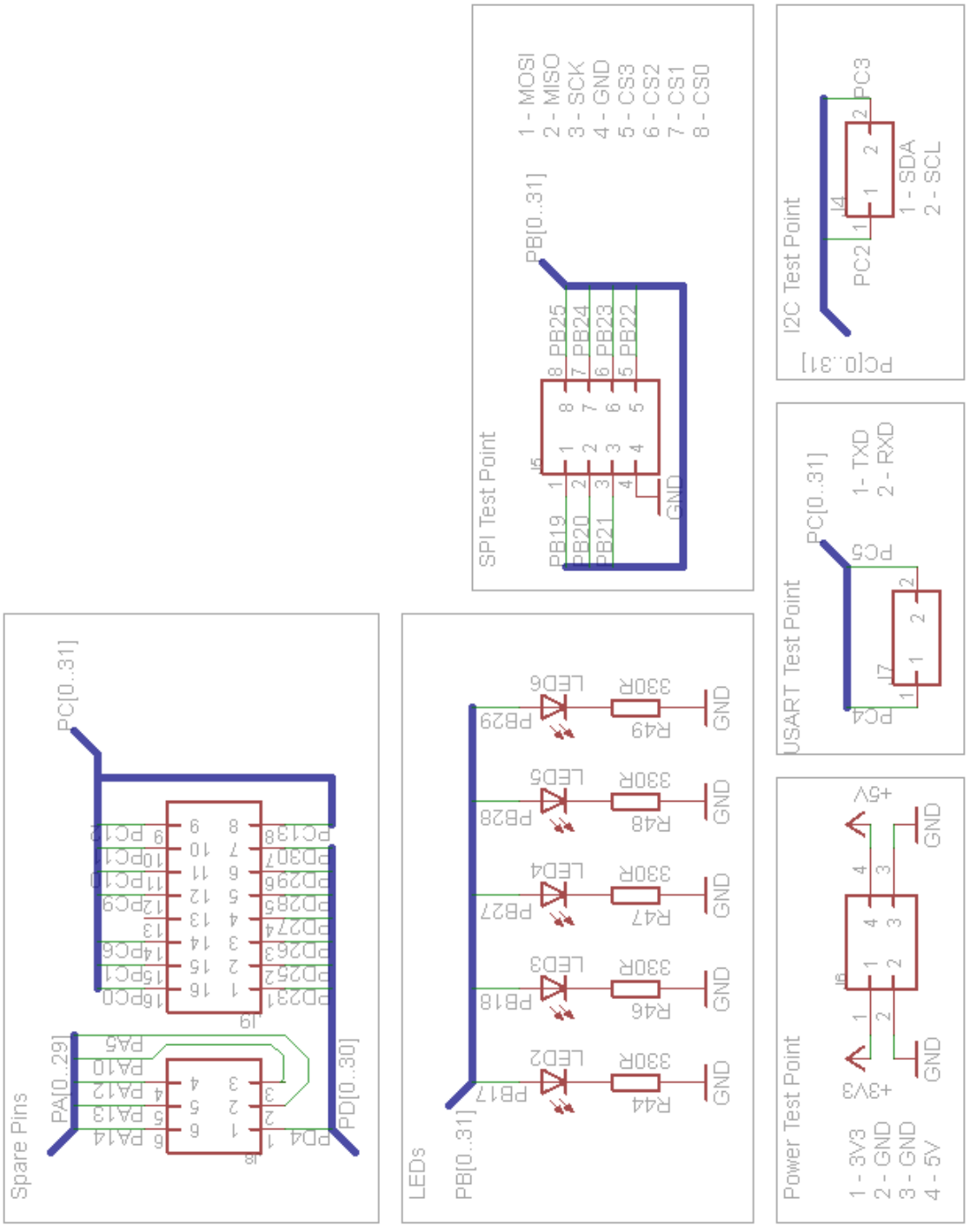


Figure B.8: The Columbus Circuit Diagram Page 6

Appendix C

PCB Design

C.1 PCB Top Side

C.2 PCB Bottom Side

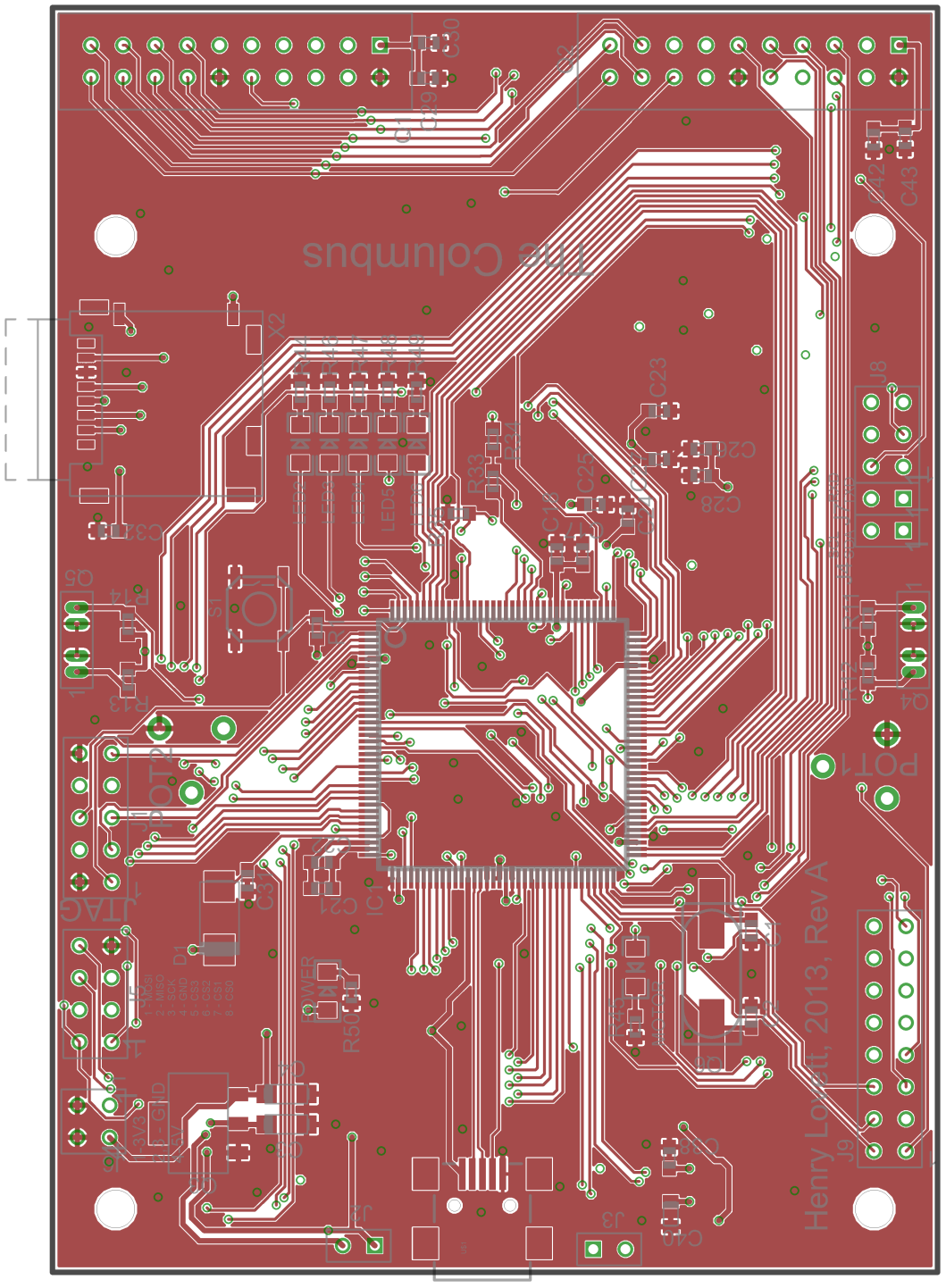


Figure C.1: The Top side of the CAD Design of the PCB

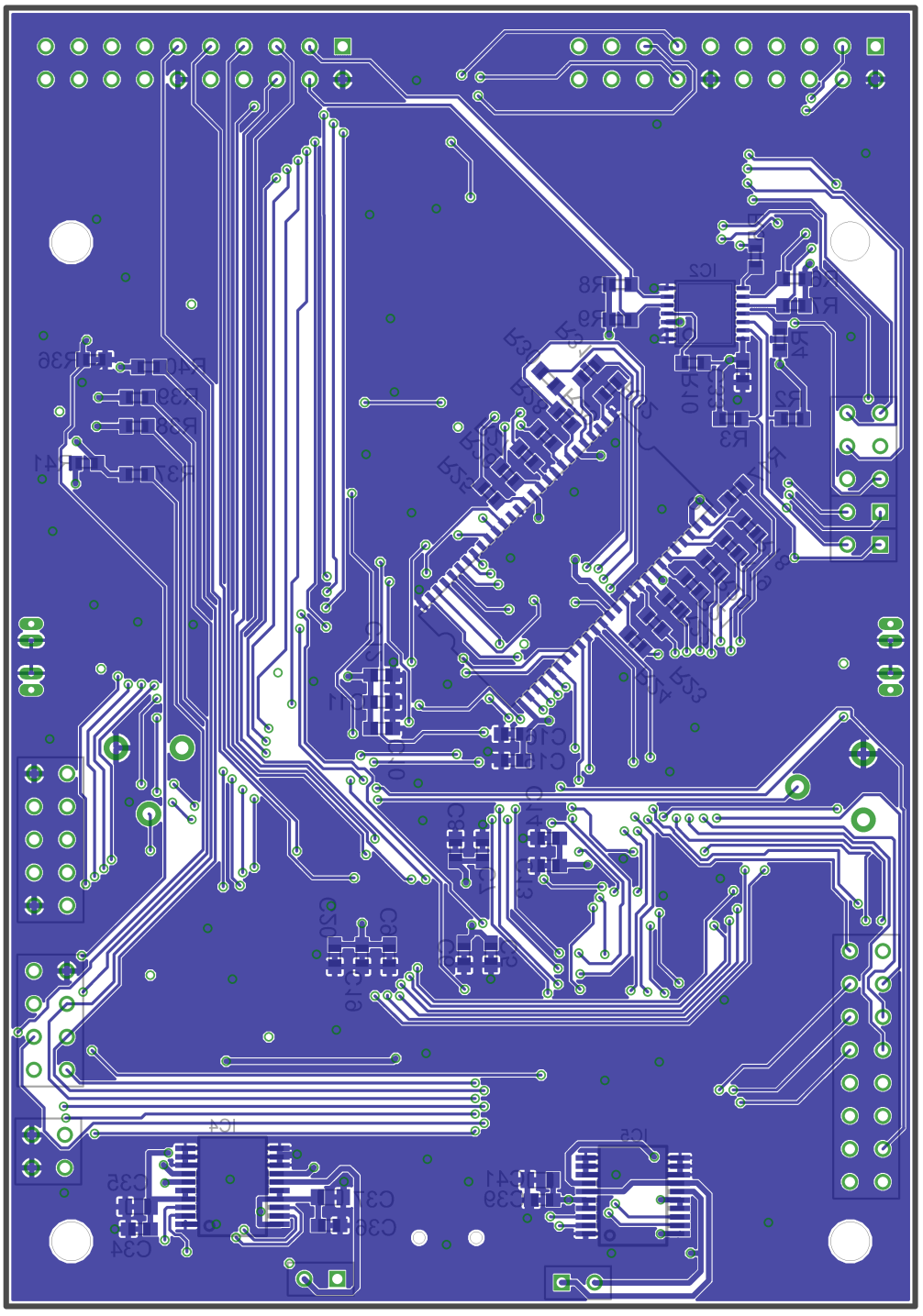


Figure C.2: The Bottom side of the CAD Design of the PCB

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)

Compnent(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	$10k\Omega$ 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	$4K7\Omega$
R1, R12, R14	$10k\Omega$
R36, R41	$100k\Omega$
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	$2.2\mu F$
C8, C10, C23, C26	$4.7\mu F$
C3, C4, C35, C37, C40, C41	$10\mu F$
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

[1]This 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).

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

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

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

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

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

$$\frac{\tan(\varphi_1)}{\tan(\frac{\varphi_0}{2})} = \frac{2x_1}{x_0} \tag{G.5}$$

$$\tan(\varphi_1) = \frac{2x_1\tan(\frac{\varphi_0}{2})}{x_0} \tag{G.6}$$

This can also be shown for the right camera:

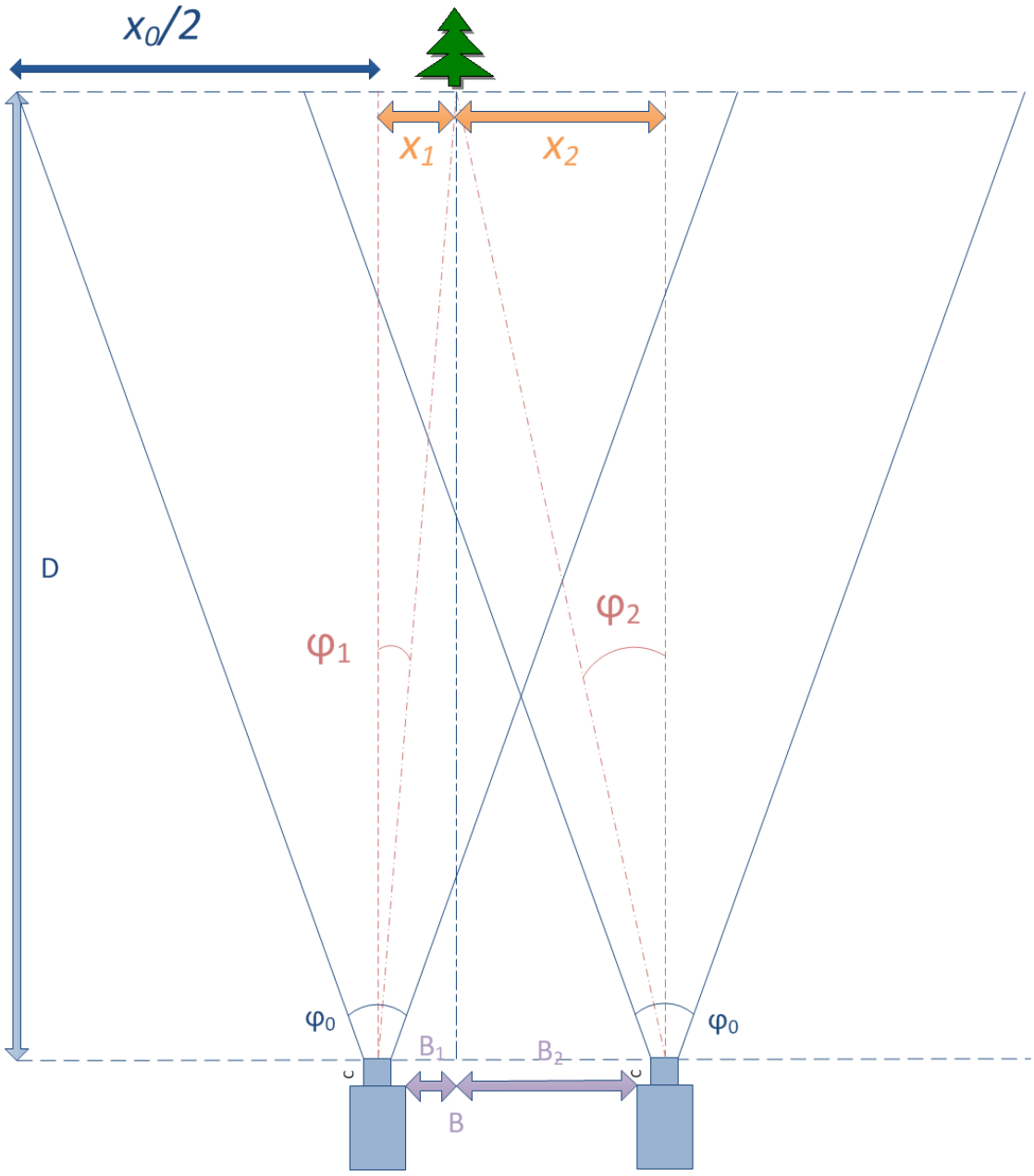


Figure G.1: Problem 1 - Object is between the Cameras

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

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

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

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

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

$$D.\tan(\varphi_1) = x_1 \tag{G.9}$$

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

$$\frac{\tan(\varphi_1)}{\tan(\frac{\varphi_0}{2})} = \frac{2x_1}{x_0} \tag{G.11}$$

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

and similarly

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

$$\theta = \varphi_2 - \varphi_1 \tag{G.14}$$

Using the sine equality rule:

$$\frac{R}{\sin(\frac{\pi}{2} - \varphi_2)} = \frac{B}{\sin(\theta)} \tag{G.15}$$

$$R = B.\frac{\sin(\frac{\pi}{2} - \varphi_2)}{\sin(\theta)} = B\frac{\cos(\varphi_2)}{\sin(\theta)} \tag{G.16}$$

$$D = \cos(\varphi_1).R \tag{G.17}$$

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

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

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

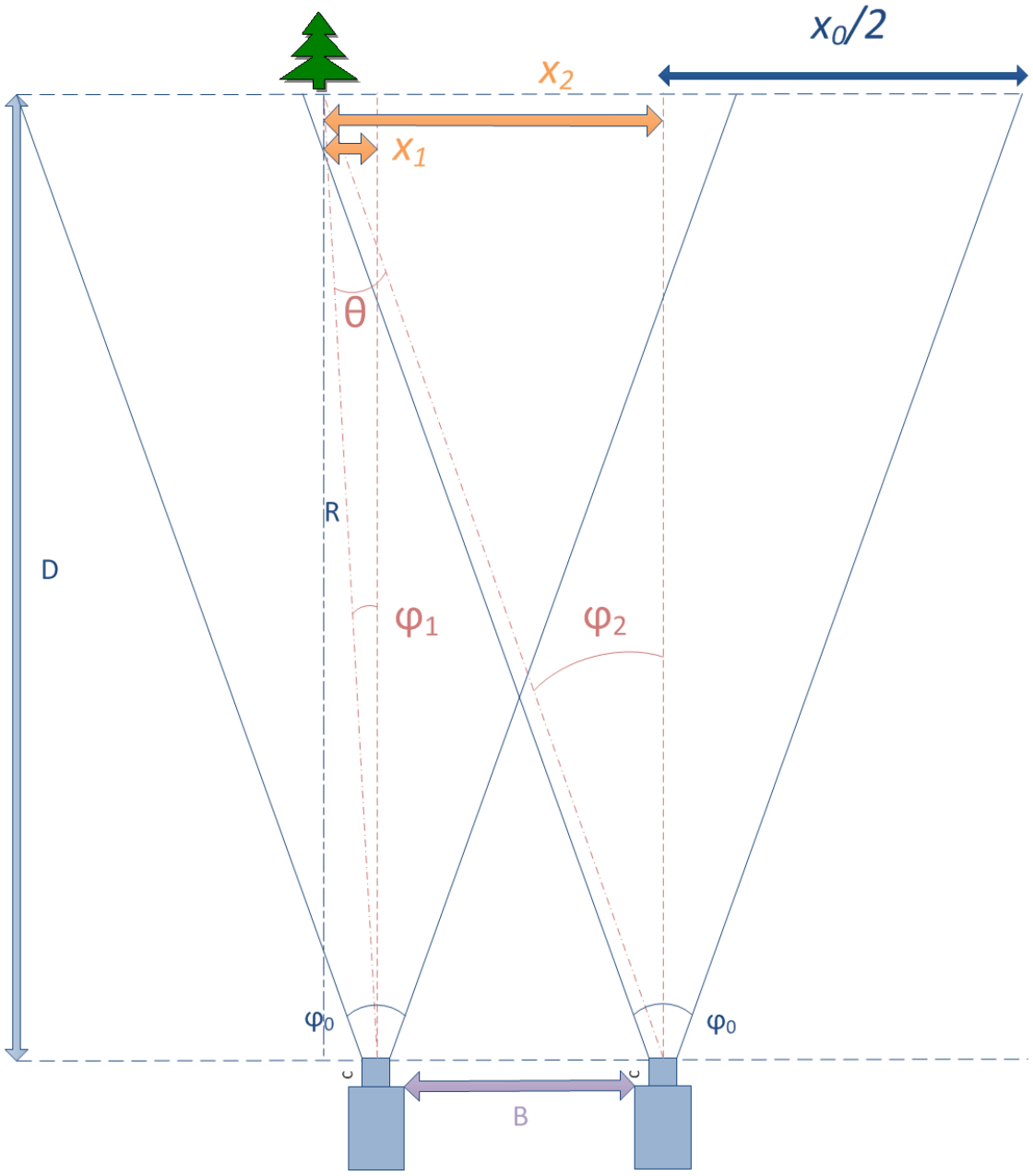


Figure G.2: Problem 2 - Object is to the same side in both cameras

G.3 Object is in front of a camera

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

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

Where φ_2 can be found from equation 4.8.

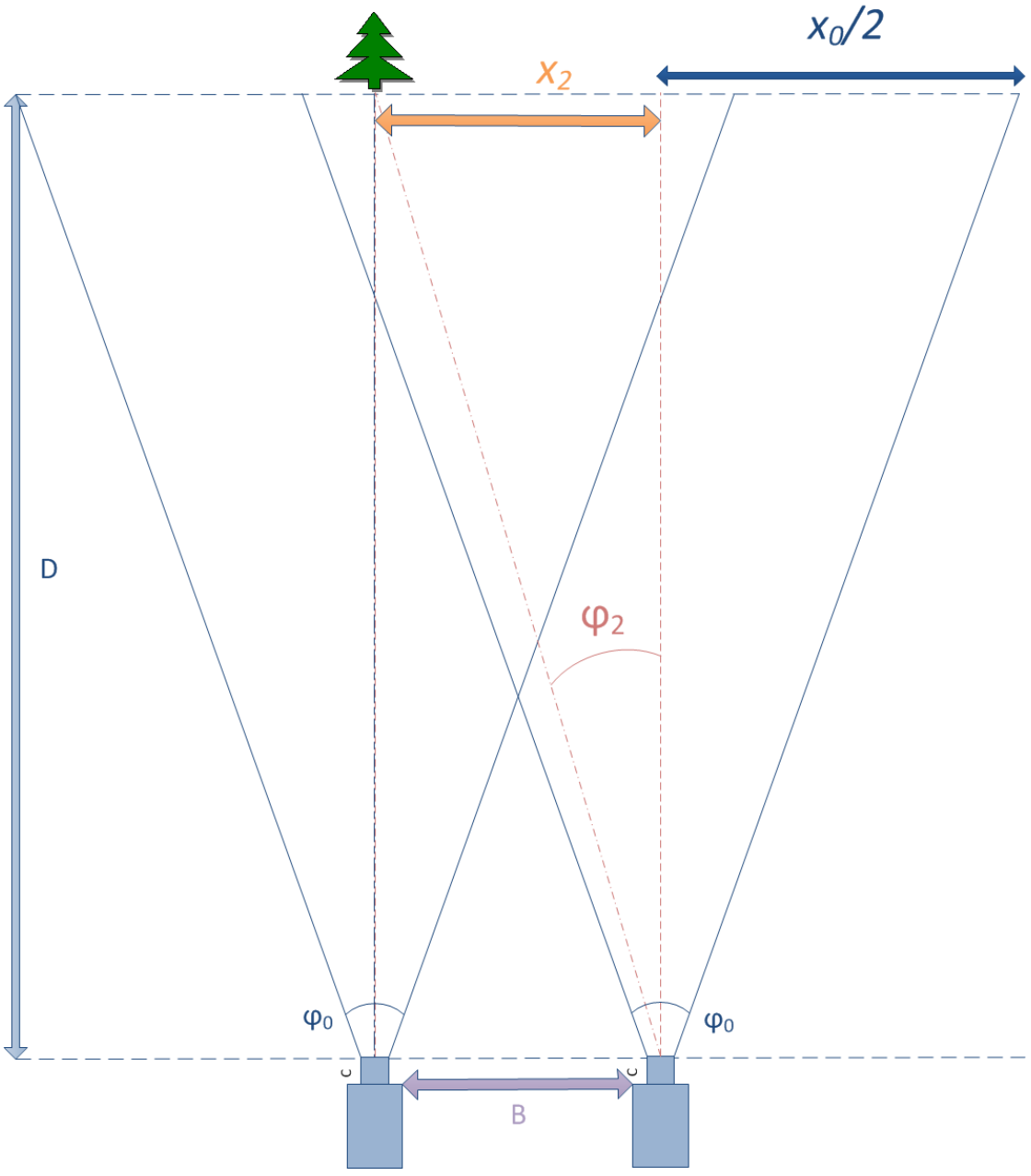


Figure G.3: Problem 3 - Object is directly in front of a camera

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
```

```
25 #define ASCII_SHIP "\t\t\t              |    |    | \n\r\t\t\t\t             )_)
       )_)  )_) \n\r\t\t\t\t           )___))___))___)\\  \n\r\t\t\t\t            )
       ____)____)_____)\\\\ \n\r\t\t\t\t          _____|____|____|____\\\\\\__ \n\r\
       t\t\t---------\\                    /--------- \n\r\t\t\t  ^^^^^
       ^^^^^^^^^^^^^^^^^^^^ \n\r\t\t\t    ^^^^      ^^^^     ^^^    ^^\n\r\t\t\t\t
                 ^^^^      ^^^\n\r"
26 #define COLUMBUS " _______  _______  _                  _______  ______
           _______ \n\r(  ____ \\(  ___  )( \\      |\\     /|(       )(  ___ \\
       |\\     /|(  ____ \\\n\r| (    \\/| (   ) || (      | )   ( || () () || (
         ) )| )   ( || (    \\/\n\r| |      | |   | || |      | |   | || || || ||
        (__/ / | |   | || (_____ \n\r| |      | |   | || |      | |   | || |(_)|
       ||  __ (  | |   | |(_____  )\n\r| |      | |   | || |      | |   | || |
       | || (  \\ \\ | |   | |      ) |\n\r| (____/\\| (___) || (____/\\| (___)
       || )   ( || )___) )| (___) |/\\____) |\n\r(_______/(_______)(_______/(
       _______)|/     \\||______/ (_______)\\_______)\n\n\r"
27 #define THE "\t\t\t_________          _______ \n\r \t\t\t\\__   __/|\\     /|(
         ____ \\ \n\r \t\t\t   ) (   | )   ( || (    \\/\n\r\t\t\t   | |   | (___
       ) || (__    \n\r \t\t\t   | |   |  ___  ||  __)   \n\r \t\t\t   | |   | (
         ) || (      \n\r \t\t\t   | |   | )   ( || (____/\\\n\r \t\t\t   )_(
       |/     \\|(_______/\n\r"
28 #define PROMPT "\n\r$>"

30 #define HELP  "\n\rColumbus Prompt Help:\n\r\
31         ? : Shows this prompt\n\r \
32         c : converts the working buffer from integer to fixed point\n\r\
33         D : Frees the Memory pointed to by the Working Buffer \n\r \
34         r : displays the contents of the working buffer\n\r\
35         R : Reads contents of signal.bin, representing 1D Signal. Integers,
       Big Endian\n\r\
36         T : Reads contents of signal2d.bin, representing 2D Signal. \n\r \
37         s : saves the working buffer\n\r\
38         P : Takes and stores Stereo Photos \n\r \
39         1 : computes the One Dimensional FFT of the working buffer. Returns
       magnitude.\n\r\
40         2 : Computes the Two Dimensional FFT of the Working Buffer. \n\r \
41         "

43 void Get_Line( char * CommandBuffer )
44 {
45   int c = 0;

47   while(c != 13)
48   {
49     c = usart_getchar(DBG_USART);
50     if(c == '\b')
51     {
52       CommandBuffer--;
53       *(CommandBuffer) = 0;
54     }
55     else
56     {
57       *(CommandBuffer) = c;
58       CommandBuffer++;
59     }
60     print_dbg_char(c);
61   }
62   usart_putchar(DBG_USART, 6);
63 }
```

```
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();

89    if(Columbus_Status.Status != STATUS_OK)
90    {
91      while(1)
92      {
93        LED2_SET;
94        LED3_SET;
95        LED4_SET;
96        LED5_SET;
97        LED6_SET;
98        delay_ms(500);
99        LED2_CLR;
100       LED3_CLR;
101       LED4_CLR;
102       LED5_CLR;
103       LED6_CLR;
104       delay_ms(500);
105     }//inifinte loop
106   }


109   print_dbg("\n\rColumbus Ready!");
110   // Insert application code here, after the board has been initialized.
111   while(1)
112   {
113     print_dbg(PROMPT);
114     Get_Line(CommandBuffer);
115     Ptr = CommandBuffer;
116     switch(*Ptr++)
117     {
118       case '?':
119         print_dbg(HELP);
120         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 *
      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 *
      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;

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;

191         case 'I':
192           print_dbg("\rInverse Fourier Transform;");
193           IFFT2D(ComplexBuffer);
194           break;

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,
    ComplexBuffer[i].imag);
206             else
207               sprintf(CommandBuffer, "%d %dj,", ComplexBuffer[i].real,
    ComplexBuffer[i].imag);
208             print_dbg(CommandBuffer);
209           }
210           print_dbg("]\n\r");
211           break;
212         case 'M': //Motor Related
213           while(*Ptr == ' ')
214             Ptr++; //Find next non - space char

216           switch(*(Ptr++))
217           {
218             case 'q': // Reset Motors
219               print_dbg("\rResetting Motors");
220               Motors_Reset();
221               break;

223             case 'F': //Move Forward
224               while(*Ptr == ' ')
225                 Ptr++; //Find next non - space char
226               i = atoi(Ptr);
227               Motors_Move(i);
228               break;
229             case 'T':
230               while(*Ptr == ' ')
231                 Ptr++; //Find next non - space char
232               i = atoi(Ptr);
233               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\rAssiging 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;

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

H.1.1.2 Bitmap.c

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

```
/*
 * Bitmap.c
 *
 * Created: 16/02/2013 23:14:34
 *  Author: hslovett
 */
#include "CustomDevices/CustomDevices.h"

const uint8_t DIBHead[DIBHEADERSIZE] = {  0x7C, 0x00, 0x00, 0x00, //Number of
    bytes
                    0x40, 0x01, 0x00, 0x00, //Width - 320
                    0xF0, 0x00, 0x00, 0x00, //Height - 240
                    0x01, 0x00,       //Planes
                    0x10, 0x00,       //Bits per Pixel
                    0x03, 0x00, 0x00, 0x00, //Compression
                    0x00, 0x58, 0x02, 0x00, //Size of Raw Data
                    0x13, 0x0B, 0x00, 0x00, //Horizontal Resolution
                    0x13, 0x0B, 0x00, 0x00, //Vertical Resolution
                    0x00, 0x00, 0x00, 0x00, //Colours in Palette
                    0x00, 0x00, 0x00, 0x00, //Important Colours
                    0x00, 0xF8, 0x00, 0x00, //Red Mask
                    0xE0, 0x07, 0x00, 0x00, //Green Mask
                    0x1F, 0x00, 0x00, 0x00, //Blue Mask
                    0x00, 0x00, 0x00, 0x00, //Alpha Mask
                    0x01, 0x00, 0x00, 0x00, //Colour Space Type
                    0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
                    0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
                    0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
                    0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
                    0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
                    0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
                    0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
                    0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
                    0x00, 0x00, 0x00, 0x00, //Colour Space Endpoints
                    0x00, 0x00, 0x00, 0x00, //Gamma Red
                    0x00, 0x00, 0x00, 0x00, //Gamma Green
                    0x00, 0x00, 0x00, 0x00, //Gamma Blue
                    0x03, 0x00, 0x00, 0x00, //Intent - Photo
                    0x00, 0x00, 0x00, 0x00, //ICC Profile Data
                    0x00, 0x00, 0x00, 0x00, //ICC Profile Size
                    0x00, 0x00, 0x00, 0x00}; //Reserved

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

H.1.1.3 CustomDevices.h

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

```
/*
 * CustomDevices.h
 *
 * Created: 16/02/2013 14:30:50
 *  Author: hslovett
 */


#ifndef CUSTOMDEVICES_H_
#define CUSTOMDEVICES_H_

//Camera
#include "CustomDevices/OV7670.h"
//I2C Mux
#include "CustomDevices/PCA9542A.h"
//MotorDriver
#include "CustomDevices/MotorDriver.h"
//SDCard
#include "CustomDevices/SD_Card.h"
//Image Processing Functions
#include "CustomDevices/ImageProcessor.h"

typedef struct {
  int Status;
  SD_Status_t *SD_Card;
  Motor_Control_t *Motors;
  OV7670_t *Cameras;
  PCA9542A_t *I2CMux;
} Columbus_Status_t;

#define SD_ERR    0x1
#define CAM_ERR   0x2
#define I2CMux_ERR  0x4

#define FFT_SIZE 64

mspace sdram_msp;
Columbus_Status_t Columbus_Status;
//TWI Methods
void twim_init (void);
void System_Test();
#endif /* CUSTOMDEVICES_H_ */
```

H.1.1.4 ImageProcessor.h

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

```
/*
 * ImageProcessor.h
 *
 * Created: 28/02/2013 17:46:37
 *  Author: hslovett
```

```
 */


#ifndef IMAGEPROCESSOR_H_
#define IMAGEPROCESSOR_H_

#define BMP_FORMAT_RGB565     1
#define BMP_FORMAT_RGB555     2
#define BMP_FORMAT_GREYSCALE    3
#define BMP_FORMAT_1xUINT     4
#define BMP_FORMAT_2xUINT8T     5
typedef struct {
  uint16_t *ImagePtr;
  int Height;
  int Width;
  uint8_t Format;
  } Image_t;



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

void FFT2DCOMPLEX( int *Signal, dsp16_complex_t *ComplexBuffer, int size );
void PrepareImage(Image_t *Image);
//int* IFFT2D (dsp16_complex_t *Result, dsp16_complex_t *Input);
void IFFT2D (dsp16_complex_t *Signal); /*Need to test this! */;
int FFT1D_Abs( int *Signal);
void Complex_Abs( int *Signal, dsp16_complex_t *ComplexBuffer, int size);
#endif /* IMAGEPROCESSOR_H_ */
```

H.1.1.5 ImageProcessor.c

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

```
/*
 * ImageProcessor.c
 *
 * Created: 28/02/2013 17:46:50
 *  Author: hslovett
 */
#include <asf.h>
#include "CustomDevices/CustomDevices.h"

/*#define FFT_SIZE 64*/
//Returns log base 2 of i - checks if it is an integer power of 2
int log_2(int i)
{
  int ret = 0;
  if((i & (i - 1)) != 0)
  {
    return -1;
  }
```

```
19    while((i & 1) == 0) //while the bit isn't in the lowest bit (already
        established this is a integer power of 2)
20    {
21      i >>= 1;
22      ret++;
23    }

25    return ret;
26  }
27  //**********************************
28  // Method:    FFT2DCOMPLEX
29  // FullName:  FFT2DCOMPLEX
30  // Access:    public
31  // Returns:   int*
32  // Qualifier:
33  // Parameter: int * Signal
34  // Parameter: A_ALIGNED dsp16_complex_t * ComplexBuffer
35  // Parameter: int size
36  //**********************************
37  void FFT2DCOMPLEX( int *Signal, dsp16_complex_t *ComplexBuffer, int size )
38  {
39    int i, j = 0;
40    int Ptr;
41    Ptr = 0;
42    A_ALIGNED dsp16_complex_t Input_C_1D[FFT_SIZE];
43    A_ALIGNED dsp16_complex_t Result_C_1D[FFT_SIZE];
44    A_ALIGNED dsp16_complex_t Result_C_2D[FFT_SIZE*FFT_SIZE];
45    A_ALIGNED dsp16_t Input_R_1D[FFT_SIZE];
46    //Stage 1 - FFT Real values from Signal. Store VERTICALLY in Result_2D
47    //print_dbg("\n\rStage 1 Reached. Iteration: \n\r");
48    for(i = 0; i < FFT_SIZE; i ++){ //for each row
49      for(j = 0; j < FFT_SIZE; j++){
50        Input_R_1D[j] = Signal[Ptr++]; //copy the data across
51      }
52      //Do the FFT
53  //    print_dbg("\r");
54  //    print_dbg_ulong(i);

56      dsp16_trans_realcomplexfft(Result_C_1D, Input_R_1D, log_2(FFT_SIZE));
57      //Copy data into 2D reult TRANSPOSED
58      for(j = 0; j < FFT_SIZE; j++){
59        Result_C_2D[i + (j * FFT_SIZE)].imag = Result_C_1D[j].imag * FFT_SIZE;//
        scale back up
60        Result_C_2D[i + (j * FFT_SIZE)].real = Result_C_1D[j].real * FFT_SIZE;
61      }
62    }
63    //print_dbg("\n\rStage 2 Reached. Iteration: \n\r");
64    //Stage 2 - FFT Complex Values from Result_2D, put back into Rows
65    for(i = 0; i < FFT_SIZE; i++){//for each row
66      for(j = 0; j < FFT_SIZE; j++){//copy the data across
67        Input_C_1D[j].imag = Result_C_2D[j + i * FFT_SIZE].imag;
68        Input_C_1D[j].real = Result_C_2D[j + i * FFT_SIZE].real;
69      }
70  //    print_dbg("\r");
71  //    print_dbg_ulong(i);
72      //Do Fourier
73      dsp16_trans_complexfft(Result_C_1D, Input_C_1D, log_2(FFT_SIZE));
74      //Copy back
```

```
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];

151     //Stage 1 - FFT Real values from Signal. Store VERTICALLY in Result_2D
152     for(i = 0; i < FFT_SIZE; i ++) //for each row
153     {
154   //    print_dbg("\n\rInput to FFT: \n\r[");
155       for(j = 0; j < FFT_SIZE; j++)
156       {
157         Input_R_1D[j] = Signal[Ptr++]; //copy the data across
158   //      print_dbg_ulong(Input_R_1D[j]);
159   //      print_dbg(", ");
160       }
161   //    print_dbg("\b\b]");
162       //Do the FFT
163       dsp16_trans_realcomplexfft(Result_C_1D, Input_R_1D, log_2(FFT_SIZE));
164       //Copy data into 2D reult TRANSPOSED
165   //    print_dbg("\n\rOutput of FFT:\n\r[");
166       for(j = 0; j < FFT_SIZE; j++)
167       {
168         Result_C_2D[i + (j * FFT_SIZE)].imag = Result_C_1D[j].imag * FFT_SIZE;//
      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

179     for(i = 0; i < FFT_SIZE; i++)//for each row
180     {
181   //    print_dbg("\n\rInput to FFT: \n\r[");
182       for(j = 0; j < FFT_SIZE; j++)//copy the data across
183       {
184         Input_C_1D[j].imag = Result_C_2D[j + i * FFT_SIZE].imag;
185         Input_C_1D[j].real = Result_C_2D[j + i * FFT_SIZE].real;
186   //      print_dbg_ulong(Input_C_1D[j].real);
187   //      print_dbg(" + j");
188   //      print_dbg_ulong(Input_C_1D[j].imag);
189   //      print_dbg(" , ");
```

```
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   {
221     int row, col;
222     uint16_t *PreparedImage;
223     //Allocate some memory in the RAM
224     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
      + col + 32];
236       }
237     }

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 {
259   int i, j = 0;
260   int Ptr;
261   Ptr = 0;
262   A_ALIGNED dsp16_complex_t Input_C_1D[FFT_SIZE];
263   A_ALIGNED dsp16_complex_t Result_C_1D[FFT_SIZE];
264   A_ALIGNED dsp16_complex_t Result_C_2D[FFT_SIZE*FFT_SIZE];
265   A_ALIGNED dsp16_t Input_R_1D[FFT_SIZE];


268   //Stage 1 - FFT Real values from Signal. Store VERTICALLY in Result_2D
269   for(i = 0; i < FFT_SIZE; i ++) //for each row
270   {
271     for(j = 0; j < FFT_SIZE; j++)
272     {
273       Input_C_1D[j].real = Signal[Ptr].real; //copy the data across
274       Input_C_1D[j].imag = Signal[Ptr].imag;
275     }

277     //Do the FFT
278     dsp16_trans_complexifft(Result_C_1D, Input_C_1D, log_2(FFT_SIZE));
279     //Copy data into 2D result TRANSPOSED

281     for(j = 0; j < FFT_SIZE; j++)
282     {
283       Result_C_2D[i + (j * FFT_SIZE)].imag = Result_C_1D[j].imag * FFT_SIZE;//
    scale back up
284       Result_C_2D[i + (j * FFT_SIZE)].real = Result_C_1D[j].real * FFT_SIZE;
285     }

287   }
288   //Stage 2 - FFT Complex Values from Result_2D, put back into Rows


291   for(i = 0; i < FFT_SIZE; i++)//for each row
292   {

294     for(j = 0; j < FFT_SIZE; j++)//copy the data across
295     {
296       Input_C_1D[j].imag = Result_C_2D[j + i * FFT_SIZE].imag;
297       Input_C_1D[j].real = Result_C_2D[j + i * FFT_SIZE].real;

299     }

301     //Do Fourier
302     dsp16_trans_complexifft(Result_C_1D, Input_C_1D, log_2(FFT_SIZE));
303     //Copy back
```

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

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.ier = 1;}
25 #define DISABLE_ACA_INTERRUPT   //{AVR32_ACIFA1.idr = 1;}
26 #define ENABLE_ACB_INTERRUPT    //{AVR32_ACIFA1.ier = 2;}
27 #define DISABLE_ACB_INTERRUPT   //{AVR32_ACIFA1.idr = 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 *
       C_b)
36 //Type Defs
37 typedef struct {
38   int Left_State;
39   int Right_State;
40   int Left_Count;
41   int Right_Count;
42   } 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;

49 void Motor_Init();
50 void Motor_Go();
51 //void Analogue_Comparator_Init();
52 void Motor_Start(int Motors);
53 void Motors_Reset(void);
54 void Motor_Stop(int Motors);
55 bool Motors_Moving();
56 int Motors_Move(int centimetres_fwd)/*Move this amount forward in centimeters
       */;
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
```

```
 *  Author: hslovett
 */
#include <asf.h>
#include "CustomDevices/CustomDevices.h"
#include <delay.h>



static void local_start_highfreq_clock(void)
{
  const scif_pll_opt_t opt = {
            .osc = SCIF_OSC0,      // Sel Osc0/PLL0 or Osc1/PLL1
            .lockcount = 16,       // lockcount in main clock for the PLL wait lock
            .div = 1,              // DIV=1 in the formula
            .mul = 6,              // MUL=7 in the formula
            .pll_div2 = 1,         // pll_div2 Divide the PLL output frequency by 2 (this settings does not change the FVCO value)
            .pll_wbwdisable = 0,  // pll_wbwdisable 1 Disable the Wide-Bandith Mode (Wide-Bandwith mode allow a faster startup time and out-of-lock time). 0 to enable the Wide-Bandith Mode.
            .pll_freq = 1,         // Set to 1 for VCO frequency range 80-180 MHz, set to 0 for VCO frequency range 160-240Mhz.
  };
  // Switch main clock to Osc0.
//  pcl_switch_to_osc(PCL_OSC0, FOSC0, OSC0_STARTUP);

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

  /* Enable PLL0 */
  scif_pll_enable(SCIF_PLL0);

  /* Wait for PLL0 locked */
  scif_wait_for_pll_locked(SCIF_PLL0) ;
}
static void pwm_start_gc(void)
{
  scif_gc_setup(AVR32_SCIF_GCLK_PWM,
                SCIF_GCCTRL_PLL0,
                AVR32_SCIF_GC_NO_DIV_CLOCK,
                0);
  scif_gc_enable(AVR32_SCIF_GCLK_PWM);
}
void Analogue_Comparator_Init()
{
  static const gpio_map_t ACIFA_GPIO_MAP =
  {
  {POT0_AC1AP1_PIN, POT0_AC1AP1_FUNCTION},
  {POT1_AC1BP1_PIN, POT1_AC1BP1_FUNCTION},
  {SENSE0_AC1AN1_PIN, SENSE0_AC1AN1_FUNCTION},
  {SENSE1_AC1BN1_PIN, SENSE1_AC1BN1_FUNCTION},
  };

  gpio_enable_module(ACIFA_GPIO_MAP, sizeof(ACIFA_GPIO_MAP) / sizeof(
    ACIFA_GPIO_MAP[0]));
```

```
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    POT0_AC1AP1_INPUT,
62    SENSE0_AC1AN1_INPUT,
63    FOSC0);

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    FOSC0);

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

80    //  INTC_register_interrupt(&ACInterruptHandler,AVR32_ACIFA1_IRQ ,
        AVR32_INTC_INT0);

82    Enable_global_interrupt();
83  }
84  void Motor_Init()
85  {
86    //Turn boths motors off
87    ML_STANDBY;
88    MR_STANDBY;

90    ML_IN1_CLR;
91    ML_IN2_CLR;

93    MR_IN1_CLR;
94    MR_IN2_CLR;

96    Motor_Control.Left_Count = 0;
97    Motor_Control.Right_Count = 0;
98    Motor_Control.Left_State = STOP;
99    Motor_Control.Right_State = STOP;

101   avr32_pwm_channel_t pwm_channel = { {0}, // cmr
102                       {0}, // cdty
103                       {0}, // cdtyupd
104                       {0}, // cprd
105                       {0}, // cprdupd
106                       {0}, // ccnt
107                       {0}, // dt
108                       {0}};// dtupd  ;  One channel config.
109 /*  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.cdty      = 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

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)
          CIRCUMFERENCE_WHEEL_MM;
342     distance_moved = number_interrupts * MIN_DISTANCE_RESOLUTION;
343     print_dbg("\n\rNumber of interrupts to move = ");
344     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
9  #ifndef OV7670_H_
10 #define OV7670_H_
11 #include <asf.h>
12 ////////////////////////////////////////////////////////////////////////
13 //  Constants
14 ////////////////////////////////////////////////////////////////////////
15 #define HEIGHT        240
16 #define WIDTH       320
17 #define PIXELSIZE     2
18 #define SETTINGS_LENGTH   167
19 #define OV7670_ADDR     0x21
20
21 #define CAMERA_LEFT     1
22 #define CAMERA_RIGHT    2
23
24 #define CAMERA_LEFT_ERR   0x10
25 #define CAMERA_RIGHT_ERR  0x20
26
27 #define BMPHEADERSIZE 14
28 #define DIBHEADERSIZE 124 //v5
29 #define FILESIZE 153738
30 ////////////////////////////////////////////////////////////////////////
31 //  Globals
32 ////////////////////////////////////////////////////////////////////////
33 const char default_settings[SETTINGS_LENGTH][2];
34 const uint8_t DIBHead[DIBHEADERSIZE];
35 const uint8_t BMPHeader[BMPHEADERSIZE];
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 VSYNC0_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_ADCCTR0    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

```
/*
 * OV7670.c
 *
 * Created: 15/02/2013 13:12:12
 *  Author: hslovett
 */


#include <asf.h>
#include "CustomDevices/CustomDevices.h"
#include "stdio.h"
#include "delay.h"
// Camera
// #include "CustomDevices/OV7670.h"
// I2C Mux
// #include "CustomDevices/PCA9542A.h"
// MotorDriver
// /*#include "CustomDevices/MotorDriver.h"*/
// SDCard
// #include "CustomDevices/SD_Card.h"

__attribute__((__interrupt__)) static void VSYNC0_Handler (void)
{
  //print_dbg("\n\rVSYNC0 Detected!");
  eic_clear_interrupt_line(&AVR32_EIC, VSYNC_0_LINE);
  //VSYNC_0_DISABLE_INTERRUPT;
  switch(OV7670_Status.VSYNC0_State)
  {
    case(TAKE_PHOTO):
      FIFO_0_WEN_SET;
      OV7670_Status.VSYNC0_State = TAKING_PHOTO;
      break;

    case(TAKING_PHOTO):
      FIFO_0_WEN_CLR;
      OV7670_Status.VSYNC0_State = TAKEN_PHOTO;
      break;

    case (TAKEN_PHOTO):
      FIFO_0_WEN_CLR;
      break;

    case(IDLE):
    default:
      VSYNC_0_DISABLE_INTERRUPT;
      FIFO_0_WEN_CLR;
      OV7670_Status.VSYNC0_State = IDLE;
      break;
```

```
49    }
50  }
51
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_TWIM0, &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_TWIM0, &Buff, 1, OV7670_ADDR, false);
102   if(status != STATUS_OK)
103     return status;
104
105   status = twim_read(&AVR32_TWIM0, &Buff, 1, OV7670_ADDR, false);
106   *Data = Buff[0];
```

```
108     return status;
110   }
111   void OV7670_Init()
112   {
114     //Check Cameras Exist
115     PCA9542A_Chan_Sel(I2C_CHANNEL_0);
116     if (twim_probe(&AVR32_TWIM0, OV7670_ADDR) == STATUS_OK)
117       OV7670_Status.Camera_0_Found = true;
118     else
119       OV7670_Status.Camera_0_Found = false;
121     PCA9542A_Chan_Sel(I2C_CHANNEL_1);
122     if (twim_probe(&AVR32_TWIM0, OV7670_ADDR) == STATUS_OK)
123       OV7670_Status.Camera_1_Found = true;
124     else
125       OV7670_Status.Camera_1_Found = false;
128     //Iniialise Cameras
129     if(OV7670_Status.Camera_0_Found)
130     {
131       PCA9542A_Chan_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
      ][1]))
144         {
145           print_dbg("\n\rCamera Initialise Fail");
146           //return FAIL;
147           OV7670_Status.Camera_0_Error = true;
148           OV7670_Status.Status = ERR_DEVICE;
149           break;
150         }
151         delay_ms(1);
152       }
153     }
154     if(OV7670_Status.Camera_1_Found)
155     {
156       PCA9542A_Chan_Sel(I2C_CHANNEL_1);
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
          ][1]))
170         {
171           print_dbg("\n\rCamera Initialise Fail");
172           //return FAIL;
173           OV7670_Status.Camera_1_Error = true;
174           OV7670_Status.Status = ERR_DEVICE;
175           break;
176         }
177         delay_ms(1);
178       }
179     }
180     PCA9542A_Chan_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
        interrupt
195     gpio_enable_pin_pull_up(VSYNC_0_PIN);
196     //Initialise EIC
197     eic_init(&AVR32_EIC, &eic_options, 1);
198     eic_options.eic_line = VSYNC_0_LINE;
199     eic_init(&AVR32_EIC, &eic_options, 1);

201     INTC_register_interrupt(&VSYNC1_Handler, AVR32_EIC_IRQ_1, AVR32_INTC_INT0);
202     INTC_register_interrupt(&VSYNC0_Handler, AVR32_EIC_IRQ_4, AVR32_INTC_INT0);
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)
        && ((OV7670_Status.VSYNC1_State != IDLE) || !OV7670_Status.Camera_1_Found)
        )
288       return CAMERAS_BUSY; //wait for cameras to be idle if they are found

290     if(Cameras & CAMERA_LEFT)
291       OV7670_Status.VSYNC0_State = TAKE_PHOTO;

293     if(Cameras & CAMERA_RIGHT)
294       OV7670_Status.VSYNC1_State = TAKE_PHOTO;
295     eic_clear_interrupt_line(&AVR32_EIC, VSYNC_1_LINE);
296     eic_clear_interrupt_line(&AVR32_EIC, VSYNC_0_LINE);
297     VSYNC_0_ENABLE_INTERRUPT;
298     VSYNC_1_ENABLE_INTERRUPT;

300     return TAKING_PHOTO;

302   }

304   bool Photos_Ready(void)
305   {
306     int status = 0;
307     if(OV7670_Status.Camera_0_Found == true) //If camera is there
308     {
309       if(OV7670_Status.Camera_0_Error == false)//and has no errors
310       {
311         if(OV7670_Status.VSYNC0_State == TAKEN_PHOTO)
312         {
313           status |= 1; //camera0 has taken photo
314         }
315       }
316       else
317         status |= 1;
318     }
319     else
320       status |= 1;

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       }
331       else
332       status |= 1;
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 exits 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 // }

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

590     FIFO_0_RCLK_SET;
591     delay_us(10);
592     FIFO_0_RCLK_CLR;
593     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

```
/*
 * OV7670_Setup.c
 *
 * Created: 15/02/2013 13:14:09
 *  Author: hslovett
 */

#include "CustomDevices/CustomDevices.h"

const char default_settings[SETTINGS_LENGTH][2]=
{
{OV_TSLB, 0x04},
{OV_COM15, 0xd0},//RGB565 / RGB555
{OV_COM7, 0x14},
{OV_HREF, 0x80},
{OV_HSTART, 0x16},
{OV_HSTOP, 0x04},
{OV_VSTRT, 0x02},
{OV_VSTOP, 0x7b},//0x7a,
{OV_VREF, 0x06},//0x0a,
{OV_COM3, 0x00}, //MSB and LSB swapped
{OV_COM14, 0x00},//
{OV_SCALING_XSC, 0x00},
{OV_SCALING_YSC, 0x00},
{OV_SCALING_DCWCTR, 0x11},
{OV_SCALING_PCLK_DIV, 0x00},//
{0xa2, 0x02},
{OV_CLKRC, 0x01},
{OV_GAM1, 0x20},
{OV_GAM2, 0x1c},
{OV_GAM3, 0x28},
{OV_GAM4, 0x3c},
{OV_GAM5, 0x55},
{OV_GAM6, 0x68},
{OV_GAM7, 0x76},
{OV_GAM8, 0x80},
{OV_GAM9, 0x88},
{OV_GAM10, 0x8f},
{OV_GAM11, 0x96},
{OV_GAM12, 0xa3},
{OV_GAM13, 0xaf},
{OV_GAM14, 0xc4},
{OV_GAM15, 0xd7},
{OV_GAM16, 0xe8},
{OV_COM8, 0xe0},
{OV_GAIN, 0x00},//AGC
{OV_AECH, 0x00},
{OV_COM4, 0x00},
{OV_COM9, 0x20},//0x38, limit the max gain
{OV_HIST6, 0x05},
{OV_HIST12, 0x07},
{OV_AEW, 0x75},
{OV_AEB, 0x63},
```

```
54  {OV_VPT, 0xA5},
55  {OV_HIST0, 0x78},
56  {OV_HIST1, 0x68},
57  {OV_HIST2, 0x03},//0x0b,
58  {OV_HIST7, 0xdf},//0xd8,
59  {OV_HIST8, 0xdf},//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, 0x0a},
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_MTXS, 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, 0x0a},
159 {0xc8, 0x80},
160 {0x79, 0x0b},
161 {0xc8, 0x01},
162 {0x79, 0x0c},
163 {0xc8, 0x0f},
164 {0x79, 0x0d},
165 {0xc8, 0x20},
166 {0x79, 0x09},
167 {0xc8, 0x80},
168 {0x79, 0x02},
169 {0xc8, 0xc0},
```

```
{0x79, 0x03},
{0xc8, 0x40},
{0x79, 0x05},
{0xc8, 0x30},
{0x79, 0x26},
{OV_COM2, 0x03},
{OV_BRIGHT, 0x00},
{OV_CONTRAS, 0x40},
{OV_COM11, 0x42},//0x82,//0xc0,//0xc2,  //night mode

};
```

H.1.1.11 PCA9542A.h

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

```
/*
 * PCA9542A.h
 *
 * Created: 15/02/2013 12:21:46
 *  Author: hslovett
 */


#ifndef PCA9542A_H_
#define PCA9542A_H_

#define A0  0
#define A1  0
#define A2  1
#define PCA9542A_ADDR (0x70 | (A2 << 2) | (A1 << 1) | A0)

#define NO_SELECT   0x00
//#define ERROR     0x01
#define I2C_CHANNEL_0 0x04
#define I2C_CHANNEL_1 0x05

//Status Codes
#define SUCCESS   0
#define DEVICE_NOT_FOUND  2

typedef struct {
  uint8_t Status;
  uint8_t ChannelSelected;
  } PCA9542A_t;

PCA9542A_t PCA9542A;
int PCA9542A_Init();
//void PCA9542A_Channel_Select(uint8_t Channel);
void PCA9542A_Chan_Sel(unsigned char Channel);
#endif /* PCA9542A_H_ */
```

H.1.1.12 PCA9542A.c

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

```
/*
 * PCA9542A.c
 *
 * Created: 15/02/2013 12:21:36
 *  Author: hslovett
 */

#include <asf.h>
#include "CustomDevices/CustomDevices.h"
//Camera
/*#include "CustomDevices/OV7670.h"*/
//I2C Mux
/*#include "CustomDevices/PCA9542A.h"*/
//MotorDriver
/*#include "CustomDevices/MotorDriver.h"*/
//SDCard
/*#include "CustomDevices/SD_Card.h"*/

int PCA9542A_Init()
{
  int status = twim_probe(&AVR32_TWIM0, PCA9542A_ADDR);
  if (status != STATUS_OK)
  {
    PCA9542A.Status = DEVICE_NOT_FOUND;
    return DEVICE_NOT_FOUND;
  }
  char buff[2] = {NO_SELECT, 0};
  status = twim_write(&AVR32_TWIM0, &buff, 1, PCA9542A_ADDR, false);
  PCA9542A.Status = STATUS_OK;
  PCA9542A.ChannelSelected = NO_SELECT;
  return status;
}


void PCA9542A_Chan_Sel(unsigned char Channel)
{
  int status = 0;
  char buff[2] = {Channel, 0};
  status = twim_write(&AVR32_TWIM0, &buff, 1, PCA9542A_ADDR, false);
  if(status == STATUS_OK)
  {
    PCA9542A.ChannelSelected = Channel;
  }
  else
  {
    PCA9542A.Status = ERR_PROTOCOL;
  }
}
```

H.1.1.13 SD_Card.h

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

```
/*
 * SD_Card.h
 *
 * Created: 10/02/2013 17:11:51
 *  Author: hslovett
 */


#ifndef SD_CARD_H_
#define SD_CARD_H_
#include "ImageProcessor.h"
#define SIGNAL_FILE "signal.bin"
#define  TWOD_SIGNAL_FILE "signal2d.bin"

typedef struct {
  uint8_t Status;
  uint32_t Memory_size;
  } SD_Status_t;
SD_Status_t SD_Status;

void local_pdca_init(void);
void sd_mmc_resources_init(void);
static void pdca_int_handler(void);
void wait();
void Log_Write_ulong(unsigned long n);
void Log_Write(char *buff, int length);
void SaveBuff( int * WorkingBuffer , int size);
int Read2DSignal( int * WorkingBuffer );
int ReadSignal( int * WorkingBuffer );
void SaveBitmap(uint16_t *Image, int width, int height, char *FileName);
//void ReadBitmap(char *Filename);
void ReadBitmap(char *Filename, Image_t *image);
void SaveBuff_CSV(char *Filename, int *WorkingBuffer, int size);
void SaveCBuff_CSV(char *Filename, dsp16_complex_t *ComplexBuffer, int size);
void Read_CSV(char *Filename, int *WorkingBuffer, int size);
#endif /* SD_CARD_H_ */
```

H.1.1.14 SD_Card.c

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

```
/*
 * SD_Card.c
 *
 * Created: 10/02/2013 17:11:58
 *  Author: hslovett
 */
//Camera
/*#include "CustomDevices/OV7670.h"*/
//I2C Mux
/*#include "CustomDevices/PCA9542A.h"*/
//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
       card
32 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*/

44 static void pdca_int_handler(void)
45 {
46   // Disable all interrupts.
47   Disable_global_interrupt();

49   // Disable interrupt channel.
50   pdca_disable_interrupt_transfer_complete(AVR32_PDCA_CHANNEL_SPI_RX);

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);

58   // Enable all interrupts.
59   Enable_global_interrupt();

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    };

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    };

90    // Assign I/Os to SPI.
91    gpio_enable_module(SD_MMC_SPI_GPIO_MAP,
92                       sizeof(SD_MMC_SPI_GPIO_MAP) / sizeof(SD_MMC_SPI_GPIO_MAP
        [0]));

94    // Initialize as master.
95    spi_initMaster(SD_MMC_SPI, &spiOptions);

97    // Set SPI selection mode: variable_ps, pcs_decode, delay.
98    spi_selectionMode(SD_MMC_SPI, 0, 0, 0);

100   // Enable SPI module.
101   spi_enable(SD_MMC_SPI);

103   // Initialize SD/MMC driver with SPI clock (PBA).
104   sd_mmc_spi_init(spiOptions, PBA_HZ);
105 }

107 /*! \brief Initialize PDCA (Peripheral DMA Controller A) resources for the SPI
        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

114     .addr = ram_buffer,
115     // memory address. We take here the address of the string dummy_data. This
        string is located in the file dummy.h

117     .size = 512,                                // transfer counter: here the
        size of the string
118     .r_addr = NULL,                             // next memory address after 1st
        transfer complete
119     .r_size = 0,                                // next transfer counter not
        used here
```

```
120       .pid = AVR32_PDCA_CHANNEL_USED_RX,        // select peripheral ID - data
          are on reception from SPI1 RX line
121       .transfer_size = PDCA_TRANSFER_SIZE_BYTE  // select size of the transfer:
          8,16,32 bits
122     };

124     // this channel is used to activate the clock of the SPI by sending a dummy
          variables
125     pdca_channel_options_t pdca_options_SPI_TX ={ // pdca channel options

127       .addr = (void *)&dummy_data,              // memory address.
128                                                 // We take here the address of
          the string dummy_data.
129                                                 // This string is located in the
           file dummy.h
130       .size = 512,                              // transfer counter: here the
          size of the string
131       .r_addr = NULL,                           // next memory address after 1st
           transfer complete
132       .r_size = 0,                              // next transfer counter not
          used here
133       .pid = AVR32_PDCA_CHANNEL_USED_TX,        // select peripheral ID - data
          are on reception from SPI1 RX line
134       .transfer_size = PDCA_TRANSFER_SIZE_BYTE  // select size of the transfer:
          8,16,32 bits
135     };

137     // Init PDCA transmission channel
138     pdca_init_channel(AVR32_PDCA_CHANNEL_SPI_TX, &pdca_options_SPI_TX);

140     // Init PDCA Reception channel
141     pdca_init_channel(AVR32_PDCA_CHANNEL_SPI_RX, &pdca_options_SPI_RX);

143     //! \brief Enable pdca transfer interrupt when completed
144     INTC_register_interrupt(&pdca_int_handler, AVR32_PDCA_IRQ_0, AVR32_INTC_INT1
          );  // pdca_channel_spi1_RX = 0

146   }

148   #define BUFFER_FILENAME   "Buffer.bin"
149   #define BUFFERCSV_FILENAME    "Buffer.csv"
150   void SaveBuff( int * WorkingBuffer , int size)
151   {
152     //If the file exists, delete it
153     if(nav_filelist_findname((FS_STRING)BUFFER_FILENAME, false))
154     {
155       nav_setcwd((FS_STRING)BUFFER_FILENAME, false, false);
156       nav_file_del(false);
157     }
158     nav_file_create((FS_STRING)BUFFER_FILENAME);
159     nav_setcwd((FS_STRING)BUFFER_FILENAME, false, true);
160     file_open(FOPEN_MODE_APPEND);
161     file_write_buf(WorkingBuffer, size * sizeof(WorkingBuffer));
162     file_close();
163   }
164   void SaveBuff_CSV(char *Filename, int *WorkingBuffer, int size)
165   {
166     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     }

189     file_close();
190   }
191   void SaveCBuff_CSV(char *Filename, dsp16_complex_t *ComplexBuffer, int size)
192   {
193     int i, j;
194     char Buff[16];
195     //If the file exists, delete it
196     nav_filelist_reset();
197     if(nav_filelist_findname((FS_STRING)Filename, false))
198     {
199       nav_setcwd((FS_STRING)Filename, false, false);
200       nav_file_del(false);
201     }
202     nav_file_create((FS_STRING)Filename);
203     nav_setcwd((FS_STRING)Filename, false, true);
204     file_open(FOPEN_MODE_W);
205     for(i = 0; i < size; i++)
206     {
207       if(ComplexBuffer[i].imag >= 0)
208         sprintf(Buff, "%d+%dj,", ComplexBuffer[i].real, ComplexBuffer[i].imag);
209       else
210         sprintf(Buff, "%d%dj,", ComplexBuffer[i].real, ComplexBuffer[i].imag);
211       //itoa(WorkingBuffer[i], Buff, 10);
212       j = 0;
213       while(Buff[j++] != 0);//count the size of data to be written
214       atoi(Buff);
215       file_write_buf(Buff, j-1);
216       //file_write_buf(",", 1);
217     }

219     file_close();
220   }
221   void Read_CSV(char *Filename, int *WorkingBuffer, int size)
222   {
223     char Buff[32];
224     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   }
362
363   void SaveBitmap(uint16_t *Image, int width, int height, char *FileName)
364   {
365     int i, j, k;
366     uint8_t *Buffer;
367
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;
383
384     Buffer = malloc(i);
385
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     }
396
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] <<
          16) | (Buffer[Offset + 3] << 24);
460   }
461   void ReadBitmap(char *Filename, Image_t *image)
462   {
463   //  Image_t image;
464     int i, j, FileSize, OffsetToArray, temp, BitCount, ImageSize;
465     uint8_t Buffer[128];
466     nav_filelist_reset();
467     if(nav_filelist_findname((FS_STRING)Filename, false) == false)//if the file
        doesn't exist
468     {
469       print_dbg("\n\rFile ");
470       print_dbg(Filename);
471       print_dbg("\n\r does not exist;");
472       return;
473     }
474     nav_setcwd((FS_STRING)Filename, false, false);
475     file_open(FOPEN_MODE_R);
476     //Read Header
477     file_read_buf(Buffer, BMPHEADERSIZE);
478     //Check for BM to confirm it is a Bitmap
479     if((Buffer[0] != 'B') || (Buffer[1] != 'M'))
480     {
481       print_dbg("\n\rBitmap Parse Fail 'BM';");
482       return;
483     }
484     //Extract file size and offset to pixel array
485     FileSize = ReadBigEndian(Buffer, BMP_HEADER_FILESIZE_OFFSET, 4);
486     OffsetToArray = ReadBigEndian(Buffer, BMP_HEADER_OFFSETTOARRAY_OFFSET, 4);
487
488     file_read_buf(Buffer, DIBHEADERSIZE);
489     temp = ReadBigEndian(Buffer, 0, 4);
490     if(temp != 0x7C) //check it is a V5 BMP DIB Header
491     {
492       print_dbg("\n\rBMP Parse: DIB Header not V5;");
493       return;
494     }
495     image->Width= ReadBigEndian(Buffer, DIB_V5_WIDTH_OFFSET, 4);
496     image->Height = ReadBigEndian(Buffer, DIB_V5_HEIGHT_OFFSET, 4);
497     BitCount = ReadBigEndian(Buffer, DIB_V5_BITCOUNT_OFFSET, 2);
498     ImageSize = ReadBigEndian(Buffer, DIB_V5_IMAGESIZE_OFFSET, 4);
499     print_dbg("\n\rBitmap Width = ");
500     print_dbg_ulong(image->Width);
501     print_dbg("\n\rBitmap Height = ");
502     print_dbg_ulong(image->Height);
503     print_dbg("\n\rBitmap File Size = ");
504     print_dbg_ulong(FileSize);
505     print_dbg("\n\rBitmap Offset to Array = ");
506     print_dbg_ulong(OffsetToArray);
507     print_dbg("\n\rBitmap Image Bitcount = ");
508     print_dbg_ulong(BitCount);
509     print_dbg("\n\rBitmap Image Size = ");
510     print_dbg_ulong(ImageSize);
511
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_TWIMS0_TWCK_0_0_PIN, AVR32_TWIMS0_TWCK_0_0_FUNCTION},
28   {AVR32_TWIMS0_TWD_0_0_PIN, AVR32_TWIMS0_TWD_0_0_FUNCTION}
29   };
30
31   // Set TWIM options
32   const twi_options_t TWIM_OPTIONS = {
33     .pba_hz = FOSC0,
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_TWIM0, &TWIM_OPTIONS);

45  }
```

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