UNIVERSITY OF SOUTHAMPTON

FACULTY OF PHYSICAL AND APPLIED SCIENCES

Electronics and Computer Science

Two Dimensional Stereoscopic Mapping 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

21st March, 2013

Turn off iNotes!

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

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Abstract Needed!

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Listings

List of Symbols

I^2C	Inter-Integrated Circuit
TWI	Two Wire Interface
SCCB	Serial Camera Control Bus
SPI	Serial Peripheral Interface
kB	KiloBytes
ISR	Interrupt Service Routine
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

Chapter 1

Introduction

Talk about what I set out to do, include some definitions etc.

What I ended up doing

The uses of my robot.

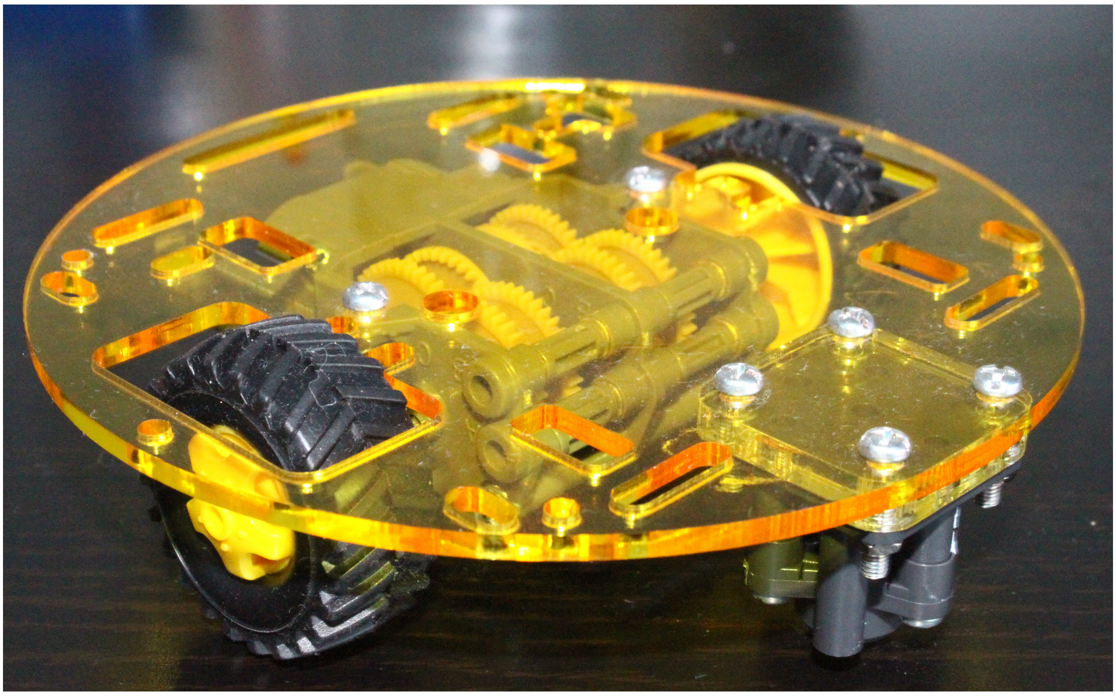


Figure 1.1: The base of the robot

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

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 will 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.

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 are then used to create a Printed Circuit Board

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 I used to gain the operation required. This code streamed continuous video to a TFT

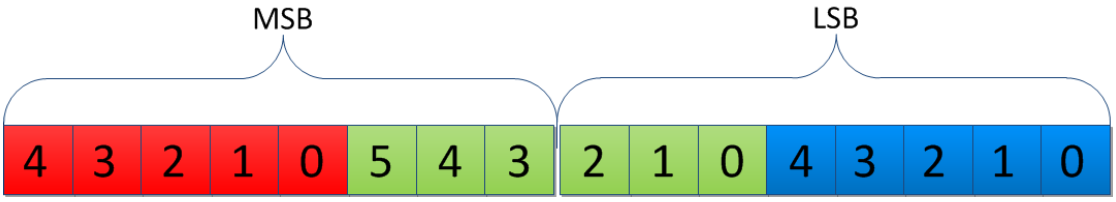


Figure 3.1: RGB565 pixel format

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 bit-banged 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 used in my application.

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.

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. In order to acquire a full frame, the first VSYNC pin is set up to interrupt the

[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"

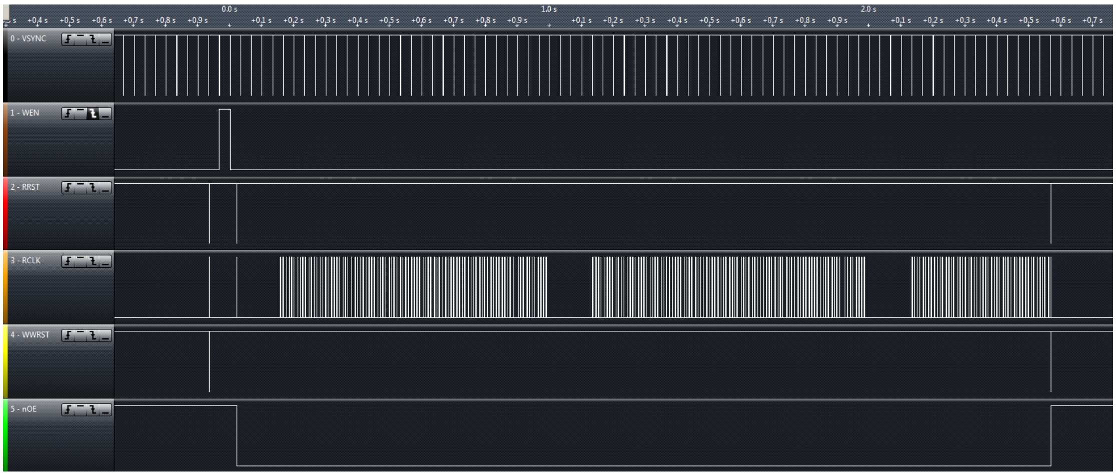


Figure 3.2: Signals generated to control the OV7670 capture and read

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. The FIFO buffer now contains an entire image.

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 a set 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, there can be no bus contention. 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 VSYNC signals, and 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, but no checking procedure is explicitly in place. Both images are then read back from the buffers and stored to memory.

	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))

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 it's 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 so the card only uses one extra enable pin in hardware to function.

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 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 C shows the make up of a Bitmap File that was used.

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

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.

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 IAR Compiler. This code was altered to compile with GCC under Atmel Studio. AVRs contain a hardware based I^2C protocol that is interrupt based in software. The interrupt service routine 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.

	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.

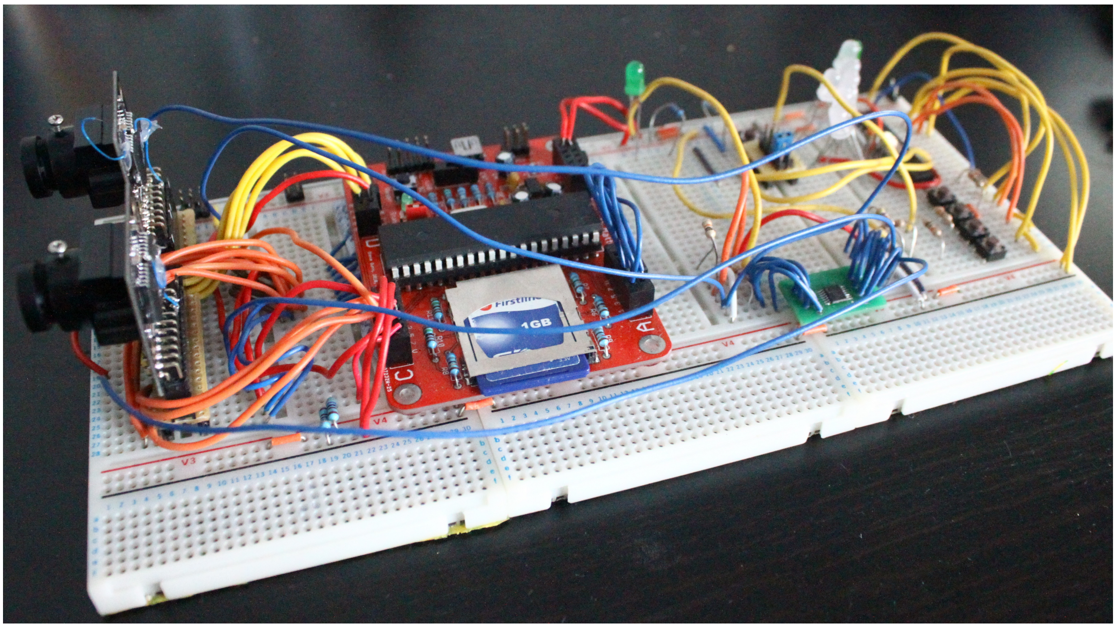


Figure 3.4: Prototype of Dual Camera operation.

3.3 Circuit Development

3.3.1 Stereo Camera Development

Figure B.2 shows the circuit diagram for the prototype. This uses the Il Matto development board for the main microcontroller. The prototype can be seen in figure 3.4. This circuit captured and stored two images from the cameras to the SD card.

3.3.2 Motor Driver Development

Testing of the Motor system - conclusion is likely to be that it is not a good method, need noise reduction

3.3.2.1 Hardware

Tachometers are devices used to measure rotational speed of a shaft. Tachometers are most commonly found in bicycles where a small magnet is attached to the wheel and a sensor is attached to the frame. The sensor can then calculate the time period between rotations and therefore can calculate the speed ((**?**))

Cite Needed

.

Here, an optosensor, TCRT1010, is used to measure rotations of the wheel and used to be able to move a distance decided by the microcontroller. The TCRT1010 package contains an IR LED and a phototransistor (Vishay Semiconductors, 2012). The schematic of a simple transistor amplifier used can be seen in figure 3.5 and was taken from **?**.

Cite Needed

The wheel's rubber absorbed the IR, so a high voltage was always seen at the collector of the phototransistor. White tippex marks were applied to the wheels at regular intervals, which reflected IR and thereby giving a cheap way to detect wheel rotation. Figure 3.6 shows the voltage at the collector (read by the ADC on the AVR) against the angle of the wheel. Five white tabs were marked on the wheel, and five dips in the voltage can be seen in figure 3.6.

Maybe do some simulations of this circuit? This could dictate a maximum speed

3.3.2.2 Firmware Development

As the voltage swing from the phototransistor does not reach 0V, the AVR cannot detect this as a logical 0. The internal ADC can be used to continually read the analogue voltage from the phototransistor and detect low points from this data.

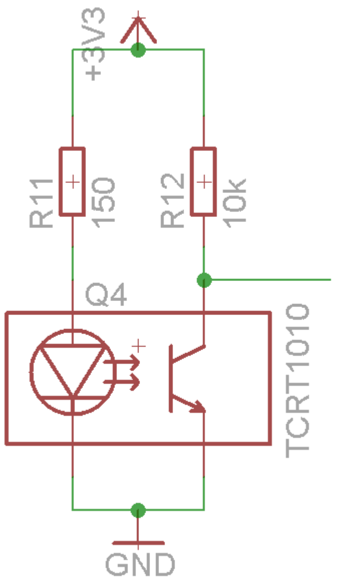


Figure 3.5: Circuit diagram of Optosensor

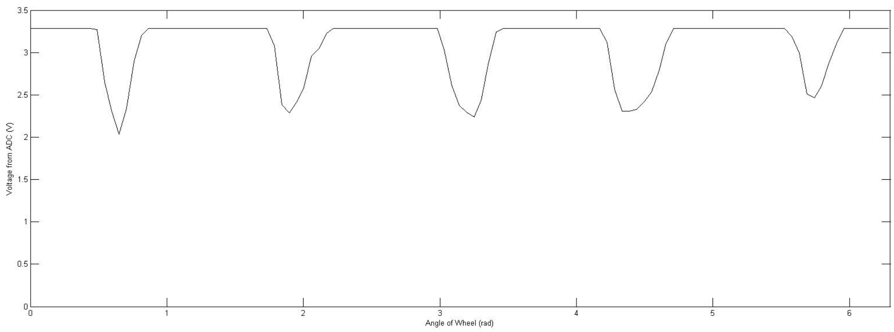


Figure 3.6: Graph of Wheel Angle against the Voltage read by the AVR

This method requires the processor to continually compare values and process the data. However, more control would be had over the noise in the data.

An alternative is to use an analogue comparator built in on most AVRs. This can be set up to run an interrupt service routine when the voltage crosses a threshold. The threshold voltage can be determined by a potentiometer. The code is primarily two methods, the set up and the ISR.

Set up is different for if a rotation or movement is wanted. Moving in a straight line takes a parameter of how far to move as a signed integer and calculates the total number of interrupts that need to occur can be calculated using (3.1). This value is put in a global variable. The PWM and input pins to set the correct direction are then set up before enabling the motor.

$$Interrupts = D \times \frac{IPR}{C_w} \tag{3.1}$$

To rotate, one of three methods can be used: Spot rotation on the centre of the robot, or pivot on either left or right wheel. For ease, the Spot rotation is the only one implemented. To calculate the distance moved, the radius to the wheels needs to be known. 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

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

Combining equations (3.1) and (3.2) gives:

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

Where A is the angle to rotate in degrees, IPR is the number of interrupts generated per full revolution of the wheel, C_w is the circumference of the wheel and C_b the $2\pi \times r_b$ and r_b is the distance from the centre of the robot to the centre of the wheel (see figure 3.7).

Maybe a figure to explain better?

The motor speed can be controlled by Pulse Width Modulation (PWM). The code sets up a low duty cycle PWM signal to drive the motors slowly. This removes the need for a controller to ensure the correct distance was moved.

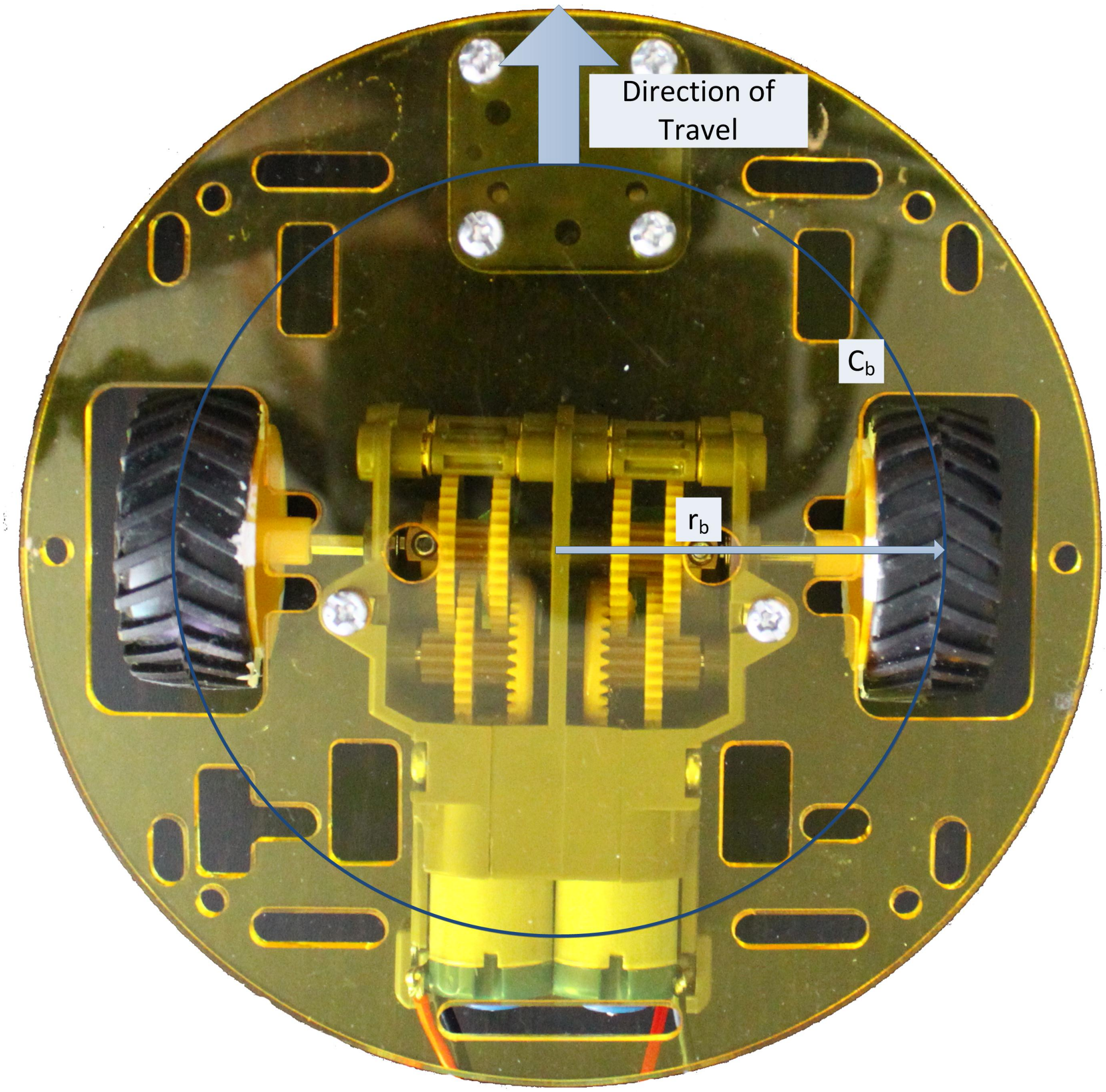
The final code can be seen in appendix D

3.3.2.3 Testing

Need to get the motors to work reasonably first

3.3.2.4 Conclusion

It doesn't work



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

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

Figure 3.7: Dimensions of Interest for Robot Movement

3.4 PCB Development

3.4.1 Circuit Design

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 save space when routing Power. Layer 2 is a 3V3 plane and layer 3 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 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, and then other devices were 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. Also, 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.

Most of the passives used were 0603 size, but some 1206 capactitors were used for decoupling the voltage regulator and a 1206 diode was used for the analogue reference circuitry. LEDs were also 1206 size. All headers were 0.1” spaced and a mini B USB socket was used.

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 0.1” 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

Component	Cost per unit (£)	Quantity	Cost (£)	Source
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	£82.84	

Table 3.3: A table of all components used and their costs.

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 table 3.3

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 E. 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 3.8.

Considerations - Power consumption of devices not exceeding VReg

3.4.3 PCB Testing

A program was written to test all the devices on the PCB. The following tests are done:

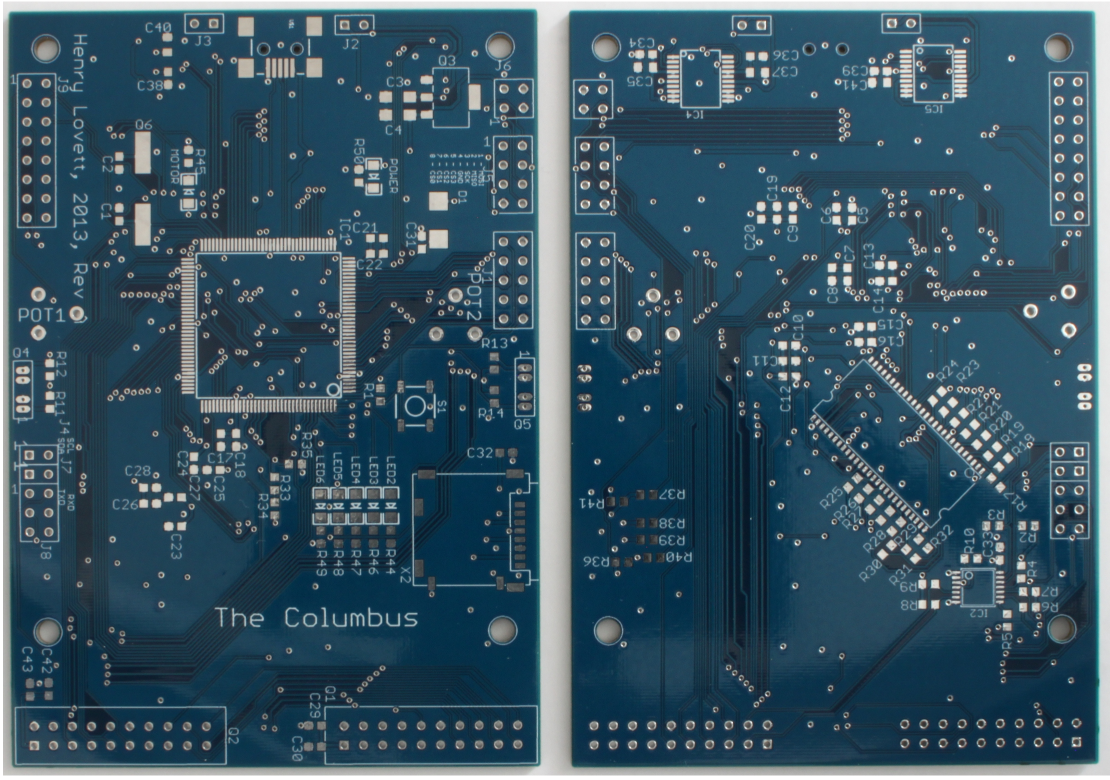


Figure 3.8: PCB with no components. Left: Top View. Right: Bottom View

1. UART Send and Receive
2. SD Card Test
3. All LEDs on and off
4. SDRAM Test
5. I^2C Test
6. Camera Test
7. Motor Test

The folowing sections explain the tests done to check the devices and protocols worked.

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 (13_{10}), the test program continues. Listing 3.1 shows the test code for the UART protocol.

Listing 3.1: UART Test Code

```
//////////////////////////////////////////////////
// UART Test ////////////////////////////////////
//////////////////////////////////////////////////
uint8_t ch;
while (true) {
  ch = usart_getchar(DBG_USART); // get one input character
  if (ch) {
    print_dbg(ch); // echo to output
  }
  if(ch == 13)
    break;
}
```

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 was also configured. 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

```
//////////////////////////////////////////////////
// SD Card Test /////////////////////////////////
//////////////////////////////////////////////////
print_dbg("\n\n\rSD Card Memory Test:\n\r");
// Test if the memory is ready - using the control access memory abstraction
   layer (/SERVICES/MEMORY/CTRL_ACCESS/)
if (mem_test_unit_ready(LUN_ID_SD_MMC_SPI_MEM) == CTRL_GOOD)
{
  // Get and display the capacity
  mem_read_capacity(LUN_ID_SD_MMC_SPI_MEM, &VarTemp);
  print_dbg("OK:\t");
  //printf_ulong((VarTemp + 1) >> (20 - FS_SHIFT_B_TO_SECTOR));
  i = ((VarTemp + 1) >> (20 - FS_SHIFT_B_TO_SECTOR));
  print_dbg_ulong(i);
  print_dbg("MB\r\n");
  print_dbg("SD Card Okay.\n\r");
}
```

```
  else
  {
    // Display an error message
    print_dbg("Not initialized: Check if memory is ready...\r\n");
  }
  nav_reset();
  // Use the last drive available as default.
  nav_drive_set(nav_drive_nb() - 1);
  // Mount it.
  nav_partition_mount();
  nav_filelist_reset();
  if(nav_filelist_findname((FS_STRING)LOG_FILE, false))
  {
    print_dbg("\n\rLog File Already Exists\n\rAttempting to delete...");
    nav_setcwd((FS_STRING)LOG_FILE, true, false);
    nav_file_del(false);

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

  if(nav_file_create((FS_STRING)LOG_FILE) == true)
    print_dbg("\n\rSuccess!");
  else
    print_dbg("\n\rNot worked...");
  print_dbg("\n\rWriting to log file.");
  Log_Write("Columbus Tester:\n\r", 18);
  nav_filelist_reset();
  nav_setcwd((FS_STRING)LOG_FILE, true, false);
  file_open(FOPEN_MODE_R);//Open File
  file_read_buf(Buffer, 8);
  noErrors = 0;
  if(Buffer[0] != 'C')
    noErrors++;
  if(Buffer[1] != 'o')
    noErrors++;
  if(Buffer[2] != 'l')
    noErrors++;
  if(Buffer[3] != 'u')
    noErrors++;
  if(Buffer[4] != 'm')
    noErrors++;
  if(Buffer[5] != 'b')
    noErrors++;
  if(Buffer[6] != 'u')
    noErrors++;
  if(Buffer[7] != 's')
    noErrors++;
  file_close();
  if(noErrors == 0)
    print_dbg("\n\rSD Card Read Successful\n\r");
  else
    print_dbg("\n\rSD Card Read Fail\n\r");
  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 Atmel Software Framework (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

```
//////////////////////////////////////////////////
// SDRAM Test ////////////////////////////////////
//////////////////////////////////////////////////
print_dbg("\n\n\rSDRAM Test:");
sdram_size = SDRAM_SIZE >> 2;
print_dbg("\n\rSDRAM size: ");
print_dbg_ulong(SDRAM_SIZE >> 20);
print_dbg(" MB\r\n");
// Determine the increment of SDRAM word address requiring an update of the
// printed progression status.
progress_inc = (sdram_size + 50) / 100;
// Fill the SDRAM with the test pattern.
for (i = 0, j = 0; i < sdram_size; i++)
{
  if (i == j * progress_inc)
  {
    print_dbg("\rFilling SDRAM with test pattern:");
    print_dbg_ulong(j++);
    print_dbg("%");
  }
  sdram[i] = i;

}
print_dbg("\rSDRAM filled with test pattern       \r\n");
```

```
// Recover the test pattern from the SDRAM and verify it.
for (i = 0, j = 0; i < sdram_size; i++)
{
  if (i == j * progress_inc)
  {
    print_dbg("\rRecovering test pattern from SDRAM: ");
    print_dbg_ulong(j++);
    print_dbg("%");
  }
  tmp = sdram[i];
  if (tmp != i)//failed
  {
    noErrors++;
  }
}
print_dbg("\rSDRAM tested: ");
print_dbg_ulong(noErrors);
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 (Philips, 20012). 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 3.4 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

```
/////////////////////////////////////////////////////
// TWI Test ////////////////////////////////////////
/////////////////////////////////////////////////////
print_dbg("\n\n\rTWI Test:\n\r");
Log_Write("\n\n\rTWI Test:\n\r", 14);
for(k = 0; tkmp < 3; k++)
{
  if(k == 0){
    print_dbg("Scanning all Channels\n\r");
  }
  else if (k == 1){
    //Channel 0
    PCA9542A_Chan_Sel(I2C_CHANNEL_0);
    print_dbg("\n\rScanning Channel 0\n\r");
  }
  else {
```

```
      //Channel 1
      PCA9542A_Chan_Sel(I2C_CHANNEL_1);
      print_dbg("\n\rScanning Channel 1\n\r");
    }

    print_dbg("h 0 1 2 3 4 5 6 7 8 9 A B C D E F\n\r");
    tmp = 0;
    for(i = 0; i < 8; i++)
    {
      print_dbg_ulong(i);
      print_dbg(" ");
      for(j = 0; j < 16; j++){
        int status = twim_probe(TWIM, tmp++);
        if(status == STATUS_OK){
          print_dbg("A");
        }
        else{
          print_dbg("-");
        }
        print_dbg(" ");
      }
      print_dbg("\n\r");
    }
  }
  noErrors = 0;
  //Check cameras exist
  PCA9542A_Chan_Sel(I2C_CHANNEL_0);
  if(twim_probe(TWIM, 0x21) != STATUS_OK)
    print_dbg("\n\rCamera 0 Not Found;");
  PCA9542A_Chan_Sel(I2C_CHANNEL_1);
  if(twim_probe(TWIM, 0x21) != STATUS_OK)
    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

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

```
////////////////////////////////////////////////////
// Camera Test ////////////////////////////////////
////////////////////////////////////////////////////
print_dbg("\n\rInitialising Cameras");
OV7670_Init();
FIFO_Reset(CAMERA_LEFT | CAMERA_RIGHT);
if(STATUS_OK == OV7670_Status.Error)
{
  print_dbg("\n\rCamera Initialise Okay!");
}
else
  print_dbg("\n\rCamara Initialise Fail.");

print_dbg("\n\rTaking Photos");

TakePhoto(CAMERA_LEFT | CAMERA_RIGHT);
while(Photos_Ready() == false)
  ;

if(Store_Both_Images() == true)
  print_dbg("\n\rImages Stored Successfully!");
else
  print_dbg("\n\rImages Store Fail.");
```

3.4.3.7 Motor Driver Test

An extensive test of the motor driver is discussed in section 3.3.2.3. 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 2cm 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

```
////////////////////////////////////////////////////
// Motor Test /////////////////////////////////////
////////////////////////////////////////////////////
print_dbg("\n\rMotor Testing:\n\rMotor Initialised");
Motor_Init();
Motors_Reset();//reset the motors to test them
while(Motors_Moving() == true)
  ;//wait for the motors to finish moving
```

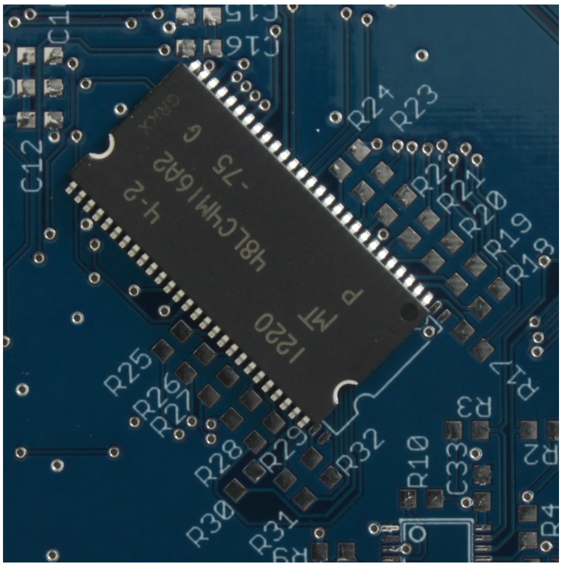


Figure 3.9: SDRAM Chip shown against its footprint.

3.4.4 PCB Faults

TCRT1010 Footprint

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 SDRAM Footprint

The SDRAM footprint made was done exactly to the specification of the pad size and locations with no consideration for soldering to. This meant the chip fit exactly on to the footprint. This made soldering difficult as pads had to be preloaded with solder and the device's pins were heated and bound to the solder. The chip does not seat flat against the PCB. It also put the device at risk as more heat had to be used that usually necessary. Figure 3.9 shows the SDRAM chip against the footprint. There is no extra space on the pad to be able to easily solder 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.

3.4.4.2 SDRAM Chip Select

The code was prototyped on the Atmel UC3C-EK development board prior to the PCB arriving. When the PCB was built, the code did not work, even with the Chip Select declaration changed. 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 to only Chip Select line 1. The Columbus was designed to used chip select line 0. Chip select 1 was available on an external pin, and a via through the routing was close to a via connected to the SDRAM chip select line. Therefore, to overcome the problem, a small enameled 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 3.11(b).

This fault was caused by not reading the datasheet carefully and ignoring a proven circuit diagram.

3.4.4.3 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 3.4 shows some examples of the problematic data bits. The data written should match the data read back.

Table 3.4: 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.

3.4.4.4 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.

3.4.4.5 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 side of the motor. The pin assignment was mixed up when created and connected the two outputs together. Figure 3.10 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

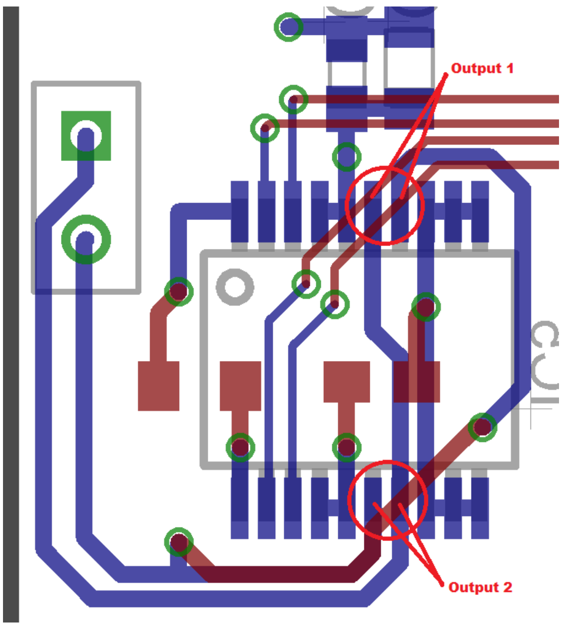


Figure 3.10: Motor Driver error. Outputs incorrectly connected

impedance 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:

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

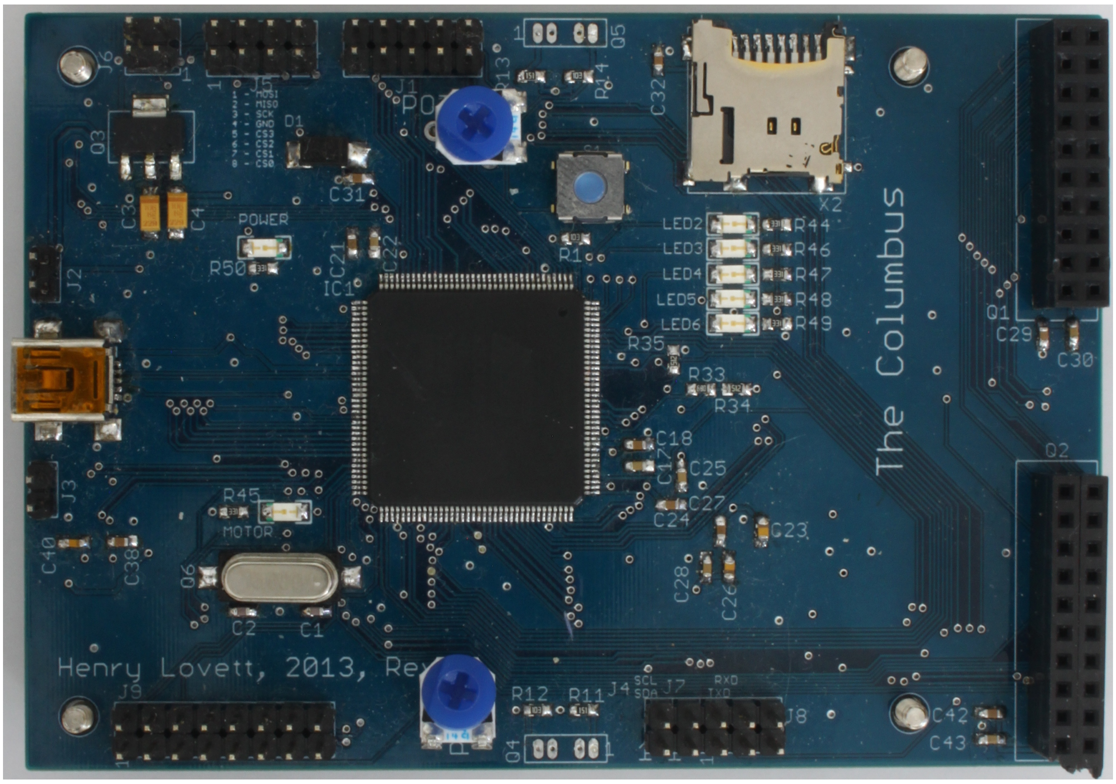
Three of the faults could have been avoided by consulting the datasheet more carefully during the circuit design stage. The footprint error was due to not being experienced in designing footprints and the data line resistors was a mistake due to lack of attention being paid.

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.

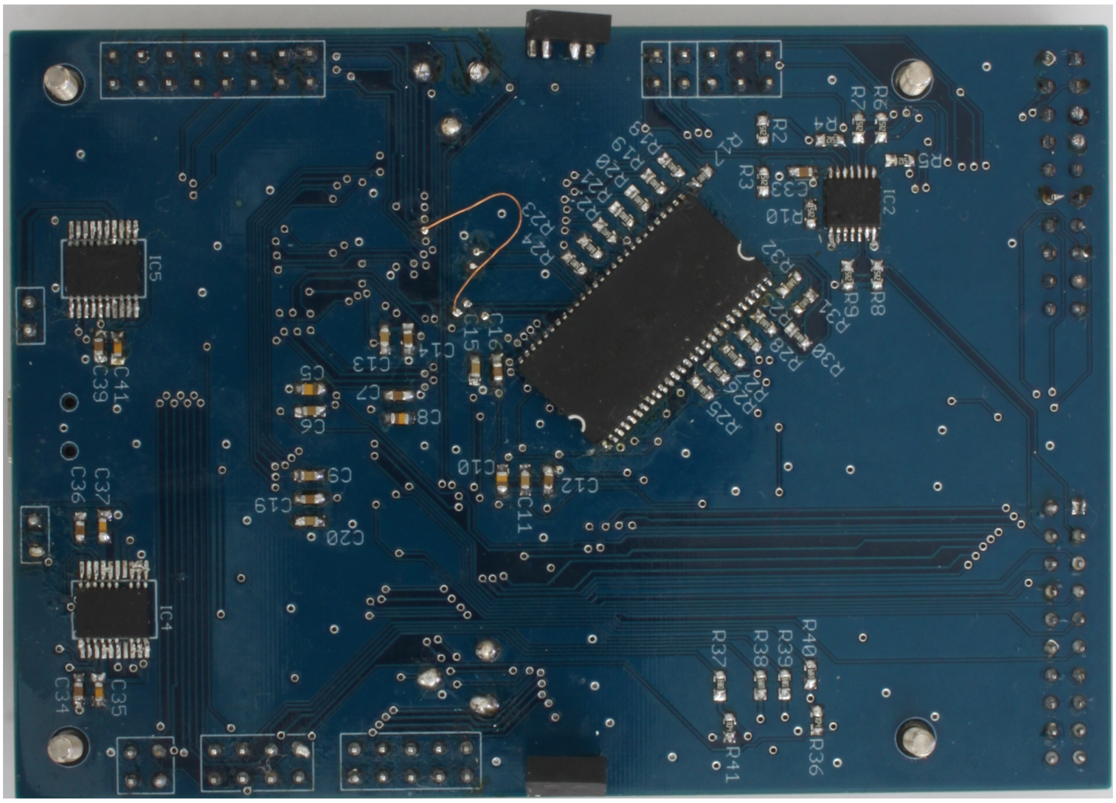
The PCB itself, was a success. It was a complex PCB with many potential things that could have gone wrong. It was the first PCB I had designed and was a four layer board, using some devices that I did not have experience with. All devices are functional (with a few small modifications) on the PCB so firmware development could continue with all hardware able to be used.

3.5 Conclusions

Overall Conclusions of the Hardware design



(a) Top view of built PCB



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

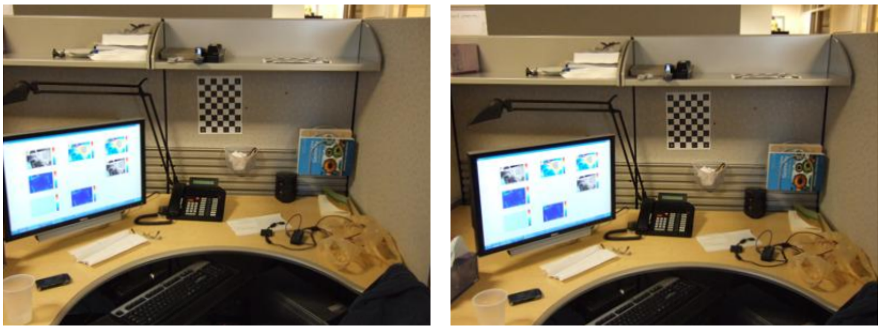
Figure 3.11: Pictures of the built PCB.

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

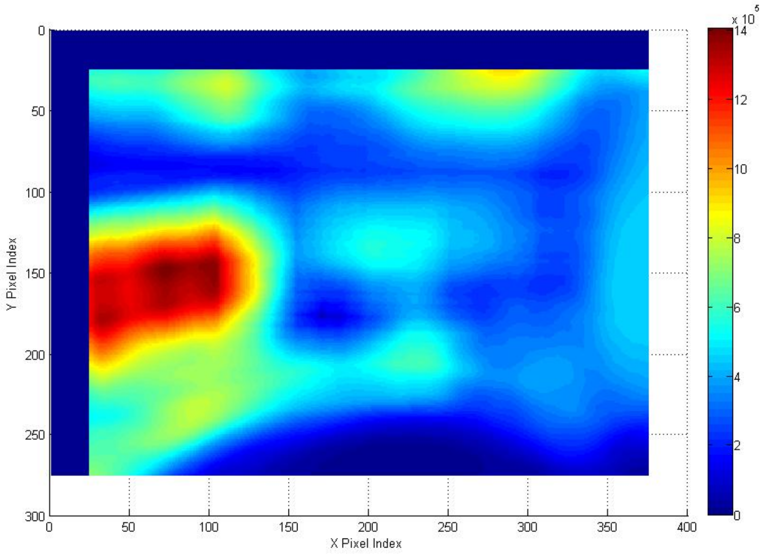
To compare these equations, a 50 by 50 window taken from the right picture was compared with the left image over the entire valid range. The coordinates on the graph give the centre pixel of the calculation.

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)).

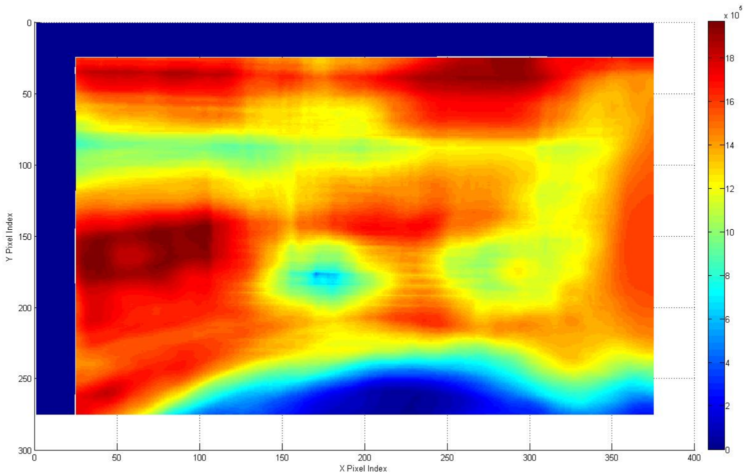
SAD results in figure 4.2(b) show large areas of matching. A minimum occurs around the location expected$(170, 175)$ of a value of 5.66×10^4. However, along the bottom of the image, where a dark area occurs below the desk in the lower part of figures 4.1, the SAD algorithm detects a greater comparison,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

SSD 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.

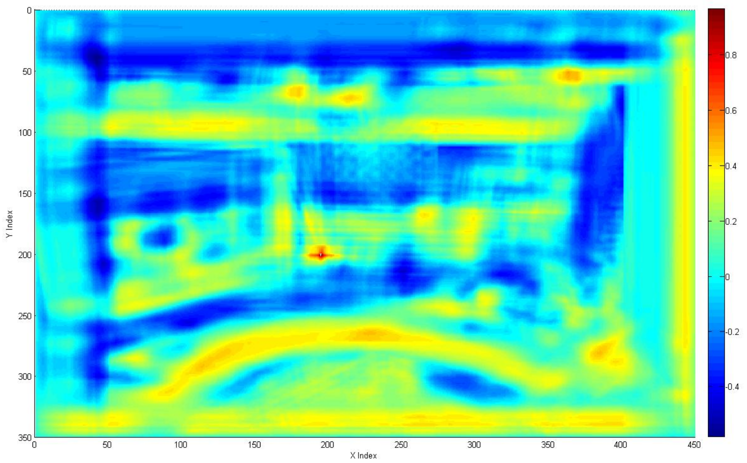
The NCC results are visible in figure 4.2(c). A match can be seen at coordinate $(195, 201)$ with a peak value of 0.9654. The coordinate is different to the previous results because the cross correlation works over the boundary of the image creating more results. The dimensions of the image are 300×400,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

The problem is broken down into three parts:

1. Object is between the cameras (Figure 4.3)
2. Object is in left or right hand sides of both images (Figure 4.4)
3. Object is directly in front of a camera (Figure 4.5)

4.2.1.1 Object is between the Cameras

Derivation from Mrovlje and Vrančić (2008).

$$B = B_1 + B_2 = D\tan(\varphi_1) + D\tan(\varphi_2) \tag{4.4}$$

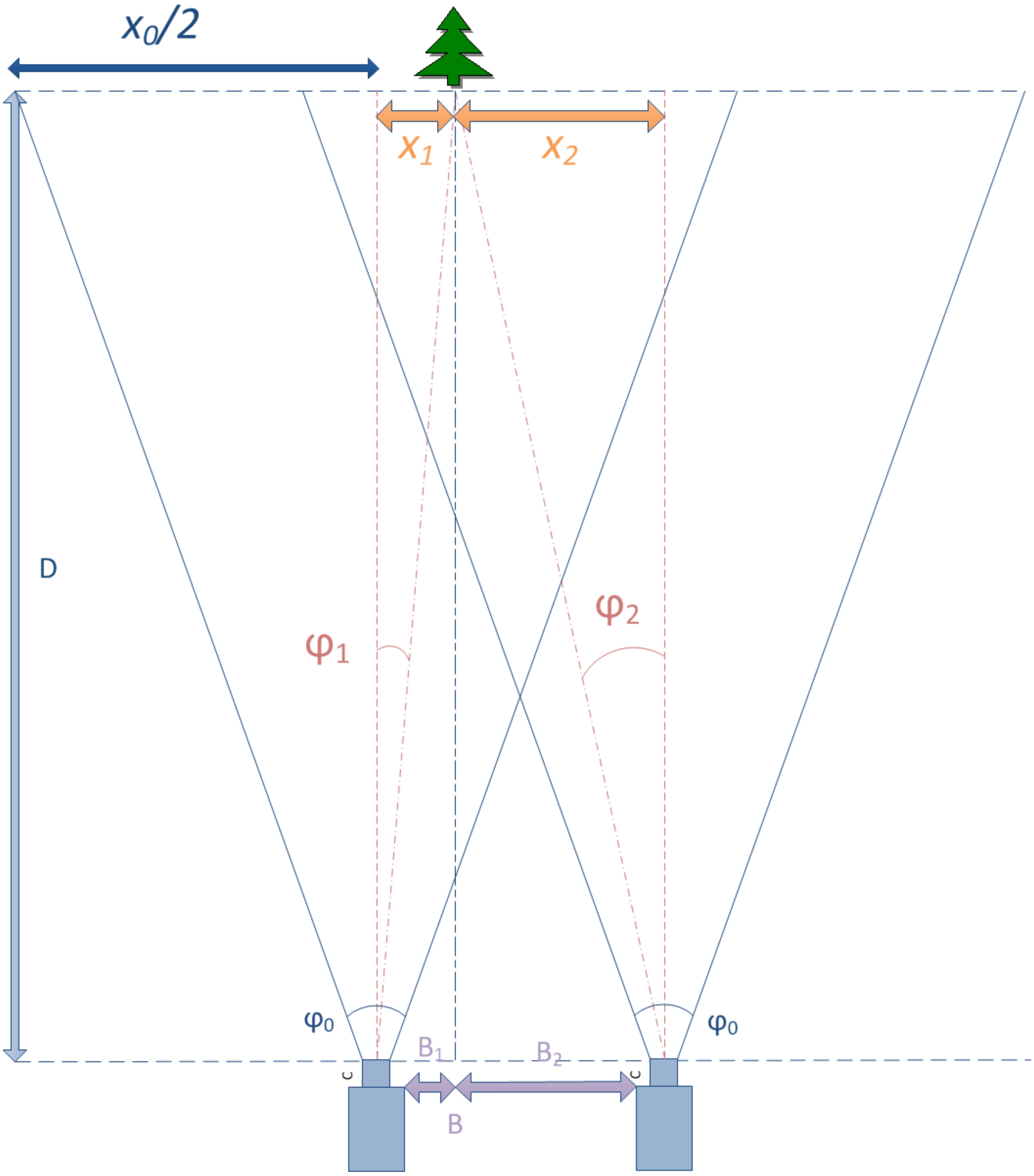


Figure 4.3: Problem 1 - Object is between the Cameras

$$D = \frac{B}{\tan(\varphi_1) + \tan(\varphi_2)} \tag{4.5}$$

$$D \tan\left(\frac{\varphi_0}{2}\right) = \frac{x_0}{2} \tag{4.6}$$

$$D \tan(\varphi_1) = x_1 \tag{4.7}$$

Dividing (4.7) by (4.6)

$$\frac{\tan(\varphi_1)}{\tan(\frac{\varphi_0}{2})} = \frac{2x_1}{x_0} \tag{4.8}$$

$$\tan(\varphi_1) = \frac{2x_1 \tan(\frac{\varphi_0}{2})}{x_0} \tag{4.9}$$

This can also be shown for the right camera:

$$\tan(\varphi_2) = \frac{-2x_2 \tan(\frac{\varphi_0}{2})}{x_0} \tag{4.10}$$

Substitution equations (4.9) and (4.10) into (4.5) gives

$$D = \frac{Bx_0}{2\tan(\frac{\varphi_0}{2})(x_1 - x_2)} \tag{4.11}$$

4.2.1.2 Object is to the same side in each camera

Derivation is based on the derivation from Tjandranegara (2005). Using figure 4.4:

$$D.\tan(\varphi_1) = x_1 \tag{4.12}$$

$$D.\tan\left(\frac{\varphi_0}{2}\right) = \frac{x_0}{2} \tag{4.13}$$

$$\frac{\tan(\varphi_1)}{\tan(\frac{\varphi_0}{2})} = \frac{2x_1}{x_0} \tag{4.14}$$

$$\varphi_1 = \arctan\left(\frac{2x_1}{x_0}\tan\left(\frac{\varphi_0}{2}\right)\right) \tag{4.15}$$

and similarly

$$\varphi_2 = \arctan\left(\frac{2x_2}{x_0}\tan\left(\frac{\varphi_0}{2}\right)\right) \tag{4.16}$$

$$\theta = \varphi_2 - \varphi_1 \tag{4.17}$$

Using the sine equality rule:

$$\frac{R}{\sin(\frac{\pi}{2} - \varphi_2)} = \frac{B}{\sin(\theta)} \tag{4.18}$$

$$R = B.\frac{\sin(\frac{\pi}{2} - \varphi_2)}{\sin(\theta)} = B\frac{\cos(\varphi_2)}{\sin(\theta)} \tag{4.19}$$

$$D = \cos(\varphi_1).R \tag{4.20}$$

Substituting (4.17) into (4.19), and then into (4.20):

$$D = B.\frac{\cos(\varphi_2).\cos(\varphi_1)}{sin(\varphi_2 - \varphi_1)} \tag{4.21}$$

Where φ_1 is defined in equation (4.15) and φ_2 is defined in equation (4.16).

4.2.1.3 Object is in front of a camera

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

$$D = B\tan\left(\frac{\pi}{2} - \varphi_2\right) \tag{4.22}$$

Where φ_2 can be found from equation 4.16.

4.2.1.4 Summary

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

Object is between the two cameras:

$$D = \frac{Bx_0}{2\tan(\frac{\varphi_0}{2})(x_1 - x_2)} \tag{4.23}$$

Object is to the same side in both images:

$$D = B.\frac{\cos(\varphi_2).\cos(\varphi_1)}{sin(\varphi_2 - \varphi_1)} \tag{4.24}$$

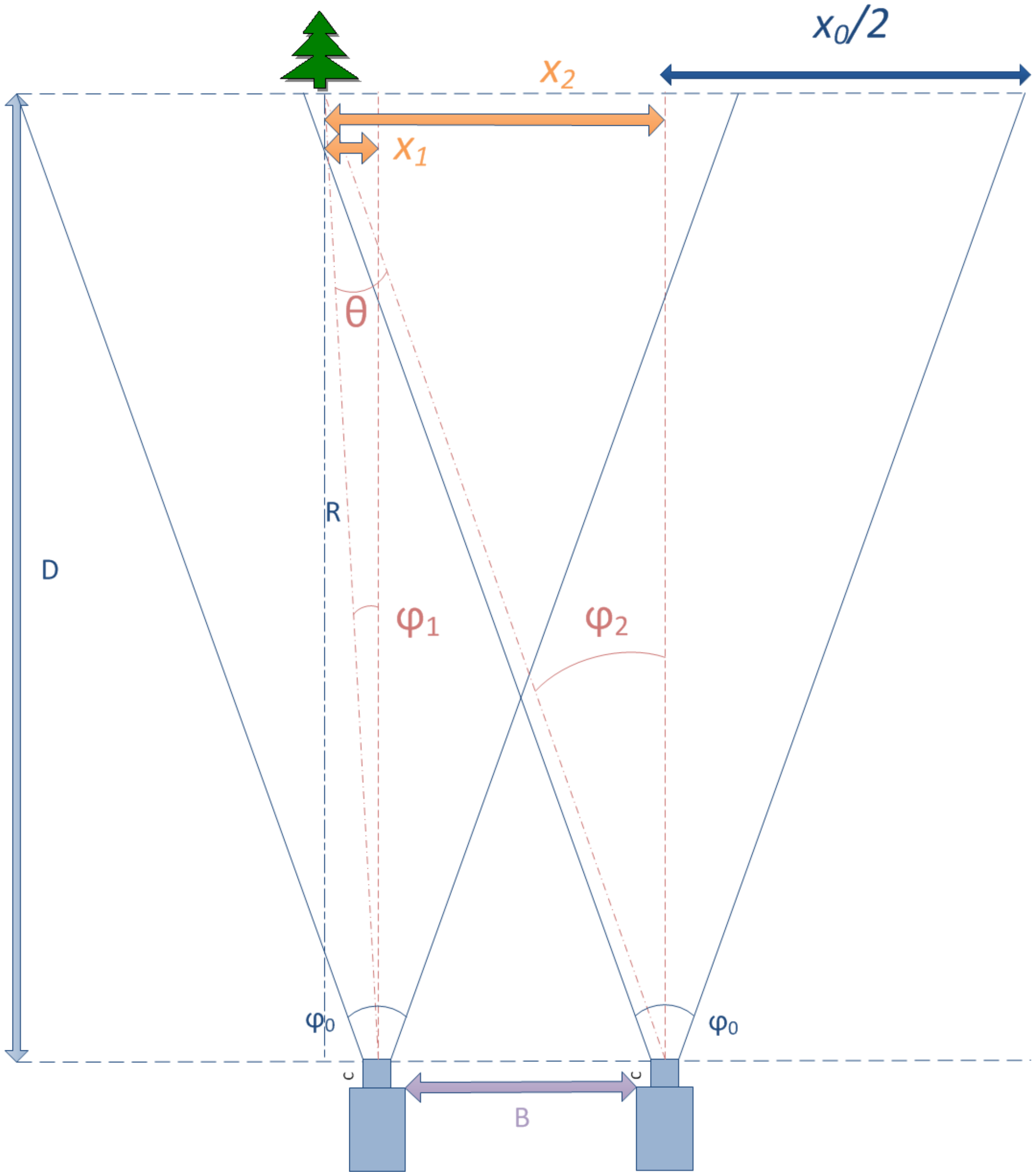


Figure 4.4: Problem 2 - Object is to the same side in both cameras

Object is directly in front of a camera:

$$D = B \tan\left(\frac{\pi}{2} - \varphi_2\right) \tag{4.25}$$

Where φ_1 is defined in equation (4.15) and φ_2 is defined in equation (4.16).

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

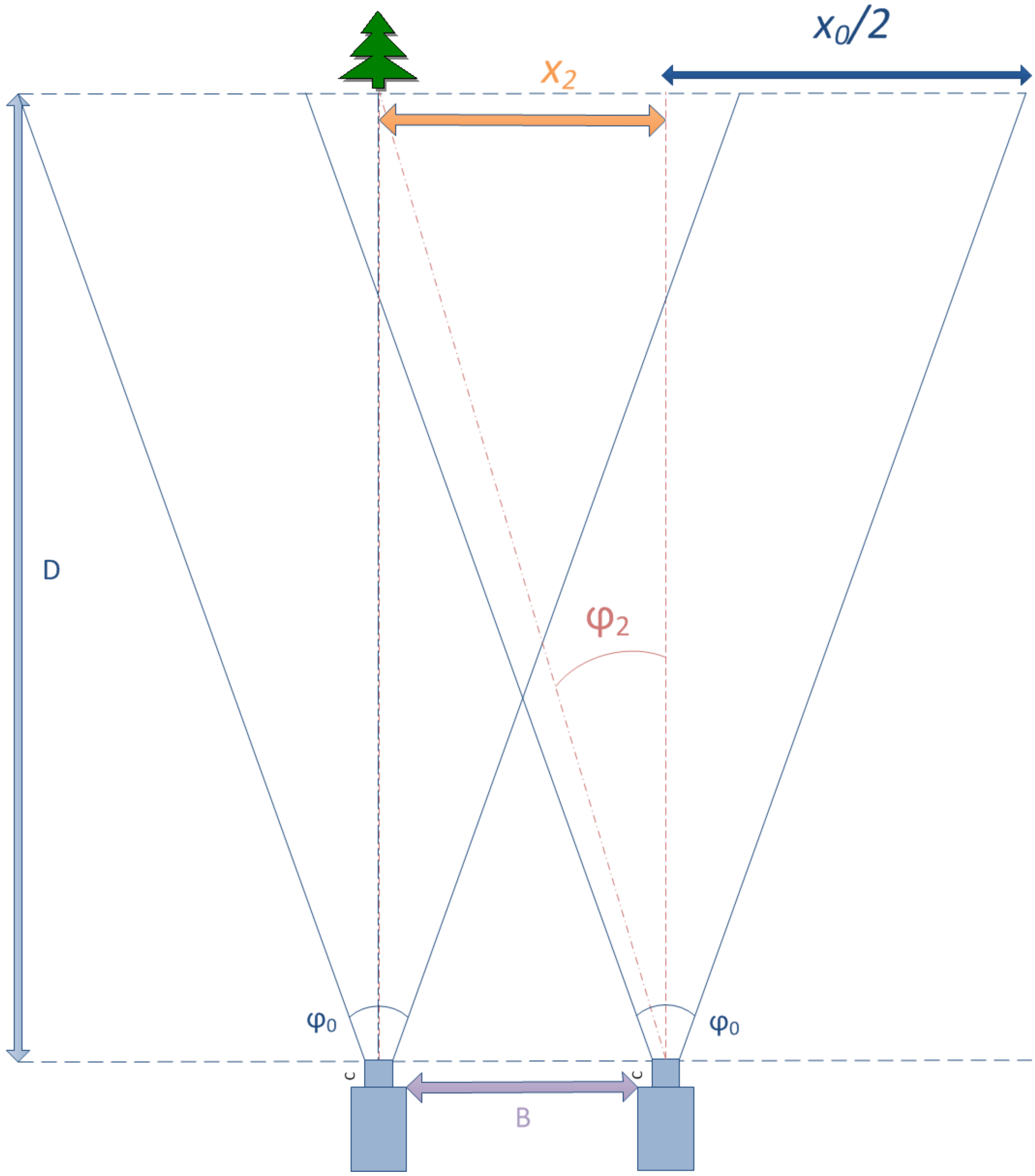
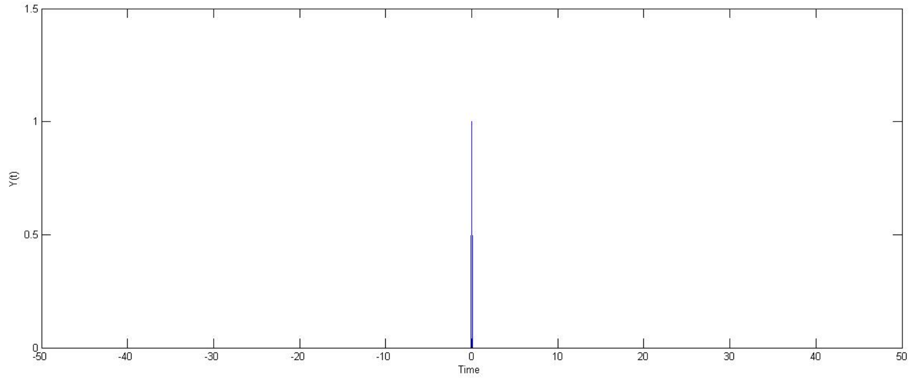


Figure 4.5: Problem 3 - Object is directly in front of a camera

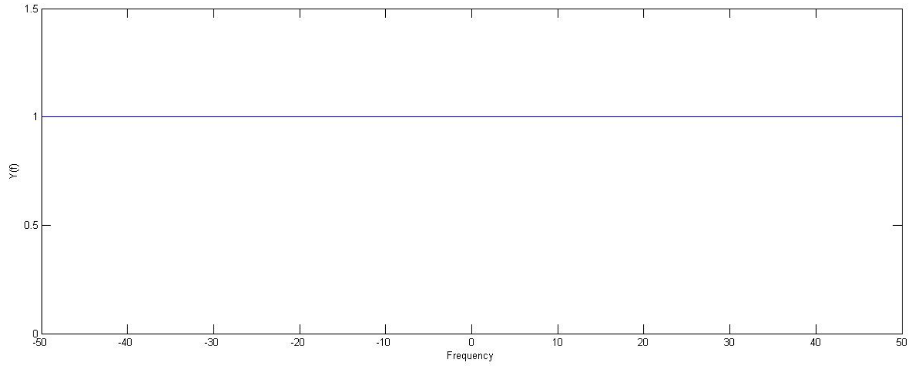
4.3 Fourier Transform

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, which is often displayed as magnitude and



(a) A graph showing a Dirac Function



(b) A graph showing the Fourier Transform of the Dirac Function

Figure 4.6: A common Fourier Transform pair: Dirac function and a flat frequency spectrum

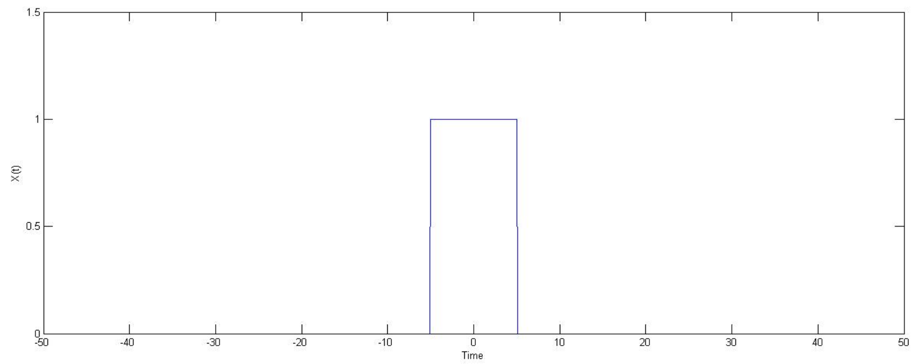
phase. The Fourier Transform is defined in equation (4.26) and two examples of signals and their Fourier Transforms are shown in figures 4.6 and 4.7.

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-\jmath 2\pi f t}dt \tag{4.26}$$

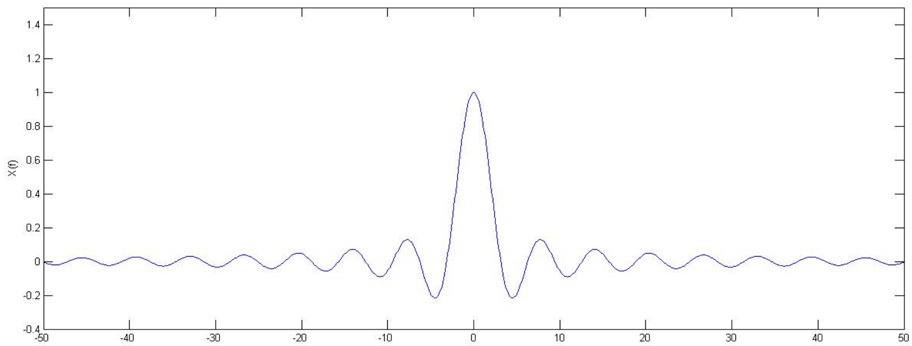
Uses of FT in signal processing

Definition of DFT and theory of FFT

The equation for the Fourier transform in equation (4.26) 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 (4.27)



(a) A graph showing rectangular pulse



(b) A graph showing the Fourier Transform of the rectangular pulse

Figure 4.7: A common Fourier Transform pair: a rectangular pulse and a sinc function

$$X[k] = \sum_{0}^{N-1} x[n] e^{-\jmath\Omega_0 kn} \tag{4.27}$$

Where Ω_0 is the sample frequency

Why this is relevant to my project - what am I using it for?

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 (4.28). As discussed in section 4.1.3, cross correlation is very similar to convolution. Convolution is defined in equation (4.29). With images, $f(t)$ is a real signal, its conjugate is exactly the same, $f(t) \equiv f^{*}(t)$given that$f(t) \in \Re$.

$$\int_{-\infty}^{\infty} f(\tau)g(t-\tau)d\tau = f(t) * g(t) = X(f) \cdot Y(f) \tag{4.28}$$

$$\int_{-\infty}^{\infty} f^{*}(\tau)g(t+\tau)d\tau = f(t) \star g(t) = X(f) \cdot Y(f) \tag{4.29}$$

$$f(t) \star g(t) = f(t) * g(-t) = F(f) \cdot G(-f) \tag{4.30}$$

example of convolution used as correlation. Include some pretty graphs

4.3.2 Two Dimensional Fast Fourier Transform

Definition

Examples

2D FFT and restrictions

Maybe make a figure to help explain?

4.3.3 Implementing the FFT in C

Include and explain code

4.3.4 Testing of the FFT on AVR

Show results of some test signals

Need to implement grey scaling method before being able to do this

Show results of actual photo being transformed

Compare to MATLAB results

4.4 Low Level Vision Algorithms

4.4.1 Noise Reduction

Why

Theory

Examples

Does it improve the reliability of matching?

4.4.2 Edge Detection

Why

Theory

Examples

Does it improve the reliability of matching?

Chapter 5

Results

5.1 Results

A full test of the system I have got

Summary of good and bad WITH EVIDENCE

Chapter 6

Conclusions and Further Work

What I have accomplished

What could be changed to make it better

Suggestions for further work

Appendix A

Gantt Chart

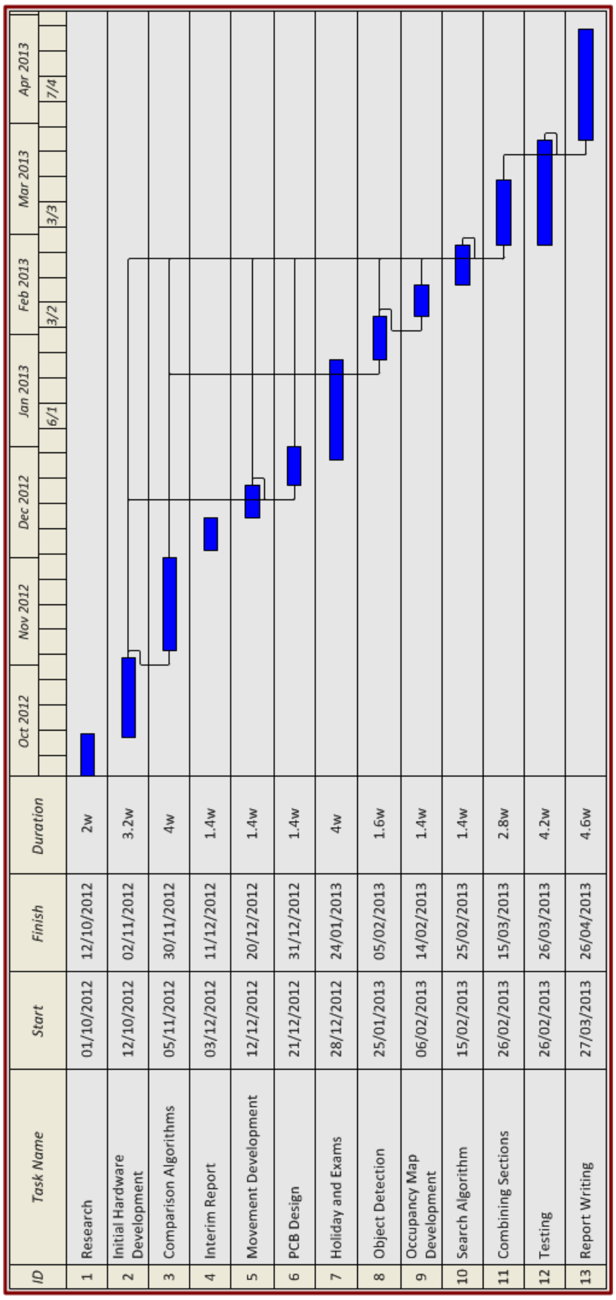


Figure A.1: Gantt Chart of how time will be spent in the areas of the project

Appendix B

Circuit Diagrams

B.1 OV7670 Breakout Board Schematic

B.2 Il Matto and Dual Camera Schematic

B.3 The Columbus Circuit Diagram

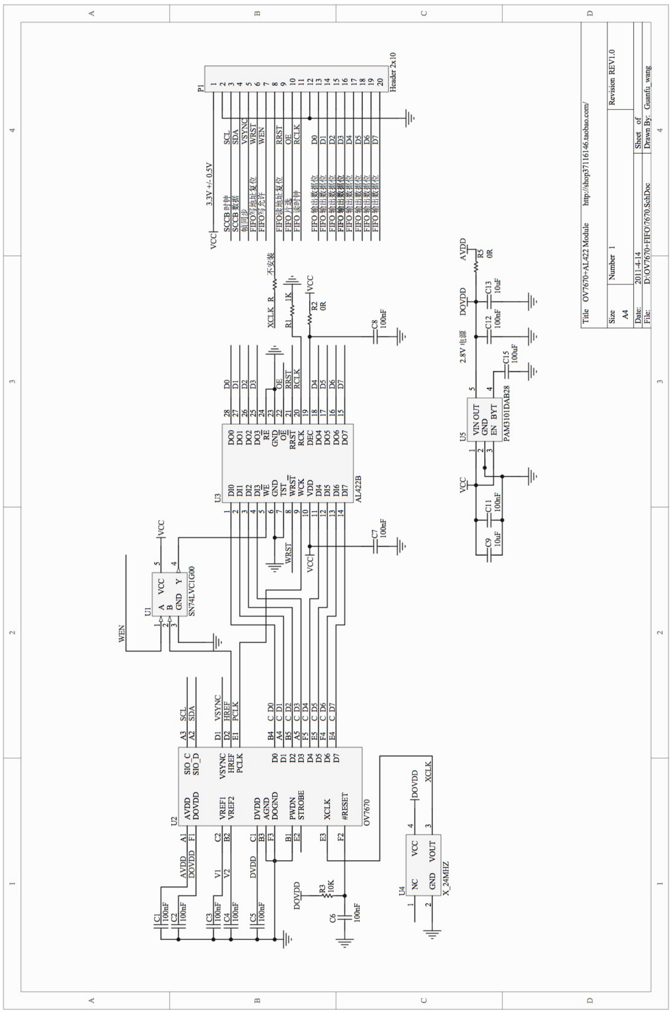


Figure B.1: The circuit diagram for the OV7670 breakout board

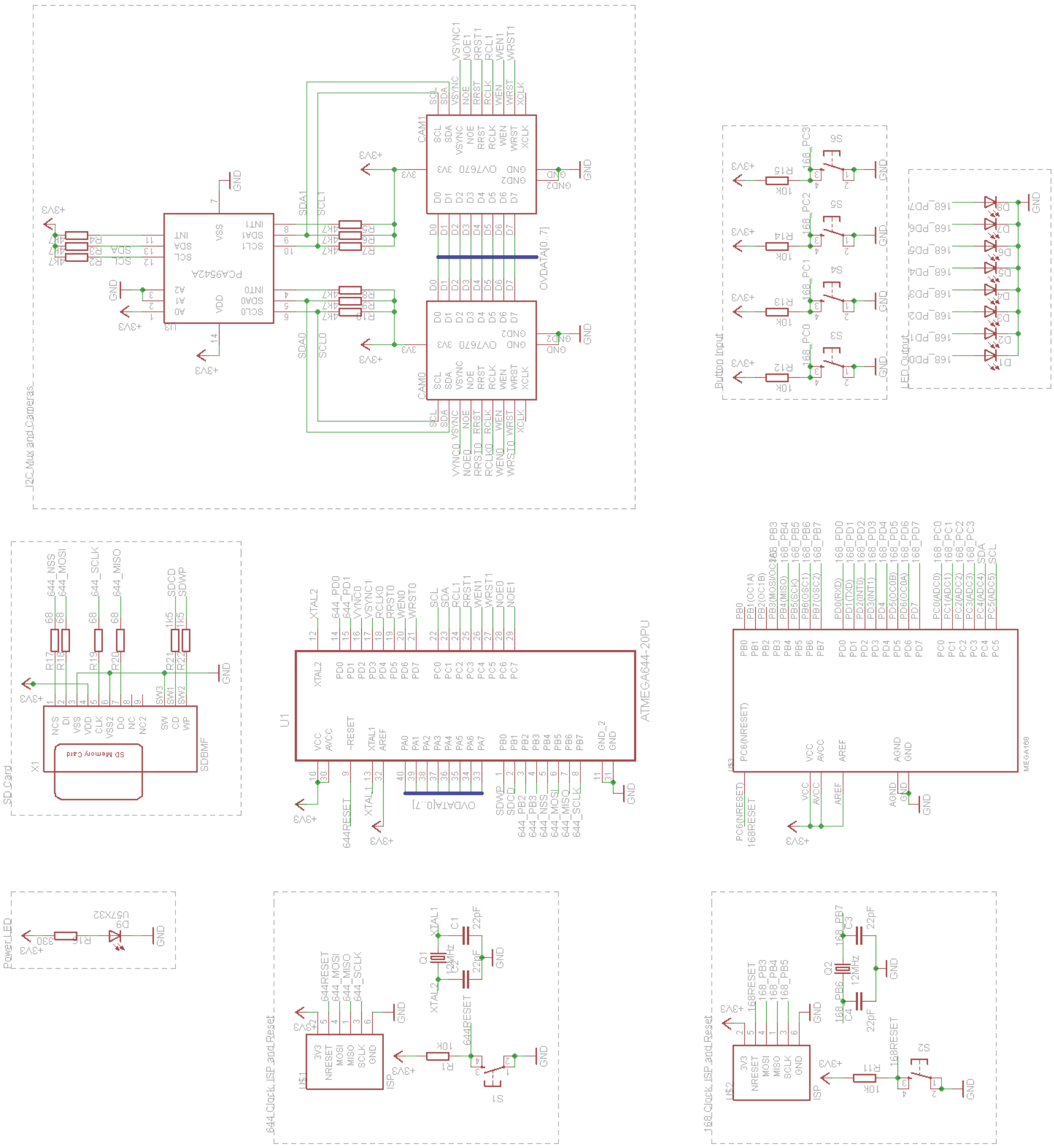


Figure B.2: The circuit diagram for Dual Cameras using the Il Matto Board

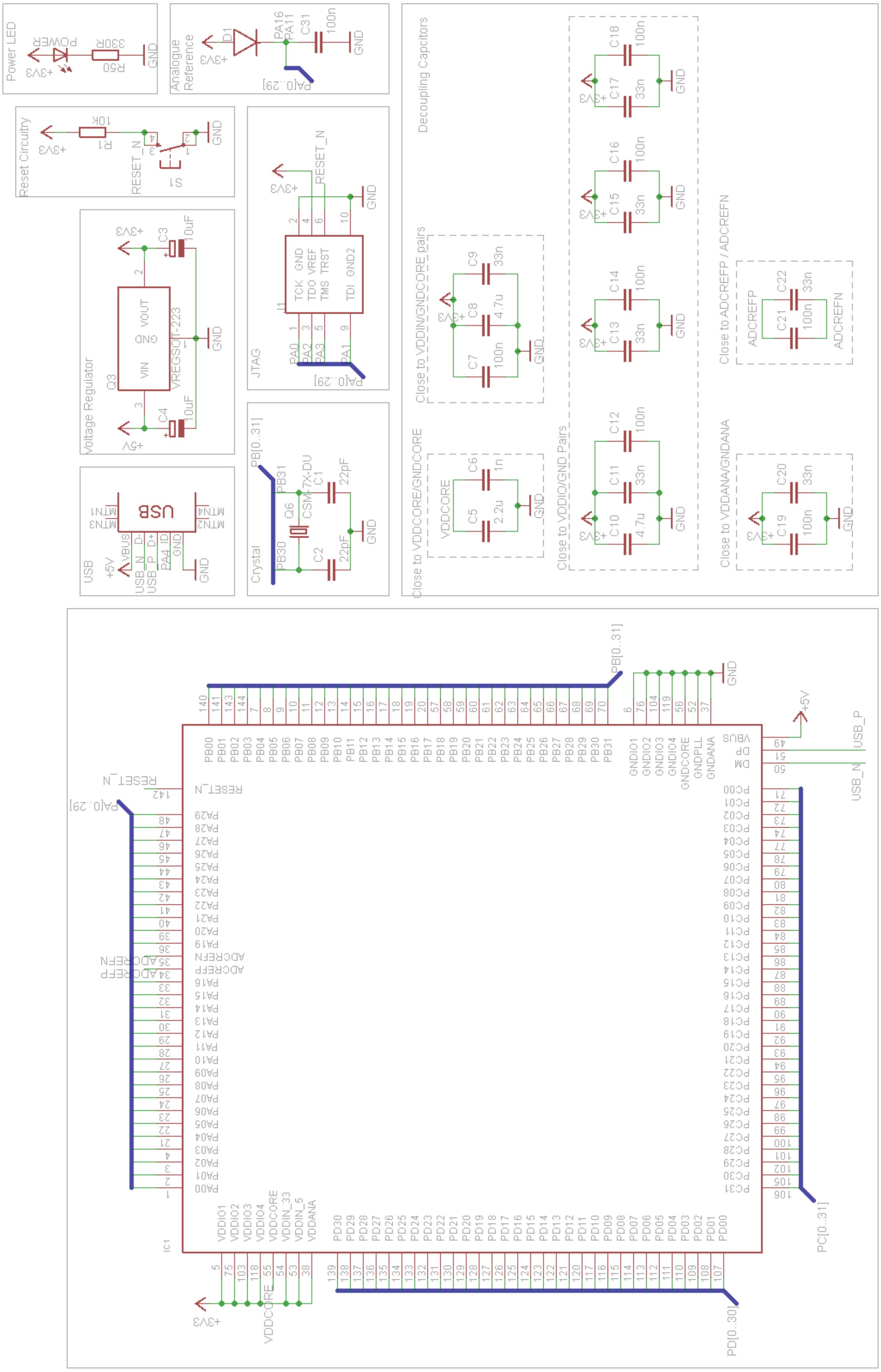


Figure B.3: The Columbus Circuit Diagram Page 1

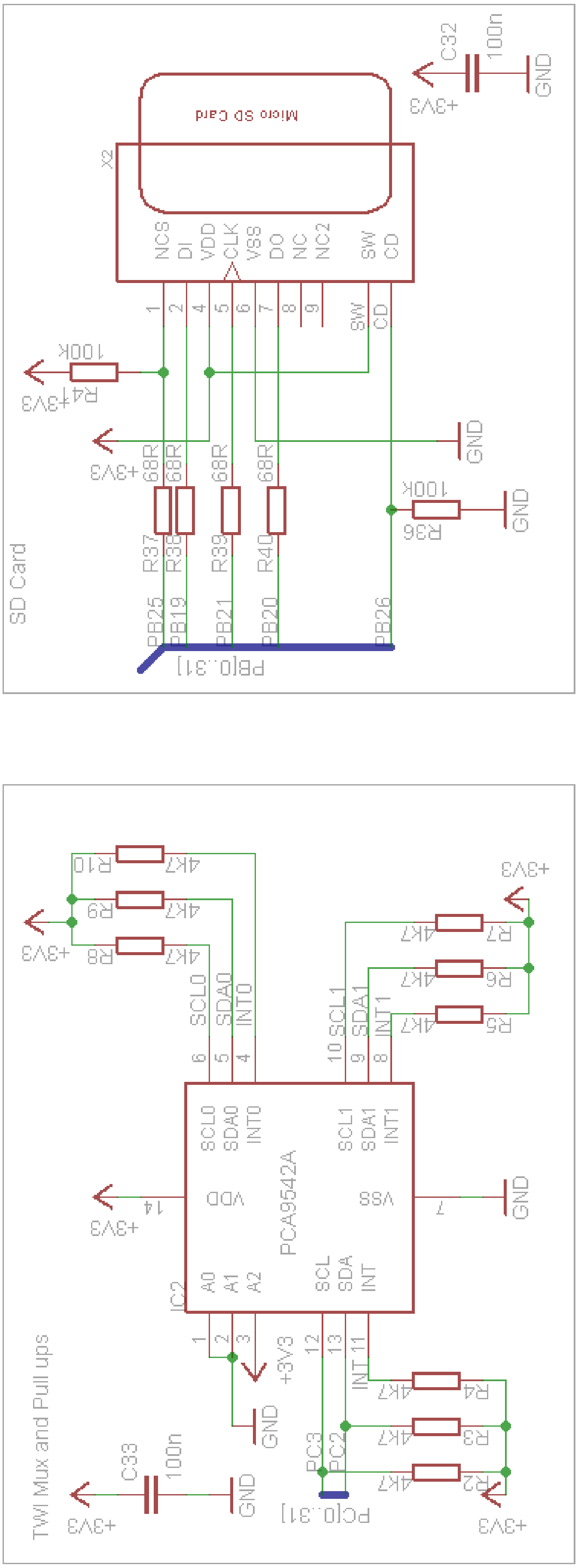


Figure B.4: The Columbus Circuit Diagram Page 2

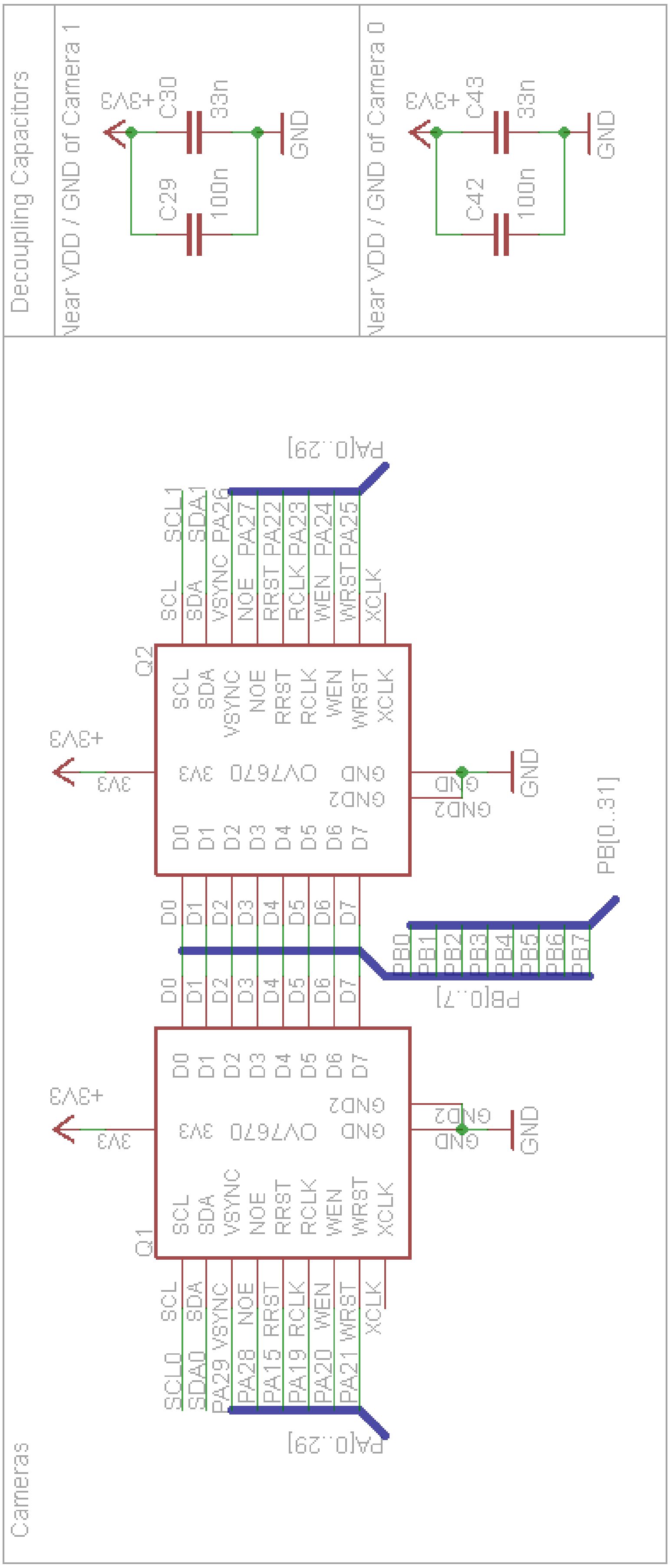


Figure B.5: The Columbus Circuit Diagram Page 3

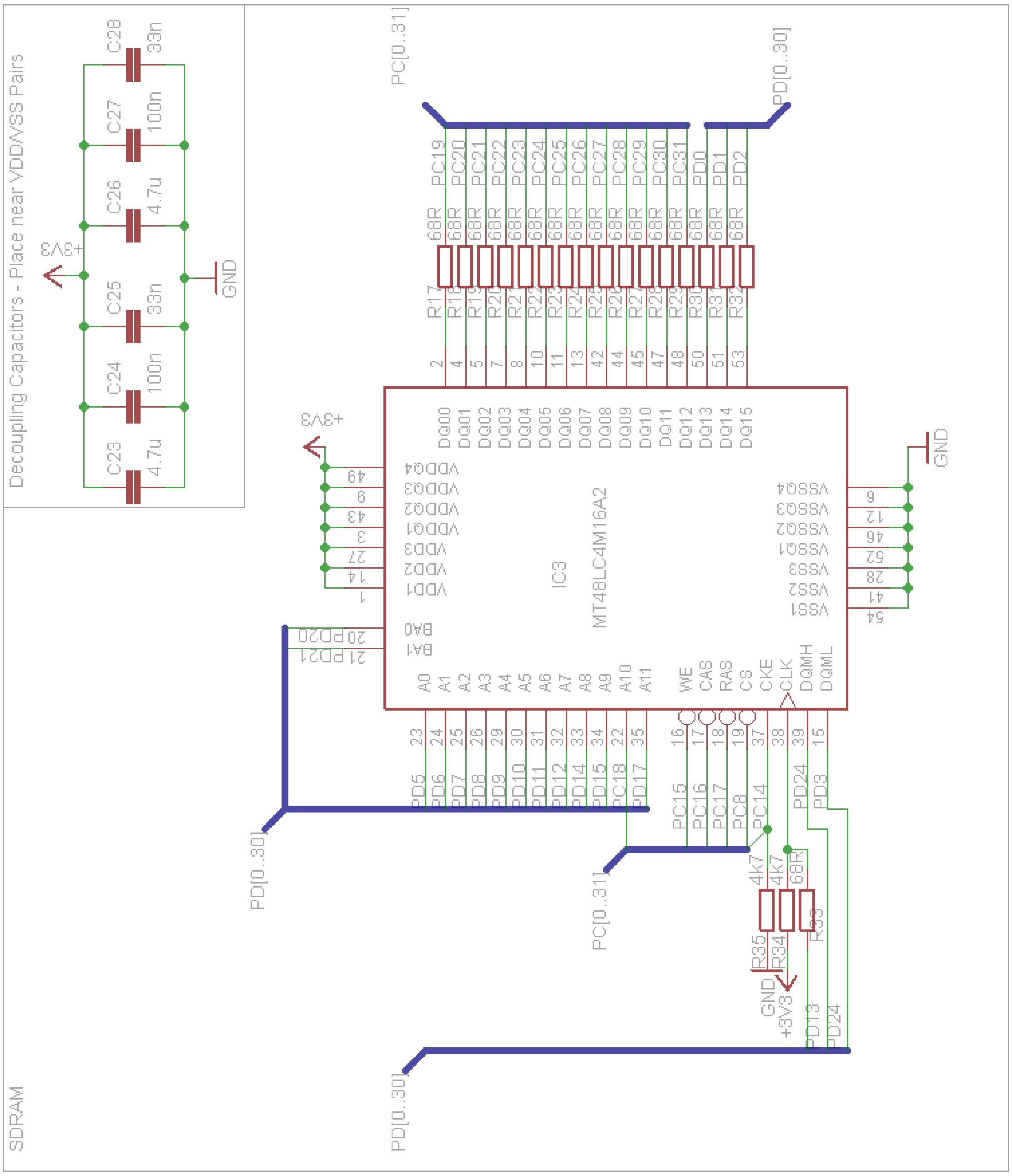


Figure B.6: The Columbus Circuit Diagram Page 4

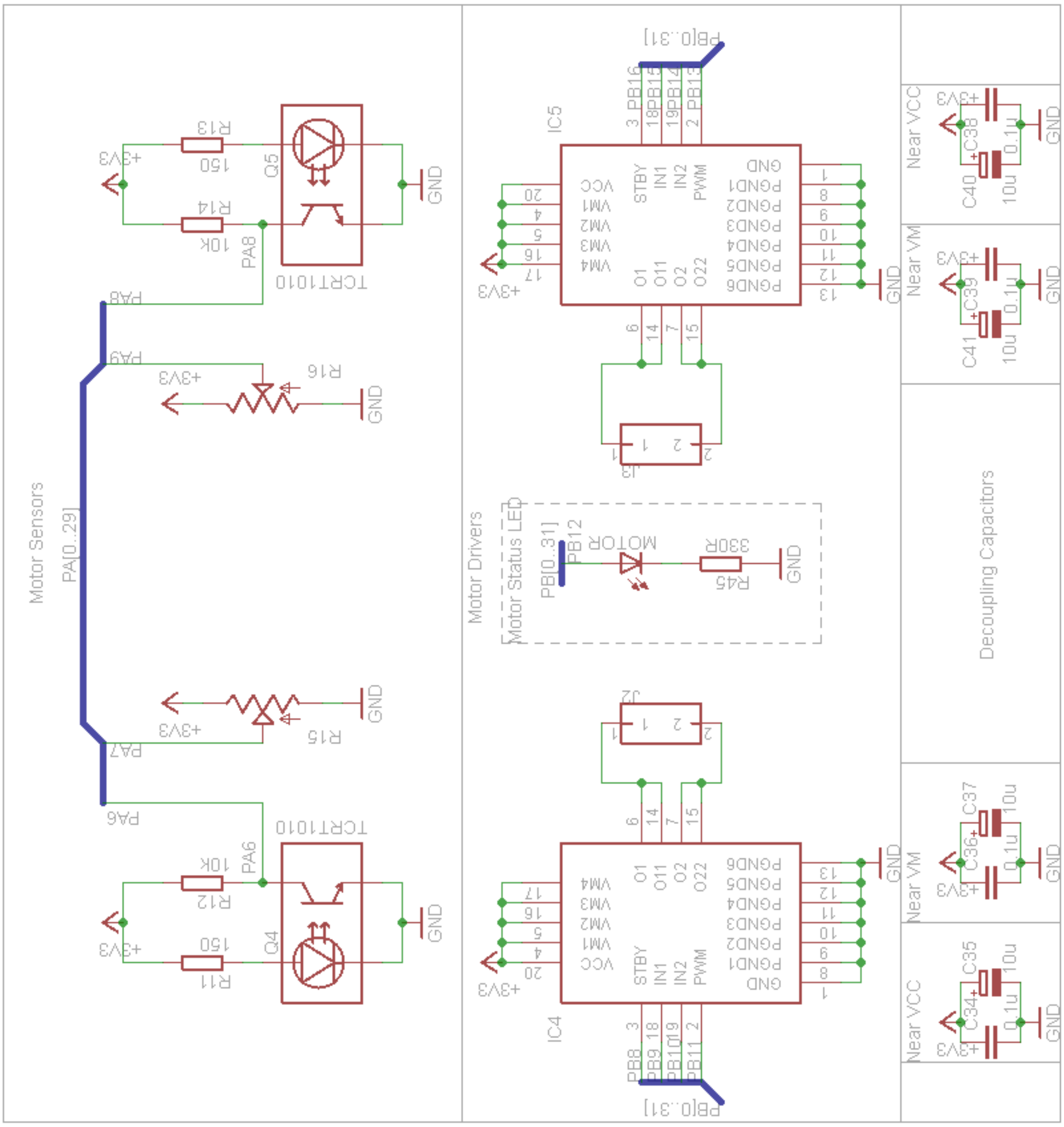


Figure B.7: The Columbus Circuit Diagram Page 5

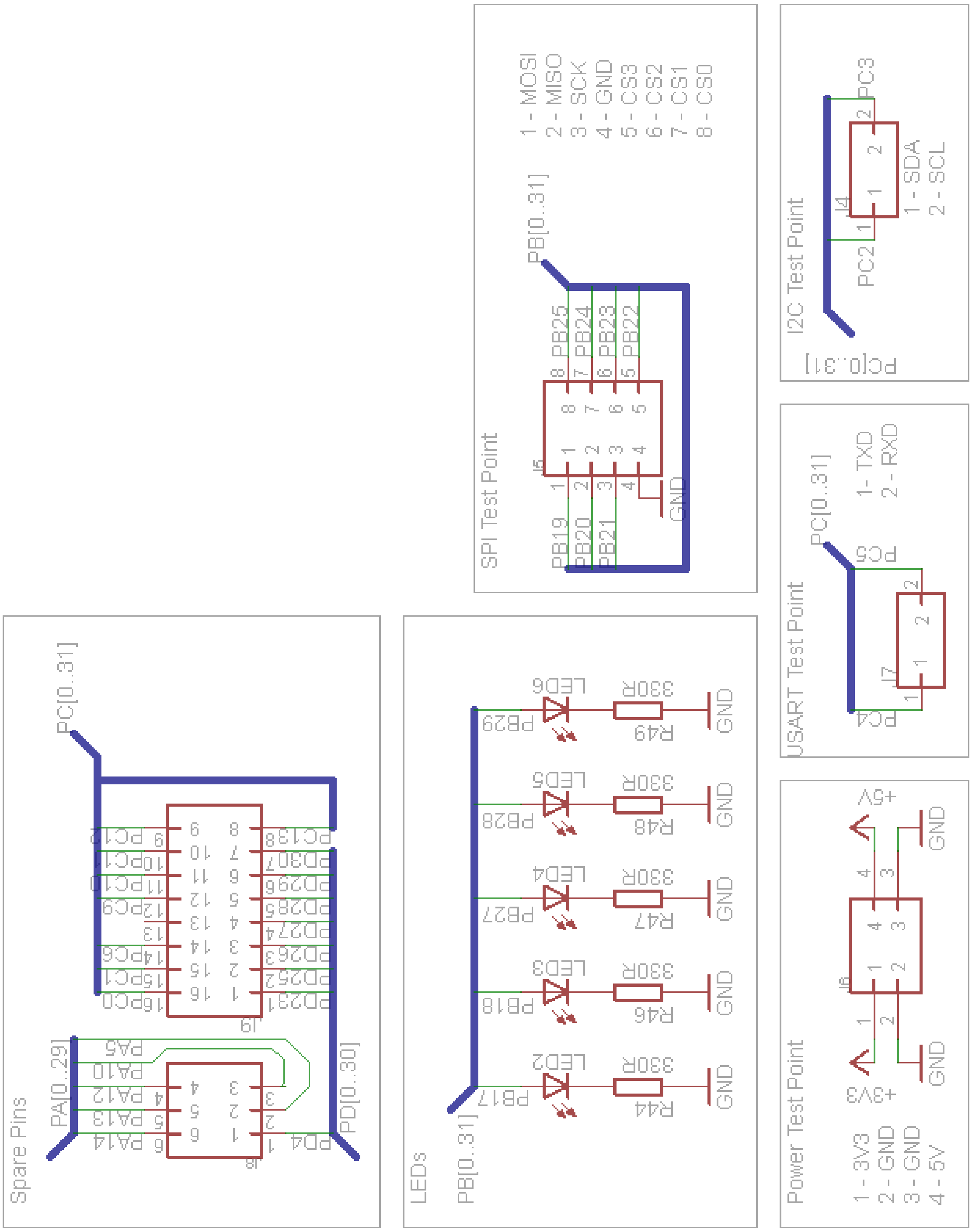


Figure B.8: The Columbus Circuit Diagram Page 6

Appendix C

Bitmap File Format

C.1 Bitmap File Format

Table C.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 C.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 C.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 D

Source Code

D.1 C Code for AVR

D.1.1 The Columbus Source Code

D.1.1.1 main.c

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

```
/**
 * \file
 *
 * \brief Empty user application template
 *
 */

/*
 * Include header files for all drivers that have been imported from
 * Atmel Software Framework (ASF).
 */
#define DSP32_FORMAT 24
#include <asf.h>
#include <conf_board.h>
#include "CustomDevices/CustomDevices.h"
#include "conf_sd_mmc_spi.h"
#include "fat.h"
#include "file.h"
#include "navigation.h"
#include "fastmath.h"
#include "delay.h"

//REF : http://www.chris.com/ASCII/index.php?art=transportation/nautical
#define ASCII_SHIP "\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 \
\t\t\t         ^^^^      ^^^\n\r"

 #define COLUMBUS " _______  _______  _               _______  ______
        _______ \n\r(  ____ \\(  ___  )( \\      |\\     /|(       )(  ___ \\
     |\\     /|(  ____ \\\n\r| (    \\/| (   ) || (      | )   ( || () () || (
       ) )| )   ( || (    \\/\n\r| |      | |   | || |      | |   | || || ||
    || (__/ / | |   | || (_____ \n\r| |      | |   | || |      | |   | || |(_)
    | ||  __ (  | |   | |(_____  )\n\r| |      | |   | || |      | |   | || |
      | || (  \\ \\ | |   | |      ) |\n\r| (____/\\| (___) || (____/\\| (___)
     || )   ( || )___) )| (___) |/\\____) |\n\r(_______/(_______)(_______/(
    _______)|/     \\||______/ (_______)\\_______)\n\n\r"
#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"

#define PROMPT "\n\r$>"

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

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

  while(c != 13)
  {
    c = usart_getchar(DBG_USART);
    if(c == '\b')
    {
      CommandBuffer--;
      *(CommandBuffer) = 0;
    }
    else
    {
      *(CommandBuffer) = c;
      CommandBuffer++;
    }
    print_dbg_char(c);
```

```
    }
    usart_putchar(DBG_USART, 6);
}

#define COMMAND_BUFFER_SIZE   32
int main (void)
{
  Image_t image;
  unsigned long i, j, tmp = 0;
  char *Ptr;
//  volatile unsigned long *sdram = SDRAM;
  char CommandBuffer[COMMAND_BUFFER_SIZE];
  int *Working_Buffer = NULL;
  int SizeOfWorking_Buffer = 0;
  A_ALIGNED dsp16_complex_t *ComplexBuffer;
  int SizeOfComplex_Buffer = 0;
  Columbus_Status.SD_Card = &SD_Status;
  Columbus_Status.Cameras = &OV7670_Status;
  Columbus_Status.I2CMux = &PCA9542A;
  Columbus_Status.SD_Card = &SD_Status;
  Columbus_Status.Motors = &Motor_Control;
  board_init();
  print_dbg("\n\r");
  print_dbg(THE);
  print_dbg(COLUMBUS);
  print_dbg(ASCII_SHIP);
  System_Test();


  //print_dbg("\n\rResetting Motors.");

//  Motors_Reset();
//  while(Motors_Moving() == true)
//    ;
  if(Columbus_Status.Status != STATUS_OK)
  {
    while(1)
    {
      LED2_SET;
      LED3_SET;
      LED4_SET;
      LED5_SET;
      LED6_SET;
      delay_ms(500);
      LED2_CLR;
      LED3_CLR;
      LED4_CLR;
      LED5_CLR;
      LED6_CLR;
      delay_ms(500);
    }//inifinte loop
  }


  print_dbg("\n\rColumbus Ready!");
  // Insert application code here, after the board has been initialized.
  while(1)
  {
```

```
    print_dbg(PROMPT);
    Get_Line(CommandBuffer);
    Ptr = CommandBuffer;
    switch(*Ptr++)
    {
      case '?':
        print_dbg(HELP);
        break;

      case '1'://1d FFT (w/ memallocs)
        print_dbg("\r1D FFT;");
        FFT1D(Working_Buffer);
        break;
      case '2':
        print_dbg("\r2D FFT;");
        FFT2Dabs(Working_Buffer);
        break;
      case '3':
        print_dbg("\rComplex FFT2D:");
        SizeOfComplex_Buffer = FFT_SIZE * FFT_SIZE;
        ComplexBuffer = mspace_malloc(sdram_msp,  SizeOfComplex_Buffer *
    sizeof(ComplexBuffer));
        FFT2DCOMPLEX(Working_Buffer, ComplexBuffer, SizeOfWorking_Buffer);
        break;

      case 'B':
        print_dbg("\rReading Bitmap;");
        ReadBitmap("Image_R_0.bmp", &image);
        print_dbg("\n\rBitmap Data Returned:\n\rImage Height = ");
        print_dbg_ulong(image.Height);
        print_dbg("\n\rImage Width = ");
        print_dbg_ulong(image.Width);
        break;

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

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

      case 'D':
        print_dbg("\rFreeing Working Buffer");
        mspace_free(sdram_msp, Working_Buffer);
        break;

      case 'i':
        print_dbg("\rImage info:");
```

```
        print_dbg("\n\rImage Pointer = ");
        print_dbg_ulong(image.ImagePtr);
        print_dbg("\n\rImage Height = ");
        print_dbg_ulong(image.Height);
        print_dbg("\n\rImage Width = ");
        print_dbg_ulong(image.Width);
        break;

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

      case 'k':
        print_dbg("\rComplex Buffer:\n\r[");
        for (i = 0; i < SizeOfComplex_Buffer; i ++)
        {
          print_dbg_ulong(ComplexBuffer[i].real);
          print_dbg(" + j");
          print_dbg_ulong(ComplexBuffer[i].imag);
          print_dbg(", ");
        }
        print_dbg("]\n\r");
        break;
      case 'M': //Motor Related
        while(*Ptr == ' ')
          Ptr++; //Find next non - space char

        switch(*(Ptr++))
        {
          case 'q': // Reset Motors
            print_dbg("\rResetting Motors");
            Motors_Reset();
            break;

          case 'F': //Move Forward
            while(*Ptr == ' ')
              Ptr++; //Find next non - space char
            i = atoi(Ptr);
            Motors_Move(i);
            break;
          case 'T':
            while(*Ptr == ' ')
            Ptr++; //Find next non - space char
            i = atoi(Ptr);
            Motors_Rotate(i);
            break;
          case 'l':
            Motor_Stop(MOTOR_L);
            break;
          case 'L':
            Columbus_Status.Motors->Left_Count = INTERRUPTS_PER_REVOLUTION +
      1;
            Columbus_Status.Motors->Left_State = FORWARD;
            Motor_Start(MOTOR_L);
            Motors_Execute();
            break;
          case 'r':
```

```
          Motor_Stop(MOTOR_R);
          break;
        case 'R':
          Columbus_Status.Motors->Right_Count = INTERRUPTS_PER_REVOLUTION +
      1;
          Columbus_Status.Motors->Right_State = FORWARD;
          Motor_Start(MOTOR_R);
          Motors_Execute();
          break;
        default:
          print_dbg("\rCommand Not Recognised");
          break;
      }

      break;

    case 'p':
      print_dbg("\rPreparing Image;");
      PrepareImage(&image);
      print_dbg("\rImage Prepared!");
      break;

    case 'P'://take a photo
      FIFO_Reset(CAMERA_LEFT | CAMERA_RIGHT);
      print_dbg("\rTaking Photos");
      if(TakePhoto(CAMERA_LEFT | CAMERA_RIGHT) == CAMERAS_BUSY){
        print_dbg("Cameras Busy");
        break;
      }
      while(Photos_Ready() == false)
        ;

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

    case 'r':
      if (Working_Buffer == 0)
      {
        print_dbg("\rWorking Buffer Not Initialised");
        break;
      }
      print_dbg("\rWorking Buffer:\n\r[");
      for(i = 0; i < SizeOfWorking_Buffer; i++)
      {
        print_dbg_ulong(Working_Buffer[i]);
        print_dbg(", ");
      }
      print_dbg("\b\b]\n\r");
      break;
    case 'R':
      Working_Buffer = mspace_malloc(sdram_msp, FFT_SIZE);
      SizeOfWorking_Buffer = FFT_SIZE;
      print_dbg("\rReading in signal.bin");
      ReadSignal(Working_Buffer);
      break;

    case 's'://save the working buffer
```

```
        print_dbg("\rSaving Working Buffer;");
        SaveBuff(Working_Buffer, SizeOfWorking_Buffer);
        break;

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

      case 'T':
        print_dbg("\rReading in 2D Signal");
        Working_Buffer = mspace_malloc(sdram_msp, FFT_SIZE * FFT_SIZE);
        SizeOfWorking_Buffer = FFT_SIZE * FFT_SIZE;
        Read2DSignal(Working_Buffer);
        break;
      case 'v':
        print_dbg("\rColumbus Status:");
        print_dbg("\n\rSD Card:\n\rStatus: ");
        print_dbg_ulong(Columbus_Status.SD_Card->Status);
        print_dbg("\n\rMemory Size : ");
        print_dbg_ulong(Columbus_Status.SD_Card->Memory_size);
        print_dbg("\n\rMotors:");
        print_dbg("\n\rLeft State : ");
        print_dbg_ulong(Columbus_Status.Motors->Left_State);
        print_dbg("\n\rLeft Count : ");
        print_dbg_ulong(Columbus_Status.Motors->Left_Count);
        print_dbg("\n\rRight State : ");
        print_dbg_ulong(Columbus_Status.Motors->Right_State);
        print_dbg("\n\rRight Count : ");
        print_dbg_ulong(Columbus_Status.Motors->Right_Count);
        print_dbg("\n\rCameras:");
        print_dbg("\n\rStatus : ");
        print_dbg_ulong(Columbus_Status.Cameras->Status);
        print_dbg("\n\rVSYNC0 State : ");
        print_dbg_ulong(Columbus_Status.Cameras->VSYNC0_State);
        print_dbg("\n\rVSYNC1 State : ");
        print_dbg_ulong(Columbus_Status.Cameras->VSYNC1_State);
        print_dbg("\n\rI2C Mux:");
        print_dbg("\n\rStatus : ");
        print_dbg_ulong(Columbus_Status.I2CMux->Status);
        print_dbg("\n\rChannel Selected : ");
        print_dbg_ulong(Columbus_Status.I2CMux->ChannelSelected);
        break;

//      case 'o'://testing storing a complex
//        print_dbg("\rFreeing Complex Buffer");
//        mspace_free(sdram_msp, ComplexBuffer);
//        print_dbg("\n\rAssiging Space to the Complex Buffer;");
//        SizeOfComplex_Buffer = 10;
//        ComplexBuffer = mspace_malloc(sdram_msp, 10*sizeof(ComplexBuffer));
//        if(ComplexBuffer == NULL)
//        {
//          print_dbg("\n\rAssign Failed;");
//          break;
//        }
//        for(i = 0; i < SizeOfComplex_Buffer; i++)
```

```
//          {
//            ComplexBuffer[i].imag = i;
//            ComplexBuffer[i].real = i;
//          }
//          for(i = 0; i < SizeOfComplex_Buffer; i ++)
//          {
//            print_dbg("\n\r");
//            print_dbg_ulong(ComplexBuffer[i].real);
//            print_dbg(" + j");
//            print_dbg_ulong(ComplexBuffer[i].imag);
//          }
//          print_dbg("\n\rFreeing Complex Buffer");
//          mspace_free(sdram_msp, ComplexBuffer);
//          SizeOfComplex_Buffer = 0;
//          break;

      default:
        print_dbg("\rCommand Not Recognised;");
        break;
    }
  }
}
```

D.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
                    };
```

D.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 16

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

D.1.1.4 dummy.c

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

```
"
    xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
    "
```

D.1.1.5 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;
```

```
int FFT1D(int *Signal);
int FFT2Dabs(int *Signal);
int log_2(int i);

int* 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! */;
#endif /* IMAGEPROCESSOR_H_ */
```

D.1.1.6 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;
  }
  while((i & 1) == 0) //while the bit isn't in the lowest bit (already
    established this is a integer power of 2)
  {
    i >>= 1;
    ret++;
  }

  return ret;
}
//One Dimensional Fast Fourier Transform
int FFT1D( int *Signal)
{
//  int size = 64;
  int log2Size, i =0;
//  double a;
//  log2Size = log_2(size);
//  if(log2Size & 1) //if it is an odd power of two
//    return 0;

  //am I making this all too complex for myself?! May just stick to defined
    size of 256.
//  A_ALIGNED dsp32_complex_t *vect1;
```

```
//  A_ALIGNED dsp32_t *vect2;

//  vect1 = mspace_malloc(sdram_msp, (sizeof(dsp32_complex_t) * size));
//  vect2 = mspace_malloc(sdram_msp, (sizeof(dsp32_t) * size));

  //Defined Sizes

  A_ALIGNED dsp16_complex_t vect1[FFT_SIZE];
  A_ALIGNED dsp16_t vect2[FFT_SIZE];
  for(i = 0; i < FFT_SIZE; i++)
  {
    vect2[i] = Signal[i];
  }
  dsp16_trans_realcomplexfft(vect1, vect2, log_2(FFT_SIZE));
  dsp16_vect_complex_abs(vect2, vect1, FFT_SIZE);
  for(i = 0; i < FFT_SIZE; i++)
  {
    Signal[i] = vect2[i] * FFT_SIZE;
  }
//  mspace_free(sdram_msp, vect1);
//  mspace_free(sdram_msp, vect2);
  return Signal;
}

int FFT2Dabs( int *Signal )
{
  int i, j = 0;
  int Ptr;
  Ptr = 0;
  A_ALIGNED dsp16_complex_t Input_C_1D[FFT_SIZE];
  A_ALIGNED dsp16_complex_t Result_C_1D[FFT_SIZE];
  A_ALIGNED dsp16_complex_t Result_C_2D[FFT_SIZE*FFT_SIZE];
  A_ALIGNED dsp16_t Input_R_1D[FFT_SIZE];

  //Stage 1 - FFT Real values from Signal. Store VERTICALLY in Result_2D
  for(i = 0; i < FFT_SIZE; i ++) //for each row
  {
//    print_dbg("\n\rInput to FFT: \n\r[");
    for(j = 0; j < FFT_SIZE; j++)
    {
      Input_R_1D[j] = Signal[Ptr++]; //copy the data across
//      print_dbg_ulong(Input_R_1D[j]);
//      print_dbg(", ");
    }
//    print_dbg("\b\b]");
    //Do the FFT
    dsp16_trans_realcomplexfft(Result_C_1D, Input_R_1D, log_2(FFT_SIZE));
    //Copy data into 2D reult TRANSPOSED
//    print_dbg("\n\rOutput of FFT:\n\r[");
    for(j = 0; j < FFT_SIZE; j++)
    {
      Result_C_2D[i + (j * FFT_SIZE)].imag = Result_C_1D[j].imag * FFT_SIZE;//
    scale back up
      Result_C_2D[i + (j * FFT_SIZE)].real = Result_C_1D[j].real * FFT_SIZE;
//      print_dbg_ulong(Result_C_2D[i + (j * FFT_SIZE)].real);
//      print_dbg(" + j");
//      print_dbg_ulong(Result_C_2D[i + (j * FFT_SIZE)].imag);
//      print_dbg(" , ");
```

```
    }
//    print_dbg("\b\b]");
  }
  //Stage 2 - FFT Complex Values from Result_2D, put back into Rows

  for(i = 0; i < FFT_SIZE; i++)//for each row
  {
//    print_dbg("\n\rInput to FFT: \n\r[");
    for(j = 0; j < FFT_SIZE; j++)//copy the data across
    {
      Input_C_1D[j].imag = Result_C_2D[j + i * FFT_SIZE].imag;
      Input_C_1D[j].real = Result_C_2D[j + i * FFT_SIZE].real;
//      print_dbg_ulong(Input_C_1D[j].real);
//      print_dbg(" + j");
//      print_dbg_ulong(Input_C_1D[j].imag);
//      print_dbg(" , ");
    }
//    print_dbg("\b\b]");
    //Do Fourier
    dsp16_trans_complexfft(Result_C_1D, Input_C_1D, log_2(FFT_SIZE));
    //Copy back

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

    for(j = 0; j < FFT_SIZE; j++)
    {
      Signal[i + (j*FFT_SIZE)] = Input_R_1D[j] * FFT_SIZE;
    }
  }
  return Signal;
}


//************************************
// Method:    FFT2DCOMPLEX
// FullName:  FFT2DCOMPLEX
// Access:    public
// Returns:   int*
// Qualifier:
// Parameter: int * Signal
// Parameter: A_ALIGNED dsp16_complex_t * ComplexBuffer
// Parameter: int size
//************************************
int* FFT2DCOMPLEX( int *Signal, dsp16_complex_t *ComplexBuffer, int size )
{
  int i, j = 0;
  int Ptr;
  Ptr = 0;
```

```
  A_ALIGNED dsp16_complex_t Input_C_1D[FFT_SIZE];
  A_ALIGNED dsp16_complex_t Result_C_1D[FFT_SIZE];
  A_ALIGNED dsp16_complex_t Result_C_2D[FFT_SIZE*FFT_SIZE];
  A_ALIGNED dsp16_t Input_R_1D[FFT_SIZE];


  //Stage 1 - FFT Real values from Signal. Store VERTICALLY in Result_2D
  for(i = 0; i < FFT_SIZE; i ++) //for each row
  {
    for(j = 0; j < FFT_SIZE; j++)
    {
      Input_R_1D[j] = Signal[Ptr++]; //copy the data across
    }

    //Do the FFT
    dsp16_trans_realcomplexfft(Result_C_1D, Input_R_1D, log_2(FFT_SIZE));
    //Copy data into 2D reult TRANSPOSED

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

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


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

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

    }

    //Do Fourier
    dsp16_trans_complexfft(Result_C_1D, Input_C_1D, log_2(FFT_SIZE));
    //Copy back


    //Calculate Abs and put back into Signal TRANSPOSED
    //dsp16_vect_complex_abs(Input_R_1D, Result_C_1D, FFT_SIZE);

    for(j = 0; j < FFT_SIZE; j++)
    {
      ComplexBuffer[i + j * FFT_SIZE].imag =  Result_C_1D[j].imag;
      ComplexBuffer[i + j * FFT_SIZE].real =  Result_C_1D[j].real;
      //Signal[i + (j*FFT_SIZE)] = Input_R_1D[j] * FFT_SIZE;
    }
  }

  return Signal;
}
```

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

  //print_dbg("\n\rPrepared Image Pointer = ");
  //print_dbg_ulong(PreparedImage);
  for(row = 0; row < 256; row ++)
  {
    for(col = 0; col < 256; col++)
    {
      if(row < 240)
        PreparedImage[row*256 + col] = Image->ImagePtr[row * 256 + col];
      else
        PreparedImage[row *256 + col] = 0;//Image->ImagePtr[(row - 240) * 256 + col + 32];
    }
  }

  mspace_free(sdram_msp, Image->ImagePtr); //free up the old image
  Image->ImagePtr = PreparedImage; //move the pointer to the prepared image
  Image->Height = 256;
  Image->Width = 256;
  //SaveBitmap(PreparedImage, 256, 256, "PreparedImage.bmp");
  //mspace_free(sdram_msp, PreparedImage);
  //return PreparedImage;
}


//************************************
// Method:    IFFT2D
// FullName:  IFFT2D
// Access:    public
// Returns:   void
// Qualifier:
// Parameter: dsp16_complex_t * Signal
//************************************
void IFFT2D (dsp16_complex_t *Signal) //Need to test this!
{
  int i, j = 0;
  int Ptr;
  Ptr = 0;
  A_ALIGNED dsp16_complex_t Input_C_1D[FFT_SIZE];
  A_ALIGNED dsp16_complex_t Result_C_1D[FFT_SIZE];
  A_ALIGNED dsp16_complex_t Result_C_2D[FFT_SIZE*FFT_SIZE];
  A_ALIGNED dsp16_t Input_R_1D[FFT_SIZE];


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

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

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

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


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

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

    }

    //Do Fourier
    dsp16_trans_complexifft(Result_C_1D, Input_C_1D, log_2(FFT_SIZE));
    //Copy back


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

    for(j = 0; j < FFT_SIZE; j++)
    {
      Signal[i + j * FFT_SIZE].imag =  Result_C_1D[j].imag;
      Signal[i + j * FFT_SIZE].real =  Result_C_1D[j].real;
      //Signal[i + (j*FFT_SIZE)] = Input_R_1D[j] * FFT_SIZE;
    }
  }

  //return Signal;
}

void ComplexMultiply(dsp16_complex_t *Result_Input1, dsp16_complex_t *Input2, int size)
{
  int i = 0;
  dsp16_complex_t c;
  for(i = 0; i < size; i++)
  {
    //(a+jb).(c+jd) = (ac - bd) + j(ad + bc)
    c.real = (Result_Input1[i].real * Input2[i].real) - (Result_Input1[i].imag * Input2[i].imag);
    c.imag = (Result_Input1[i].real * Input2[i].imag) + (Result_Input1[i].imag * Input2[i].real);
    Result_Input1[i].imag = c.imag;
```

```
      Result_Input1[i].real = c.real;
    }
  }
```

D.1.1.7 MotorDriver.h

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

```
/*
 * MotorDriver.h
 *
 * Created: 10/02/2013 18:11:55
 *  Author: hslovett
 */


#ifndef MOTORDRIVER_H_
#define MOTORDRIVER_H_
#include <asf.h>
//Definitions
#define MOTOR_L     ML_PWM_CHANNEL_ID
#define MOTOR_R   MR_PWM_CHANNEL_ID

#define FORWARD     2
#define BACKWARD    3
#define LEFT_SPOT   4
#define RIGHT_SPOT    5
#define SPOT_PIVOT    6
#define STOP      7


#define ENABLE_ACA_INTERRUPT    //{AVR32_ACIFA1.ier = 1;}
#define DISABLE_ACA_INTERRUPT   //{AVR32_ACIFA1.idr = 1;}
#define ENABLE_ACB_INTERRUPT    //{AVR32_ACIFA1.ier = 2;}
#define DISABLE_ACB_INTERRUPT   //{AVR32_ACIFA1.idr = 2;}
#define INTERRUPTS_PER_REVOLUTION 5 //Interrupts caused per full rotation of a
     wheel
#define CIRCUMFERENCE_WHEEL_MM    116 //in millimeters
#define CIRCUMFERENCE_WHEEL_CM    12 //in centimeters
#define MIN_RESOLUTION        CIRCUMFERENCE_WHEEL_CM /
    INTERRUPTS_PER_REVOLUTION
#define C_ROT_MM          276
#define ROTATION_CONST        (INTERRUPTS_PER_REVOLUTION * C_ROT_MM) / (
    CIRCUMFERENCE_WHEEL_MM * 360)
//Type Defs
typedef struct {
  int Left_State;
  int Right_State;
  int Left_Count;
  int Right_Count;
  } Motor_Control_t;

//Globals
pwm_opt_t pwm_opt;                // PWM option config.
```

```
avr32_pwm_channel_t pwm_channel;
Motor_Control_t Motor_Control;

void Motor_Init();
void Motor_Go();
void Analogue_Comparator_Init();
void Motor_Start(int Motors);
void Motors_Reset(void);
void Motor_Stop(int Motors);
bool Motors_Moving();
void Motors_Move(int centimetres_fwd)/*Move this amount forward in centimeters
     */;
void Motors_Execute();
void Motors_Rotate(int angle_degs);
/*static void ACInterruptHandler(void);*/
#endif /* MOTORDRIVER_H_ */
```

D.1.1.8 MotorDriver.c

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

```
/*
 * MotorDriver.c
 *
 * Created: 10/02/2013 18:12:07
 *  Author: hslovett
 */
#include <asf.h>
#include "CustomDevices/CustomDevices.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"*/



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_setup(  AVR32_SCIF_GCLK_PWM,
//          SCIF_GCCTRL_OSC0,
//          AVR32_SCIF_GC_NO_DIV_CLOCK,
//          0);
  // Now enable the generic clock
  scif_gc_enable(AVR32_SCIF_GCLK_PWM);
}
// #  define EXAMPLE_PWM_L_PIN             AVR32_PWM_PWML_0_1_PIN
// #  define EXAMPLE_PWM_L_FUNCTION        AVR32_PWM_PWML_0_1_FUNCTION
// #  define EXAMPLE_PWM_H_PIN             AVR32_PWM_PWMH_0_1_PIN
// #  define EXAMPLE_PWM_H_FUNCTION        AVR32_PWM_PWMH_0_1_FUNCTION
// #  define EXAMPLE_PWM_CHANNEL_ID        0
void Motor_Init()
{
  //Turn boths motors off
  ML_STANDBY;
  MR_STANDBY;

  ML_IN1_CLR;
  ML_IN2_CLR;

  MR_IN1_CLR;
  MR_IN2_CLR;

  Motor_Control.Left_Count = 0;
  Motor_Control.Right_Count = 0;
  Motor_Control.Left_State = STOP;
  Motor_Control.Right_State = STOP;

  avr32_pwm_channel_t pwm_channel = {{0}, // cmr
                        {0}, // cdty
                        {0}, // cdtyupd
                        {0}, // cprd
                        {0}, // cprdupd
                        {0}, // ccnt
```

```
                       {0}, // dt
                       {0}};// dtupd  ;  One channel config.
/*  unsigned int channel_id;*/

  // Start PLL for PWM
  local_start_highfreq_clock();
  // Start Enable Generic Clock with PLL as source clock
  pwm_start_gc();


//  gpio_enable_module_pin(EXAMPLE_PWM_L_PIN, EXAMPLE_PWM_L_FUNCTION);
//  gpio_enable_module_pin(EXAMPLE_PWM_H_PIN, EXAMPLE_PWM_H_FUNCTION);
//  gpio_enable_module_pin(M0_PWM_H_PIN, M0_PWM_H_FUNCTION);
//  gpio_enable_module_pin(AVR32_PIN_PB10, AVR32_PWM_PWMH_1_1_FUNCTION); // PWM1 Low
  gpio_enable_module_pin(ML_PWM_H_PIN, ML_PWM_H_FUNCTION);
  gpio_enable_module_pin(MR_PWM_H_PIN, MR_PWM_H_FUNCTION); //PWM1 Low
  //gpio_enable_module_pin(M1_PWM_H_PIN, M1_PWM_H_FUNCTION);
  // PWM controller configuration.
  pwm_opt.diva = AVR32_PWM_DIVA_CLK_OFF;
  pwm_opt.divb = AVR32_PWM_DIVB_CLK_OFF;
  pwm_opt.prea = AVR32_PWM_PREA_CCK;
  pwm_opt.preb = AVR32_PWM_PREB_CCK;

  pwm_opt.fault_detection_activated = false;
  pwm_opt.sync_channel_activated    = true;
  pwm_opt.sync_update_channel_mode  = PWM_SYNC_UPDATE_MANUAL_WRITE_MANUAL_UPDATE;
  pwm_opt.sync_channel_select[0]    = false;
  pwm_opt.sync_channel_select[1]    = false;
  pwm_opt.sync_channel_select[2]    = false;
  pwm_opt.sync_channel_select[3]    = false;
  pwm_opt.cksel                     = PWM_CKSEL_GCLK;
  pwm_init(&pwm_opt);

  // Update the period
  pwm_update_period_value(10);

  // Channel configuration
  pwm_channel.CMR.dte   = 0;        // Enable Deadtime for complementary Mode
  pwm_channel.CMR.dthi  = 0;        // Deadtime Inverted on PWMH
  pwm_channel.CMR.dtli  = 0;        // Deadtime Not Inverted on PWML
  pwm_channel.CMR.ces   = 0;        // 0/1 Channel Event at the End of PWM Period
  pwm_channel.CMR.calg  = PWM_MODE_LEFT_ALIGNED;       // Channel mode.
  pwm_channel.CMR.cpol  = PWM_POLARITY_HIGH;            // Channel polarity.
  pwm_channel.CMR.cpre  = AVR32_PWM_CPRE_CCK;           // Channel prescaler.
  pwm_channel.cdty      = 50;       // Channel duty cycle, should be < CPRD.
  pwm_channel.cprd      = 200;       // Channel period.

/*  channel_id = M0_PWM_CHANNEL_ID;*/
  pwm_channel_init(ML_PWM_CHANNEL_ID, &pwm_channel); // Set channel configuration to channel 0
  //pwm_start_channels((1 << channel_id));  // Start channel 0 & 1.
/*  channel_id = M1_PWM_CHANNEL_ID; */
  pwm_channel_init(MR_PWM_CHANNEL_ID, &pwm_channel); // Set channel configuration to channel 0
  //pwm_start_channels((1 << channel_id));  // Start channel 0 & 1.
```

```
  Analogue_Comparator_Init();
}
__attribute__((__interrupt__)) static void ACInterruptHandler(void)
{
  //print_dbg("\n\rACIFA Interrupt Entered.");
  acifa_clear_flags(&AVR32_ACIFA1, 3);

  if (acifa_is_acb_inp_higher(&AVR32_ACIFA1)) //LEFT MOTOR
  {
    LED5_CLR; //wheel not on white tab
  }
  else
  {
    LED5_SET;
    Motor_Control.Left_Count --;
    print_dbg("\n\rLeft Wheel Interrupt");
    DISABLE_ACB_INTERRUPT;
    //delay_ms(100);
  }

  if (acifa_is_aca_inp_higher(&AVR32_ACIFA1))
  {

    LED6_CLR;

  }
  else
  {
    LED6_SET;
    Motor_Control.Right_Count --;
    print_dbg("\n\rRight Wheel Interrupt");
    //delay_ms(100);
    DISABLE_ACA_INTERRUPT;
  }

  int temp = 0;
  if(Motor_Control.Left_Count <= 0) //if we have reached the end of the
    movement on left wheel
    temp |= MOTOR_L;

  if(Motor_Control.Right_Count <= 0)
    temp |= MOTOR_R;
  if(temp != 0)
    Motor_Stop(temp); //Stop the Motor
  //delay_ms(100);

}
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]));
  //Make it an interrupt
  Disable_global_interrupt();

  //INTC_init_interrupts();
  acifa_configure_hysteresis(&AVR32_ACIFA1, ACIFA_COMP_SELA, 2);
  acifa_configure(&AVR32_ACIFA1,
  ACIFA_COMP_SELA,
  POT0_AC1AP1_INPUT,
  SENSE0_AC1AN1_INPUT,
  FOSC0);

  acifa_configure_hysteresis(&AVR32_ACIFA1, ACIFA_COMP_SELB, 2);
  acifa_configure(&AVR32_ACIFA1,
  ACIFA_COMP_SELB,
  POT1_AC1BP1_INPUT,
  SENSE1_AC1BN1_INPUT,
  FOSC0);

  //    //Reset Wheels
  /*    Motor_Go(FORWARD);*/
  //M0_IN1_CLR;
  //    M1_IN1_CLR;
  //    while(acifa_is_aca_inp_higher(&AVR32_ACIFA1) == false)
  //      ;
  //    M0_IN1_CLR;
  //
  //    M1_IN1_SET;
  //    while(!acifa_is_acb_inp_higher(&AVR32_ACIFA1))
  //      ;
  //    M1_IN1_CLR;


  //Motor_Go(S)
  //acifa_enable_interrupt(&AVR32_ACIFA1, (1 << AVR32_ACIFA_ACBINT )| (1 <<
    AVR32_ACIFA_ACAINT));//Enable ACBINT and ACAINT
  ENABLE_ACA_INTERRUPT;
  ENABLE_ACB_INTERRUPT;
  AVR32_ACIFA1.ier = 3; //enable interrupts
  //acifa_enable_interrupt_toggle(&AVR32_ACIFA1, ACIFA_COMP_SELA);
  //acifa_enable_interrupt_toggle(&AVR32_ACIFA1, ACIFA_COMP_SELB);
  acifa_enable_interrupt_inp_lower(&AVR32_ACIFA1, ACIFA_COMP_SELA);
  acifa_enable_interrupt_inp_lower(&AVR32_ACIFA1, ACIFA_COMP_SELB);
  acifa_start(&AVR32_ACIFA1, (ACIFA_COMP_SELA|ACIFA_COMP_SELB));




  INTC_register_interrupt(&ACInterruptHandler,AVR32_ACIFA1_IRQ ,
    AVR32_INTC_INT0);

  Enable_global_interrupt();
}
void Motor_Start(int Motors)
{
  if(Motors & MOTOR_L)
  {
```

```
    if(Motor_Control.Left_State == FORWARD)
    {
      ML_IN1_SET;
      ML_IN2_CLR;
    }
    else if (Motor_Control.Left_State == BACKWARD)
    {
      ML_IN1_CLR;
      ML_IN2_SET;
    }
    else //Somethings gone wrong
    {
      ML_IN1_CLR;
      ML_IN2_CLR;
      return;//don't start any pwm channel
    }
    ML_GO;
    pwm_start_channels((1 << MOTOR_L)); //Start PWM Channel on M0 line
  }

  if(Motors & MOTOR_R)
  {
    if(Motor_Control.Right_State == FORWARD)
    {
      MR_IN1_SET;
      MR_IN2_CLR;
    }
    else if (Motor_Control.Right_State == BACKWARD)
    {
      MR_IN1_CLR;
      MR_IN2_SET;
    }
    else //Somethings gone wrong
    {
      MR_IN1_CLR;
      MR_IN2_CLR;
      return;//don't start any pwm channel
    }
    MR_GO;
    pwm_start_channels((1 << MOTOR_R));
  }
}
void Motors_Execute()
{
  while(Motors_Moving())
  {
    ENABLE_ACA_INTERRUPT;
    ENABLE_ACB_INTERRUPT;
    for(int i = 0; i < 750; i++)
    {
      delay_ms(1);
    }
  }
}
void Motor_Stop(int Motors)
{
  if(Motors & MOTOR_L)
  {
```

```
    ML_STANDBY;
    Motor_Control.Left_State = STOP;
    pwm_stop_channels((1 << MOTOR_L)); //Start PWM Channel on M0 line
  }

  if(Motors & MOTOR_R)
  {
    MR_STANDBY;
    Motor_Control.Right_State = STOP;
    pwm_stop_channels((1 << MOTOR_R));
  }
}
void Motors_Move(int centimetres_fwd)//Move this amount forward in centimeters
{
  //Calculate number of interrupts of each wheel
  int number_interrupts;
  if(centimetres_fwd > 0)
  {
    Motor_Control.Left_State = FORWARD;
    Motor_Control.Right_State = FORWARD;
  }
  else
  {
    centimetres_fwd = Abs(centimetres_fwd);
    Motor_Control.Left_State = BACKWARD;
    Motor_Control.Right_State = BACKWARD;
  }
  number_interrupts = (centimetres_fwd * (int)INTERRUPTS_PER_REVOLUTION) / (
    int)CIRCUMFERENCE_WHEEL_CM;
  print_dbg("\n\rNumber of interrupts to move = ");
  print_dbg_ulong(number_interrupts);

  Motor_Control.Left_Count = number_interrupts;
  Motor_Control.Right_Count = number_interrupts;
  Motor_Start(MOTOR_L | MOTOR_R);
  Motors_Execute();
}

void Motors_Reset(void)
{
  Motor_Control.Left_State = FORWARD;
  Motor_Control.Left_Count = 1;
  Motor_Control.Right_State = FORWARD;
  Motor_Control.Right_Count = 1;
  Motor_Start(MOTOR_L | MOTOR_R);
}

bool Motors_Moving()
{
//  if(Motor_Control.Left_State != STOP)
//  {
//    if(Motor_Control.Right_State != STOP)
//    {
//      return true;
//    }
//    else
//      return false;
//  }
```

```
//  else
//  {
//    return false;
//  }
  if(Motor_Control.Left_State != STOP) //Left is moving
  {
    return true;
  }
  else if (Motor_Control.Right_State != STOP) //Right is moving
  {
    return true;
  }
  else
  {
    return false;
  }
}


void Motors_Rotate(int angle_degs)
{
  int interrupts_to_move = 0;
  //calculate interrupts to move
  interrupts_to_move = angle_degs * ROTATION_CONST;
//  if(Pivot_Type == LEFT_SPOT)
//  {
//    //Right wheel moves
//    Motor_Control.Left_Count = 0;
//    Motor_Control.Left_State = STOP;
//    if(interrupts_to_move > 0)
//    {
//      Motor_Control.Right_State = FORWARD;
//    }
//    else
//    {
//      Motor_Control.Right_State = BACKWARD;
//    }
//    Motor_Control.Right_Count = Abs(interrupts_to_move);
//  }
//  else if (Pivot_Type == RIGHT_SPOT)
//  {
//    //Left Wheel Moves
//    Motor_Control.Right_Count = 0;
//    Motor_Control.Right_State = STOP;
//    if(interrupts_to_move > 0)
//    {
//      Motor_Control.Left_State = FORWARD;
//    }
//    else
//    {
//      Motor_Control.Left_State = BACKWARD;
//    }
//    Motor_Control.Left_Count = Abs(interrupts_to_move);
//  }
//  else if (Pivot_Type == SPOT_PIVOT)
//  {
    //Both Wheels Move
    if(interrupts_to_move > 0)
```

```
    {
      Motor_Control.Left_State = FORWARD;
      Motor_Control.Right_State = BACKWARD;
    }
    else
    {
      Motor_Control.Right_State = FORWARD;
      Motor_Control.Left_State = BACKWARD;
    }
    Motor_Control.Left_Count = Abs(interrupts_to_move);
    Motor_Control.Right_Count = Abs(interrupts_to_move);
    Motor_Start(MOTOR_L | MOTOR_R);
//  }
}
```

D.1.1.9 OV7670.h

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

```
/*
 * OV7670.h
 *
 * Created: 15/02/2013 13:12:00
 *  Author: hslovett
 */


#ifndef OV7670_H_
#define OV7670_H_
#include <asf.h>
//////////////////////////////////////////////////////////////////////////
//  Constants
//////////////////////////////////////////////////////////////////////////
#define HEIGHT        240
#define WIDTH       320
#define PIXELSIZE     2
#define SETTINGS_LENGTH   167
#define OV7670_ADDR     0x21

#define CAMERA_LEFT     1
#define CAMERA_RIGHT    2

#define CAMERA_LEFT_ERR   0x10
#define CAMERA_RIGHT_ERR  0x20

#define BMPHEADERSIZE 14
#define DIBHEADERSIZE 124 //v5
#define FILESIZE 153738
//////////////////////////////////////////////////////////////////////////
//  Globals
//////////////////////////////////////////////////////////////////////////
const char default_settings[SETTINGS_LENGTH][2];
const uint8_t DIBHead[DIBHEADERSIZE];
const uint8_t BMPHeader[BMPHEADERSIZE];
```

```
typedef struct {
  uint8_t Status;
  bool Camera_0_Found;
  bool Camera_1_Found;
  bool Camera_0_Error;
  bool Camera_1_Error;
  uint8_t VSYNC0_State;
  uint8_t VSYNC1_State;
  } OV7670_t ;

OV7670_t OV7670_Status;

#define IDLE       0
#define TAKE_PHOTO    1
#define TAKING_PHOTO  2
#define TAKEN_PHOTO   3
#define CAMERAS_BUSY  4

#define Image0Name  "Image_L_%d.bmp"
#define Image1Name  "Image_R_%d.bmp"
///////////////////////////////////////////////////////////////////////////
//  Methods
///////////////////////////////////////////////////////////////////////////
void OV7670_Init(void);             //Initialises Camera
void FIFO_Init();
int TakePhoto(uint8_t Cameras);
bool Photos_Ready(void);
void Store_Image_0();
void Store_Image_1();
void FIFO_Reset(uint8_t CameraID);
bool Store_Both_Images();
//void FIFO_Reset(uint8_t CameraID);
///////////////////////////////////////////////////////////////////////////
//  Pins & Macros
///////////////////////////////////////////////////////////////////////////
#define FIFO_0_RCLK   AVR32_PIN_PA19
#define FIFO_0_nRRST  AVR32_PIN_PA15
#define FIFO_0_WEN    AVR32_PIN_PA20
#define FIFO_0_WRST   AVR32_PIN_PA21
#define FIFO_0_nOE    AVR32_PIN_PA28
#define FIFO_0_VSYNC  AVR32_PIN_PA29

#define FIFO_1_RCLK   AVR32_PIN_PA23
#define FIFO_1_nRRST  AVR32_PIN_PA22
#define FIFO_1_WEN    AVR32_PIN_PA24
#define FIFO_1_WRST   AVR32_PIN_PA25
#define FIFO_1_nOE    AVR32_PIN_PA27

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

#define VSYNC_0_PIN         AVR32_EIC_EXTINT_4_0_PIN
#define VSYNC_0_FUNCTION      AVR32_EIC_EXTINT_4_0_FUNCTION
```

```c
#define VSYNC_0_LINE        4
#define VSYNC_0_ENABLE_INTERRUPT  {eic_enable_interrupt_line(&AVR32_EIC, VSYNC_0_LINE);}
#define VSYNC_0_DISABLE_INTERRUPT {eic_disable_interrupt_line(&AVR32_EIC, VSYNC_0_LINE);}


#define FIFO_0_RCLK_SET   {gpio_set_gpio_pin(FIFO_0_RCLK);}
#define FIFO_0_nRRST_SET  {gpio_set_gpio_pin(FIFO_0_nRRST);}
#define FIFO_0_WEN_SET    {gpio_set_gpio_pin(FIFO_0_WEN);}
#define FIFO_0_WRST_SET   {gpio_set_gpio_pin(FIFO_0_WRST);}
#define FIFO_0_nOE_SET    {gpio_set_gpio_pin(FIFO_0_nOE);}

#define FIFO_0_RCLK_CLR   {gpio_clr_gpio_pin(FIFO_0_RCLK);}
#define FIFO_0_nRRST_CLR  {gpio_clr_gpio_pin(FIFO_0_nRRST);}
#define FIFO_0_WEN_CLR    {gpio_clr_gpio_pin(FIFO_0_WEN);}
#define FIFO_0_WRST_CLR   {gpio_clr_gpio_pin(FIFO_0_WRST);}
#define FIFO_0_nOE_CLR    {gpio_clr_gpio_pin(FIFO_0_nOE);}



#define FIFO_1_RCLK_SET   {gpio_set_gpio_pin(FIFO_1_RCLK);}
#define FIFO_1_nRRST_SET  {gpio_set_gpio_pin(FIFO_1_nRRST);}
#define FIFO_1_WEN_SET    {gpio_set_gpio_pin(FIFO_1_WEN);}
#define FIFO_1_WRST_SET   {gpio_set_gpio_pin(FIFO_1_WRST);}
#define FIFO_1_nOE_SET    {gpio_set_gpio_pin(FIFO_1_nOE);}

#define FIFO_1_RCLK_CLR   {gpio_clr_gpio_pin(FIFO_1_RCLK);}
#define FIFO_1_nRRST_CLR  {gpio_clr_gpio_pin(FIFO_1_nRRST);}
#define FIFO_1_WEN_CLR    {gpio_clr_gpio_pin(FIFO_1_WEN);}
#define FIFO_1_WRST_CLR   {gpio_clr_gpio_pin(FIFO_1_WRST);}
#define FIFO_1_nOE_CLR    {gpio_clr_gpio_pin(FIFO_1_nOE);}


#define CAMERA_INPUT  {(uint8_t)((AVR32_GPIO.port[1].pvr) & 0xFF);}
///////////////////////////////////////////////////////////////////////////
//Camera Register Address definitions
///////////////////////////////////////////////////////////////////////////
#define OV_GAIN     0x00  //Gain Control Setting - ACG[7:0]
#define OV_BLUE     0x01  //Blue Channel Gain
#define OV_RED      0x02  //Red Channel Gain
#define OV_VREF     0x03  //Vertical Frame Control & ACG[9:8]
#define OV_COM1     0x04  //CCIR656 enable, AEC low bits (AECHH, AECH)
#define OV_BAVE     0x05  //U/B Average level - AUTO UPDATED
#define OV_GbAVE    0x06  //Y/Gb Average Level - AUTO UPDATED
#define OV_AECHH    0x07  //Exposure value [15:10] (AECH, COM1)
#define OV_RAVE     0x08  //V/R Average level - AUTO UPDATED
#define OV_COM2     0x09  //Soft Sleep, Output drive capability
#define OV_PID      0x0A  //Product ID MSB  Read only
#define OV_VER      0x0B  //Product ID LSB  Read Only
#define OV_COM3     0x0C  //Output data MSB/LSB swap + other stuff
#define OV_COM4     0x0D  //Average values - MUST BE SAME AS COM17
#define OV_COM5     0x0E  //RESERVED
#define OV_COM6     0x0F  //COM6
#define OV_AECH     0x10  //Exposure value [9:2] (see AECHH, COM1)
#define OV_CLKRC    0x11  //Internal Clock options
#define OV_COM7     0x12  //RESET, Output format
#define OV_COM8     0x13  //Common control 8
```

```
#define OV_COM9     0x14  //Automatic Gain Ceiling
#define OV_COM10    0x15  //PCLK, HREF and VSYNC options
#define OV_RSVD     0x16  //RESERVED
#define OV_HSTART   0x17  //Output format Horizontal Frame start
#define OV_HSTOP    0x18  //Output format Horizontal Frame end
#define OV_VSTRT    0x19  //Output format Vertical Frame start
#define OV_VSTOP    0x1A  //Output format Vertical Frame Stop
#define OV_PSHFT    0x1B  //Pixel Delay Select
#define OV_MIDH     0x1C  //Manufacturer ID MSB -  READ ONLY
#define OV_MIDL     0x1D  //Manufacturer ID LSB -  READ ONLY
#define OV_MVFP     0x1E  //Mirror / VFlip Enable
#define OV_LAEC     0x1F  //RESERVED
#define OV_ADCCTR0    0x20  //ADC Control
#define OV_ADCCTR1    0x21  //RESERVED
#define OV_ADCCTR2    0x22  //RESERVED
#define OV_ADCCTR3    0x23  //RESERVED
#define OV_AEW      0x24  //ACG/AEC Stable Operating Region Upper Limit
#define OV_AEB      0x25  //ACG/AEC Stable Operation Region Lower Limit
#define OV_VPT      0x26  //ACG/AEC Fast Mode Operation Region
#define OV_BBIAS    0x27  //B Channel Signal Output Bias
#define OV_GbBIAS   0x28  //Gb Channel Output Bias
#define OV_RSVD1    0x29  //RESERVED
#define OV_EXHCH    0x2A  //Dummy Pixel Insert MSB
#define OV_EXHCL    0x2B  //Dummy Pixel Insert LSB
#define OV_RBIAS    0x2C  //R Channel Signal Output Bias
#define OV_ADVFL    0x2D  //LSB of insert dummy line in vertical direction
#define OV_ADVFH    0x2E  //MSB of insert dummy line in vertical direction
#define OV_YAVE     0x2F  //Y/G Channel Average Value
#define OV_HSYST    0x30  //HSYNC Rising Edge Delay (low 8 bits)
#define OV_HSYEN    0x31  //HSYNCE Falling Edge Delay (low 8 bits)
#define OV_HREF     0x32  //HREF Control
#define OV_CHLF     0x33  //Array Current Control - RESERVED
#define OV_ARBLM    0x34  //Array Reference Control - RESERVED
#define OV_RSVD2    0x35  //RESERVED
#define OV_RSVD3    0x36  //RESERVED
#define OV_ADCCTRL    0x37  //ADC Control - RESERVED
#define OV_ACOM     0x38  //ADC and Analog Common Mode Control - RESERVED
#define OV_OFON     0x39  //ADC Offset Control
#define OV_TSLB     0x3A  //Line Buffer Test Option
#define OV_COM11    0x3B  //COM11
#define OV_COM12    0x3C  //COM12
#define OV_COM13    0x3D  //COM13
#define OV_COM14    0x3E  //COM14
#define OV_EDGE     0x3F  //Edge Detection Adjustment
#define OV_COM15    0x40  //COM15
#define OV_COM16    0x41  //COM16
#define OV_COM17    0x42  //COM17
#define OV_AWBC1    0x43
#define OV_AWBC2    0x44
#define OV_AWBC3    0x45
#define OV_AWBC4    0x46
#define OV_AWBC5    0x47
#define OV_AWBC6    0x48
#define OV_RSVD4    0x49
#define OV_RSVD5    0x40
#define OV_RSVD6    0x4A
#define OV_REG4B    0x4B
#define OV_DNSTH    0x4C
```

```
#define OV_RSVD7    0x4D
#define OV_RSVD8    0x4E
#define OV_MTX1     0x4F
#define OV_MTX2     0x50
#define OV_MTX3     0x51
#define OV_MTX4     0x52
#define OV_MTX5     0x53
#define OV_MTX6     0x54
#define OV_BRIGHT   0x55
#define OV_CONTRAS    0x56
#define OV_CONTRASCNTR  0x57
#define OV_MTXS     0x58
#define OV_RSVD9    0x59
#define OV_RSVD9_1    0x5A
#define OV_RSVD9_2    0x5B
#define OV_RSVD9_3    0x5C
#define OV_RSVD9_4    0x5D
#define OV_RSVD9_5    0x5E
#define OV_RSVD9_6    0x5F
#define OV_RSVD10   0x60
#define OV_RSVD11   0x61
#define OV_LCC1     0x62
#define OV_LCC2     0x63
#define OV_LCC3     0x64
#define OV_LCC4     0x65
#define OV_LCC5     0x66
#define OV_MANU     0x67
#define OV_MANV     0x68
#define OV_GFIX     0x69
#define OV_GGAIN    0x6A
#define OV_DBLV     0x6B
#define OV_AWBCTR3    0x6C
#define OV_AWBCTR2    0x6D
#define OV_AWBCTR1    0x6E
#define OV_AWBCTR0    0x6F
#define OV_SCALING_XSC  0x70
#define OV_SCALING_YSC  0x71
#define OV_SCALING_DCWCTR 0x72
#define OV_SCALING_PCLK_DIV 0x73
#define OV_REG74    0x74
#define OV_REG75    0x75
#define OV_REG76    0x76
#define OV_REG77    0x77
#define OV_RSVD12   0x78
#define OV_RSVD13   0x79
#define OV_GAM1     0x7A
#define OV_GAM2     0x7B
#define OV_GAM3     0x7C
#define OV_GAM4     0x7D
#define OV_GAM5     0x7E
#define OV_GAM6     0x7F
#define OV_GAM7     0x80
#define OV_GAM8     0x81
#define OV_GAM9     0x82
#define OV_GAM10    0x83
#define OV_GAM11    0x84
#define OV_GAM12    0x85
#define OV_GAM13    0x86
```

```
#define OV_GAM14    0x87
#define OV_GAM15    0x88
#define OV_GAM16    0x89
#define OV_RSVD14   0x8A
#define OV_RSVD15   0x8B
#define OV_RSVD16   0x8C
#define OV_RSVD17   0x8D
#define OV_RSVD18   0x8E
#define OV_RSVD19   0x8F
#define OV_RSVD20   0x90
#define OV_RSVD21   0x91
#define OV_DM_LNL   0x92
#define OV_DM_LNH   0x93
#define OV_LCC6     0x94
#define OV_LCC7     0x95
#define OV_RSVD22   0x96
#define OV_RSVD23   0x97
#define OV_RSVD24   0x98
#define OV_RSVD25   0x99
#define OV_RSVD26   0x9A
#define OV_RSVD27   0x9B
#define OV_RSVD28   0x9C
#define OV_BD50ST   0x9D
#define OV_BD60ST   0x9E
#define OV_HIST0    0x9F
#define OV_HIST1    0xA0
#define OV_HIST2    0xA1
#define OV_HIST3    0xA2
#define OV_HIST4    0xA3
#define OV_HIST5    0xA4
#define OV_HIST6    0xA5
#define OV_HIST7    0xA6
#define OV_HIST8    0xA7
#define OV_HIST9    0xA8
#define OV_HIST10   0xA9
#define OV_HIST11   0xAA
#define OV_HIST12   0xAB
#define OV_STR_OPT    0xAC
#define OV_STR_R    0xAD
#define OV_STR_G    0xAE
#define OV_STR_B    0xAF
#define OV_RSVD28_1   0xB0
#define OV_RSVD29   0xB1
#define OV_RSVD30   0xB2
#define OV_THL_ST   0xB3
#define OV_RSVD31   0xB4
#define OV_THL_DLT    0xB5
#define OV_RSVD32   0xB6
#define OV_RSVD33   0xB7
#define OV_RSVD34   0xB8
#define OV_RSVD35   0xB9
#define OV_RSVD36   0xBA
#define OV_RSVD37   0xBB
#define OV_RSVD38   0xBC
#define OV_RSVD39   0xBD
#define OV_AD_CHB   0xBE
#define OV_AD_CHR   0xBF
#define OV_AD_CHGb    0xC0
```

```
#define OV_AD_CHGr     0xC1
#define OV_RSVD40    0xC2
#define OV_RSVD41    0xC3
#define OV_RSVD42    0xC4
#define OV_RSVD43    0xC5
#define OV_RSVD44    0xC6
#define OV_RSVD45    0xC7
#define OV_RSVD46    0xC8
#define OV_SATCTR    0xC9



#endif /* OV7670_H_ */
```

D.1.1.10 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;
  }
}

__attribute__((__interrupt__)) static void VSYNC1_Handler (void)
{
  //print_dbg("\n\rVSYNC1 Detected!");
  eic_clear_interrupt_line(&AVR32_EIC, VSYNC_1_LINE);
  //VSYNC_1_DISABLE_INTERRUPT;
    switch(OV7670_Status.VSYNC1_State)
    {
      case(TAKE_PHOTO):
      FIFO_1_WEN_SET;
      OV7670_Status.VSYNC1_State = TAKING_PHOTO;
      //print_dbg("\n\rCase: Take Photo;");
      break;

      case(TAKING_PHOTO):
      FIFO_1_WEN_CLR;
      OV7670_Status.VSYNC1_State = TAKEN_PHOTO;
      //print_dbg("\n\rCase: Taking Photo;");
      break;

      case (TAKEN_PHOTO):
      FIFO_1_WEN_CLR;
      //print_dbg("\n\rCase: Taken Photo;");
      break;

      case(IDLE):
      default:
      VSYNC_1_DISABLE_INTERRUPT;
      FIFO_1_WEN_CLR;
      OV7670_Status.VSYNC1_State = IDLE;
      //print_dbg("\n\rCase: Idle;");
      break;
    }
}
unsigned char Write_Reg(unsigned char Register, unsigned char Data)
{
  /*  I2C Traffic Generated:
   *  S | OV_7670 + W | A | RegID | A | Data | A | P |
   */
  uint8_t Buff[2] = {Register, Data};
  int status = twim_write(&AVR32_TWIM0, &Buff, 2, OV7670_ADDR, false);
  return status;
}
unsigned char Read_Reg(unsigned char Register, unsigned char *Data)
```

```
{
  /*  I2C Traffic Generated:
   *  S | OV_ADDR + W | A | RegID | A | P |
   *  S | OV_ADDR + R | A | Data  |~A | P |
   */
  unsigned char Buff[2] = {Register, 0};
  int status = twim_write(&AVR32_TWIM0, &Buff, 1, OV7670_ADDR, false);
  if(status != STATUS_OK)
    return status;

  status = twim_read(&AVR32_TWIM0, &Buff, 1, OV7670_ADDR, false);
  *Data = Buff[0];

  return status;

}
void OV7670_Init()
{

  //Check Cameras Exist
  PCA9542A_Chan_Sel(I2C_CHANNEL_0);
  if (twim_probe(&AVR32_TWIM0, OV7670_ADDR) == STATUS_OK)
    OV7670_Status.Camera_0_Found = true;
  else
    OV7670_Status.Camera_0_Found = false;

  PCA9542A_Chan_Sel(I2C_CHANNEL_1);
  if (twim_probe(&AVR32_TWIM0, OV7670_ADDR) == STATUS_OK)
    OV7670_Status.Camera_1_Found = true;
  else
    OV7670_Status.Camera_1_Found = false;


  //Iniialise Cameras
  if(OV7670_Status.Camera_0_Found)
  {
    PCA9542A_Chan_Sel(I2C_CHANNEL_0);
    //Reset Camera
    if(STATUS_OK != Write_Reg(OV_COM7, 0x80))
    {
      print_dbg("\n\rCamera Reset Fail");
      OV7670_Status.Camera_0_Error = true;
      OV7670_Status.Status = ERR_DEVICE;
      //return FAIL;
    }
    delay_ms(10); //wait for Camera to reset
    for (int i = 0; i < SETTINGS_LENGTH; i++)
    {
      if(STATUS_OK != Write_Reg(default_settings[i][0], default_settings[i][1]))
      {
        print_dbg("\n\rCamera Initialise Fail");
        //return FAIL;
        OV7670_Status.Camera_0_Error = true;
        OV7670_Status.Status = ERR_DEVICE;
        break;
      }
      delay_ms(1);
```

```
      }
    }
    if(OV7670_Status.Camera_1_Found)
    {
      PCA9542A_Chan_Sel(I2C_CHANNEL_1);

      //Reset Camera
      if(STATUS_OK != Write_Reg(OV_COM7, 0x80))
      {
        print_dbg("\n\rCamera Reset Fail");
        OV7670_Status.Camera_1_Error = true;
        OV7670_Status.Status = ERR_DEVICE;
        //return FAIL;
      }
      delay_ms(10); //wait for Camera to reset
      for (int i = 0; i < SETTINGS_LENGTH; i++)
      {
        if(STATUS_OK != Write_Reg(default_settings[i][0], default_settings[i
      ][1]))
        {
          print_dbg("\n\rCamera Initialise Fail");
          //return FAIL;
          OV7670_Status.Camera_1_Error = true;
          OV7670_Status.Status = ERR_DEVICE;
          break;
        }
        delay_ms(1);
      }
    }
    PCA9542A_Chan_Sel(NO_SELECT);

    //Initialise VSYNC Interrupts
    eic_options_t eic_options;
    eic_options.eic_mode = EIC_MODE_EDGE_TRIGGERED;
    eic_options.eic_edge = EIC_EDGE_FALLING_EDGE;
    eic_options.eic_async = EIC_SYNCH_MODE;
    eic_options.eic_line = VSYNC_1_LINE;
    //eic_options.eic_line = VSYNC_0_LINE;

    Disable_global_interrupt();
    gpio_enable_module_pin(VSYNC_1_PIN, VSYNC_1_FUNCTION);
    gpio_enable_module_pin(VSYNC_0_PIN, VSYNC_0_FUNCTION);

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

    INTC_register_interrupt(&VSYNC1_Handler, AVR32_EIC_IRQ_1, AVR32_INTC_INT0);
    INTC_register_interrupt(&VSYNC0_Handler, AVR32_EIC_IRQ_4, AVR32_INTC_INT0);
    //Enable interrupt on VSYNC1
    eic_enable_line(&AVR32_EIC, VSYNC_1_LINE);
    eic_enable_line(&AVR32_EIC, (VSYNC_0_LINE));
    VSYNC_1_ENABLE_INTERRUPT;
    VSYNC_0_ENABLE_INTERRUPT;
```

```
  FIFO_Init();
  Enable_global_interrupt();

}
void FIFO_Init()
{
  //Disable both outputs
  FIFO_0_nOE_SET
  FIFO_1_nOE_SET

  //Reset Buffer 0
  FIFO_0_WRST_CLR;
  FIFO_0_RCLK_CLR;
  FIFO_0_nRRST_SET;
  FIFO_0_WEN_CLR;
  delay_us(10);
  FIFO_0_RCLK_SET;
  delay_us(10);
  FIFO_0_RCLK_CLR;
  FIFO_0_nRRST_CLR;
  delay_us(10);
  FIFO_0_RCLK_SET;
  delay_us(10);
  FIFO_0_RCLK_CLR;
  FIFO_0_nRRST_SET;
  delay_us(10);
  FIFO_0_WRST_SET;

  //Reset Buffer 1
  FIFO_1_WRST_CLR;
  FIFO_1_RCLK_CLR;
  FIFO_1_nRRST_SET;
  FIFO_1_WEN_CLR;
  delay_us(10);
  FIFO_1_RCLK_SET;
  delay_us(10);
  FIFO_0_RCLK_CLR;
  FIFO_1_nRRST_CLR;
  delay_us(10);
  FIFO_1_RCLK_SET;
  delay_us(10);
  FIFO_1_RCLK_CLR;
  FIFO_1_nRRST_SET;
  delay_us(10);
  FIFO_1_WRST_SET;
}

void FIFO_Reset(uint8_t CameraID)
{
  FIFO_0_nOE_SET;
  FIFO_1_nOE_SET;
  if(CameraID & CAMERA_LEFT)
  {
    FIFO_0_WRST_CLR;
    FIFO_0_nRRST_CLR;
    FIFO_0_RCLK_SET;
    delay_us(10);
```

```
    FIFO_0_RCLK_CLR;
    FIFO_0_nRRST_SET;
    FIFO_0_WRST_SET;
  }
  if(CameraID & CAMERA_RIGHT)
  {
    FIFO_1_WRST_CLR;
    FIFO_1_nRRST_CLR;
    FIFO_1_RCLK_SET;
    delay_us(10);
    FIFO_1_RCLK_CLR;
    FIFO_1_nRRST_SET;
    FIFO_1_WRST_SET;
  }

}

int TakePhoto(uint8_t Cameras)
{

  //Only want to take pictures on cameras found
  if(((OV7670_Status.VSYNC0_State != IDLE) || !OV7670_Status.Camera_0_Found)
    && ((OV7670_Status.VSYNC1_State != IDLE) || !OV7670_Status.Camera_1_Found)
    )
    return CAMERAS_BUSY; //wait for cameras to be idle if they are found

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

  if(Cameras & CAMERA_RIGHT)
    OV7670_Status.VSYNC1_State = TAKE_PHOTO;
  eic_clear_interrupt_line(&AVR32_EIC, VSYNC_1_LINE);
  eic_clear_interrupt_line(&AVR32_EIC, VSYNC_0_LINE);
  VSYNC_0_ENABLE_INTERRUPT;
  VSYNC_1_ENABLE_INTERRUPT;

  return TAKING_PHOTO;

}

bool Photos_Ready(void)
{
  int status = 0;
  if(OV7670_Status.Camera_0_Found == true) //If camera is there
  {
    if(OV7670_Status.Camera_0_Error == false)//and has no errors
    {
      if(OV7670_Status.VSYNC0_State == TAKEN_PHOTO)
      {
        status |= 1; //camera0 has taken photo
      }
    }
    else
      status |= 1;
  }
  else
    status |= 1;
```

```
    if(OV7670_Status.Camera_1_Found == true) //If camera is there
    {
      if(OV7670_Status.Camera_1_Error == false)//and has no errors
      {
        if(OV7670_Status.VSYNC1_State == TAKEN_PHOTO)
        {
          status |= 1; //camera0 has taken photo
        }
      }
      else
      status |= 1;
    }
    else
      status |= 1;

    if(status)
      return true;
    else
      return false;
}



bool Store_Both_Images()
{
    if(Photos_Ready() == false)
      return false;

    Store_Image_1();
    FIFO_Reset(CAMERA_RIGHT);

    Store_Image_0();
    FIFO_Reset(CAMERA_LEFT);

    OV7670_Status.VSYNC0_State = IDLE;
    OV7670_Status.VSYNC1_State = IDLE;
    return true;
}
// void Store_Image_0()
// {
//   int i,j;
//   //Image0
//   //make file
//   //delete file if it exits already
//   char Filename_buff[15];
//   i = 0;
//   while(1)
//   {
//     nav_filelist_reset();
//     sprintf(&Filename_buff, Image0Name, i++);
//     if(nav_filelist_findname((FS_STRING)Filename_buff, false))
//     {
//       //nav_setcwd((FS_STRING)Image0Name, true, false);
// //        print_dbg("\n\r File Exists");
// //        print_dbg(&Filename_buff);
//       //nav_file_del(false);
//     }
//     else
```

```
//    {
//      break;
//    }
//  }
//  nav_file_create((FS_STRING)Filename_buff);//create file
//
//  file_open(FOPEN_MODE_W);
//  //write bitmap headers
//  file_write_buf(BMPHeader, BMPHEADERSIZE);
//  file_write_buf(DIBHead, DIBHEADERSIZE);
//
//  //read and write image data
//  //Image0
//  //reset read pointer
//  FIFO_0_nRRST_CLR;
//  FIFO_0_RCLK_SET;
//
//  FIFO_0_RCLK_CLR;
//  FIFO_0_nRRST_SET;
//  delay_us(10);
//  //enable output
//  FIFO_0_nOE_CLR;
//  uint8_t buffer[WIDTH * 2];
//
//  for(j = 0; j < HEIGHT; j++)
//  {
//    for(i = 0; i < WIDTH*2; i+=2)
//    {
//      FIFO_0_RCLK_SET;
//      delay_us(10);
//      buffer[i+1] = ((AVR32_GPIO.port[1].pvr) & 0xFF);//CAMERA_INPUT;
//      delay_us(10);
//      FIFO_0_RCLK_CLR;
//      delay_us(10);
//      FIFO_0_RCLK_SET;
//      delay_us(10);
//      buffer[i] = ((AVR32_GPIO.port[1].pvr) & 0xFF);//CAMERA_INPUT;
//      delay_us(10);
//      FIFO_0_RCLK_CLR;
//      delay_us(10);
//    }
//    file_write_buf(&buffer, WIDTH * 2);
//  }
//  FIFO_0_nOE_SET;
//  file_close();
//
//
// }

// void Store_Image_1()
// {
//  int i, j;
//  uint8_t buffer[WIDTH * 2];
//  char Filename_buff[15];
//    //uint8_t *Buffer_ram;
//    //Buffer_ram = mspace_malloc(sdram_msp, WIDTH * 2);
// //    if(Buffer_ram == NULL)
// //    {
```

```
// //      print_dbg("\n\rBuffer allocation fail.\n\r");
// //      return;
// //    }
//  i = 0;
//  //make file
//  //delete file if it exits already
//  nav_filelist_reset();
//  while(1)
//  {
//    sprintf(&Filename_buff, Image1Name, i++);
//    if(nav_filelist_findname((FS_STRING)Filename_buff, false))
//    {
//      //nav_setcwd((FS_STRING)Image1Name, true, false);
//      //print_dbg("\n\rImage1.bmp File Exists");
//      //nav_file_del(false);
//    }
//    else
//    {
//      break;
//    }
//  }
//  nav_file_create((FS_STRING)Filename_buff);//create file
//  file_open(FOPEN_MODE_W);
//  //write bitmap headers
//  file_write_buf(BMPHeader, BMPHEADERSIZE);
//  file_write_buf(DIBHead, DIBHEADERSIZE);
//  //Image1
//  //reset read pointer
//  FIFO_1_nRRST_CLR;
//
//  FIFO_1_RCLK_SET;
//  delay_us(10);
//  FIFO_1_RCLK_CLR;
//  FIFO_1_nRRST_SET;
//
//  //enable output
//  FIFO_1_nOE_CLR;
// // uint8_t buffer[WIDTH * 2];
//
//  for(j = 0; j < HEIGHT; j++)
//  {
//    for(i = 0; i < WIDTH*2; i+=2)
//    {
//      FIFO_1_RCLK_SET;
//      delay_us(10);
//      buffer[i+1] = ((AVR32_GPIO.port[1].pvr) & 0xFF);//CAMERA_INPUT;
//      delay_us(10);
//      FIFO_1_RCLK_CLR;
//      delay_us(10);
//      FIFO_1_RCLK_SET;
//      delay_us(10);
//      buffer[i] = ((AVR32_GPIO.port[1].pvr) & 0xFF);//CAMERA_INPUT;
//      delay_us(10);
//      FIFO_1_RCLK_CLR;
//      delay_us(10);
//    }
//    file_write_buf(&buffer, WIDTH * 2);
//  }
```

```
//
//  FIFO_1_nOE_SET;//disable output
//  file_close();
//  //mspace_free(sdram_msp, Buffer_ram);
// /* mspace_free(sdram_msp, Buffer_ram);*/
// }

void Store_Image_1()
{
  int i, j;
  //uint8_t buffer[WIDTH * 2];
  char Filename_buff[15];
  uint8_t *Buffer_ram;
  Buffer_ram = mspace_malloc(sdram_msp, HEIGHT * WIDTH * 2);
  i = 0;
  //make file
  //delete file if it exits already
  nav_filelist_reset();
  while(1)
  {
    sprintf(&Filename_buff, Image1Name, i++);
    if(nav_filelist_findname((FS_STRING)Filename_buff, false))
    {
      ;
    }
    else
    {
      break;
    }
  }

  //Image1
  //reset read pointer
  FIFO_1_nRRST_CLR;

  FIFO_1_RCLK_SET;
  delay_us(10);
  FIFO_1_RCLK_CLR;
  FIFO_1_nRRST_SET;

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

  for(j = 0; j < HEIGHT * WIDTH * 2; j+= 2)
  {
    FIFO_1_RCLK_SET;
    delay_us(10);
    Buffer_ram[j+1] = ((AVR32_GPIO.port[1].pvr) & 0xFF);//CAMERA_INPUT;
    delay_us(10);
    FIFO_1_RCLK_CLR;
    delay_us(10);
    FIFO_1_RCLK_SET;
    delay_us(10);
    Buffer_ram[j] = ((AVR32_GPIO.port[1].pvr) & 0xFF);//CAMERA_INPUT;
    delay_us(10);
    FIFO_1_RCLK_CLR;
    delay_us(10);
```

```
  }

  FIFO_1_nOE_SET;//disable output
/*  file_close();*/
  SaveBitmap(Buffer_ram, WIDTH, HEIGHT, Filename_buff);
  mspace_free(sdram_msp, Buffer_ram);
}

void Store_Image_0()
{
  int i, j;
  //uint8_t buffer[WIDTH * 2];
  char Filename_buff[15];
  uint16_t *Buffer_ram;
  Buffer_ram = mspace_malloc(sdram_msp, HEIGHT * WIDTH );
  i = 0;
  //make file
  //delete file if it exits already
  nav_filelist_reset();
  while(1)
  {
    sprintf(&Filename_buff, Image0Name, i++);
    if(nav_filelist_findname((FS_STRING)Filename_buff, false))
    {
      ;
    }
    else
    {
      break;
    }
  }

  //Image1
  //reset read pointer
  FIFO_0_nRRST_CLR;

  FIFO_0_RCLK_SET;
  delay_us(10);
  FIFO_0_RCLK_CLR;
  FIFO_0_nRRST_SET;

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

  for(j = 0; j < HEIGHT * WIDTH; j++)
  {
    FIFO_0_RCLK_SET;
    delay_us(10);
    Buffer_ram[j] = ((AVR32_GPIO.port[1].pvr) & 0xFF);//CAMERA_INPUT;
    delay_us(10);
    FIFO_0_RCLK_CLR;
    delay_us(10);
    FIFO_0_RCLK_SET;
    delay_us(10);
    Buffer_ram[j] |= (((AVR32_GPIO.port[1].pvr) & 0xFF) << 8);//CAMERA_INPUT;
    delay_us(10);
    FIFO_0_RCLK_CLR;
```

```
    delay_us(10);
  }

  FIFO_0_nOE_SET;//disable output
/*  file_close();*/
  SaveBitmap(Buffer_ram, WIDTH, HEIGHT, Filename_buff);
  mspace_free(sdram_msp, Buffer_ram);
}
```

D.1.1.11 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},
{OV_VPT, 0xA5},
{OV_HIST0, 0x78},
{OV_HIST1, 0x68},
{OV_HIST2, 0x03},//0x0b,
{OV_HIST7, 0xdf},//0xd8,
{OV_HIST8, 0xdf},//0xd8,
{OV_HIST9, 0xf0},
{OV_HIST10, 0x90},
{OV_HIST11, 0x94},
{OV_COM8, 0xe5},
{OV_COM5, 0x61},
{OV_COM6, 0x4b},
{0x16, 0x02},
{OV_MVFP, 0x27},//0x37,
{0x21, 0x02},
{0x22, 0x91},
{0x29, 0x07},
{0x33, 0x0b},
{0x35, 0x0b},
{0x37, 0x1d},
{0x38, 0x71},
{OV_OFON, 0x2a},//
{OV_COM12, 0x78},
{0x4d, 0x40},
{0x4e, 0x20},
{OV_GFIX, 0x0c},///////////////////////
{OV_DBLV, 0x60},//PLL
{OV_REG74, 0x19},
{0x8d, 0x4f},
{0x8e, 0x00},
{0x8f, 0x00},
{0x90, 0x00},
{0x91, 0x00},
{OV_DM_LNL, 0x00},//0x19,//0x66
{0x96, 0x00},
{0x9a, 0x80},
{0xb0, 0x84},
{0xb1, 0x0c},
{0xb2, 0x0e},
{OV_THL_ST, 0x82},
{0xb8, 0x0a},
{OV_AWBC1, 0x14},
{OV_AWBC2, 0xf0},
{OV_AWBC3, 0x34},
{OV_AWBC4, 0x58},
{OV_AWBC5, 0x28},
```

```
{OV_AWBC6, 0x3a},
{0x59, 0x88},
{0x5a, 0x88},
{0x5b, 0x44},
{0x5c, 0x67},
{0x5d, 0x49},
{0x5e, 0x0e},
{OV_LCC3, 0x04},
{OV_LCC4, 0x20},
{OV_LCC5, 0x05},
{OV_LCC6, 0x04},
{OV_LCC7, 0x08},
{OV_AWBCTR3, 0x0a},
{OV_AWBCTR2, 0x55},
{OV_AWBCTR1, 0x11},
{OV_AWBCTR0, 0x9f},//0x9e for advance AWB
{OV_GGAIN, 0x40},
{OV_BLUE, 0x40},
{OV_RED, 0x40},
{OV_COM8, 0xe7},
{OV_COM10, 0x02},//VSYNC negative
{OV_MTX1, 0x80},
{OV_MTX2, 0x80},
{OV_MTX3, 0x00},
{OV_MTX4, 0x22},
{OV_MTX5, 0x5e},
{OV_MTX6, 0x80},
{OV_MTXS, 0x9e},
{OV_COM16, 0x08},
{OV_EDGE, 0x00},
{OV_REG75, 0x05},
{OV_REG76, 0xe1},
{OV_DNSTH, 0x00},
{OV_REG77, 0x01},
{OV_COM13, 0xc2}, //0xc0,
{OV_REG4B, 0x09},
{OV_SATCTR, 0x60},
{OV_COM16, 0x38},
{OV_CONTRAS, 0x40},
{0x34, 0x11},
{OV_COM11, 0x02},//0x00,//0x02,
{OV_HIST5, 0x89},//0x88,
{0x96, 0x00},
{0x97, 0x30},
{0x98, 0x20},
{0x99, 0x30},
{0x9a, 0x84},
{0x9b, 0x29},
{0x9c, 0x03},
{OV_BD50ST, 0x4c},
{OV_BD60ST, 0x3f},
{0x78, 0x04},
{0x79, 0x01},//Some weird thing with reserved registers.
{0xc8, 0xf0},
{0x79, 0x0f},
{0xc8, 0x00},
{0x79, 0x10},
{0xc8, 0x7e},
```

```
{0x79, 0x0a},
{0xc8, 0x80},
{0x79, 0x0b},
{0xc8, 0x01},
{0x79, 0x0c},
{0xc8, 0x0f},
{0x79, 0x0d},
{0xc8, 0x20},
{0x79, 0x09},
{0xc8, 0x80},
{0x79, 0x02},
{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

};
```

D.1.1.12 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_ */
```

D.1.1.13 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;
  }
}
```

D.1.1.14 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);
#endif /* SD_CARD_H_ */
```

D.1.1.15 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
/*#include "CustomDevices/MotorDriver.h"*/
//SDCard
/*#include "CustomDevices/SD_Card.h"*/
#include "CustomDevices/CustomDevices.h"
#include "conf_sd_mmc_spi.h"
#include <asf.h>

// Dummy char table
const char dummy_data[] =
#include "dummy.h"
;
// PDCA Channel pointer
volatile avr32_pdca_channel_t* pdca_channelrx ;
volatile avr32_pdca_channel_t* pdca_channeltx ;
// Used to indicate the end of PDCA transfer
volatile bool end_of_transfer;
// Local RAM buffer for the example to store data received from the SD/MMC
    card
volatile char ram_buffer[1000];


void wait()
{
  volatile int i;
  for(i = 0 ; i < 5000; i++);
}
/* interrupt handler to notify if the Data reception from flash is
 * over, in this case lunch the Memory(ram_buffer) to USART transfer and
 * disable interrupt*/

static void pdca_int_handler(void)
{
  // Disable all interrupts.
  Disable_global_interrupt();

  // Disable interrupt channel.
  pdca_disable_interrupt_transfer_complete(AVR32_PDCA_CHANNEL_SPI_RX);

  sd_mmc_spi_read_close_PDCA();//unselects the SD/MMC memory.
  wait();
  // Disable unnecessary channel
  pdca_disable(AVR32_PDCA_CHANNEL_SPI_TX);
  pdca_disable(AVR32_PDCA_CHANNEL_SPI_RX);

  // Enable all interrupts.
  Enable_global_interrupt();
```

```c
  end_of_transfer = true;
}

/*! \brief Initializes SD/MMC resources: GPIO, SPI and SD/MMC.
 */
void sd_mmc_resources_init(void)
{
  // GPIO pins used for SD/MMC interface
  static const gpio_map_t SD_MMC_SPI_GPIO_MAP =
  {
    {SD_MMC_SPI_SCK_PIN,  SD_MMC_SPI_SCK_FUNCTION },  // SPI Clock.
    {SD_MMC_SPI_MISO_PIN, SD_MMC_SPI_MISO_FUNCTION},  // MISO.
    {SD_MMC_SPI_MOSI_PIN, SD_MMC_SPI_MOSI_FUNCTION},  // MOSI.
    {SD_MMC_SPI_NPCS_PIN, SD_MMC_SPI_NPCS_FUNCTION}   // Chip Select NPCS.
  };

  // SPI options.
  spi_options_t spiOptions =
  {
    .reg          = SD_MMC_SPI_NPCS,
    .baudrate     = SD_MMC_SPI_MASTER_SPEED,  // Defined in conf_sd_mmc_spi.h.
    .bits         = SD_MMC_SPI_BITS,          // Defined in conf_sd_mmc_spi.h.
    .spck_delay   = 0,
    .trans_delay  = 0,
    .stay_act     = 1,
    .spi_mode     = 0,
    .modfdis      = 1
  };

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

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

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

  // Enable SPI module.
  spi_enable(SD_MMC_SPI);

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

/*! \brief Initialize PDCA (Peripheral DMA Controller A) resources for the SPI
     transfer and start a dummy transfer
 */
void local_pdca_init(void)
{
  // this PDCA channel is used for data reception from the SPI
  pdca_channel_options_t pdca_options_SPI_RX ={ // pdca channel options

    .addr = ram_buffer,
```

```
    // memory address. We take here the address of the string dummy_data. This
     string is located in the file dummy.h

    .size = 512,                              // transfer counter: here the
    size of the string
    .r_addr = NULL,                           // next memory address after 1st
     transfer complete
    .r_size = 0,                              // next transfer counter not
    used here
    .pid = AVR32_PDCA_CHANNEL_USED_RX,        // select peripheral ID - data
    are on reception from SPI1 RX line
    .transfer_size = PDCA_TRANSFER_SIZE_BYTE  // select size of the transfer:
    8,16,32 bits
  };

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

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

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

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

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

}

#define BUFFER_FILENAME   "Buffer.bin"
void SaveBuff( int * WorkingBuffer , int size)
{
  //If the file exists, delete it
  if(nav_filelist_findname((FS_STRING)BUFFER_FILENAME, false))
  {
    nav_setcwd((FS_STRING)BUFFER_FILENAME, false, false);
    nav_file_del(false);
  }
  nav_file_create((FS_STRING)BUFFER_FILENAME);
```

```
  nav_setcwd((FS_STRING)BUFFER_FILENAME, false, true);
  file_open(FOPEN_MODE_APPEND);
  file_write_buf(WorkingBuffer, size * sizeof(WorkingBuffer));
  file_close();
}

void Log_Write(char *buff, int length)
{
  nav_setcwd((FS_STRING)LOG_FILE, true, false);
  file_open(FOPEN_MODE_APPEND);
  if(length == -1)
    length = sizeof(buff);
  file_write_buf(buff, length);
  file_close();
}
void Log_Write_ulong(unsigned long n)
{
  char tmp[11];
  int i = sizeof(tmp) - 1;

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

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

int ReadSignal( int * WorkingBuffer )
{
  bool status_b;
  int Status, temp;
  char c = 0;
  if(Columbus_Status.SD_Card->Status != STATUS_OK)
    return ERR_IO_ERROR;
  nav_filelist_reset();
  nav_setcwd((FS_STRING)SIGNAL_FILE, false, false);
  status_b = file_open(FOPEN_MODE_R);
  if(status_b == false)
  {
    print_dbg("File Open Error");
    return ERR_IO_ERROR;
  }


  //Status = file_read_buf(WorkingBuffer, 16);
  for(Status = 0; Status < FFT_SIZE; Status++)
  {
//    print_dbg("\n\r Read from file: ");
    c = 0;
    temp = 0;
    temp |= file_getc() << 24;
    temp |= file_getc() << 16;
    temp |= file_getc() << 8;
```

```
    temp |= file_getc();

//    print_dbg_char(c);

    WorkingBuffer[Status] = temp;
//    print_dbg("  Working Buff = ");
//    print_dbg_char(WorkingBuffer[Status]);
  }
  file_close();
  return STATUS_OK;
}

int Read2DSignal( int * WorkingBuffer )
{
  bool status_b;
  int Status, temp;
  char c = 0;
  if(Columbus_Status.SD_Card->Status != STATUS_OK)
  return ERR_IO_ERROR;
  nav_filelist_reset();
  nav_setcwd((FS_STRING)TWOD_SIGNAL_FILE, false, false);
  status_b = file_open(FOPEN_MODE_R);
  if(status_b == false)
  {
    print_dbg("File Open Error");
    return ERR_IO_ERROR;
  }


  //Status = file_read_buf(WorkingBuffer, 16);
  for(Status = 0; Status < FFT_SIZE * FFT_SIZE; Status++)
  {
    //    print_dbg("\n\r Read from file: ");
    c = 0;
    temp = 0;
    temp |= file_getc() << 24;
    temp |= file_getc() << 16;
    temp |= file_getc() << 8;
    temp |= file_getc();

    //    print_dbg_char(c);

    WorkingBuffer[Status] = temp;
    //    print_dbg("  Working Buff = ");
    //    print_dbg_char(WorkingBuffer[Status]);
  }
  file_close();
  return STATUS_OK;
}

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

  nav_filelist_reset();
  if(nav_filelist_findname((FS_STRING)FileName, false))
  {
```

```
    nav_setcwd((FS_STRING)FileName, true, false);
    nav_file_del(false);
  }
  nav_file_create((FS_STRING)FileName);
  file_open(FOPEN_MODE_W);
  //write a modified bitmap header
  //Calculate which is the biggest:
  i = width * 2;
  if(height > i)
    i = height;
  if(DIBHEADERSIZE > i)
    i = DIBHEADERSIZE;

  Buffer = malloc(i);

  for(i = 0; i < BMPHEADERSIZE; i++)//copy all the header
  {
    Buffer[i] = BMPHeader[i];
  }
  //edit the size field
  j = width * height * 2 + BMPHEADERSIZE + DIBHEADERSIZE;
  for(i = 0; i < 4; i ++)
  {
    Buffer[i + 2] = (uint8_t)(j >> 8*i);
  }

  file_write_buf(Buffer, BMPHEADERSIZE);

  //DIB Header
  for(i = 0; i < DIBHEADERSIZE; i ++)
  {
    Buffer[i] = DIBHead[i];
  }
  Buffer[4] = (uint8_t)(width & 0xFF);
  Buffer[5] = (uint8_t)((width >> 8) & 0xFF);
  Buffer[6] = (uint8_t)((width >> 16) & 0xFF);
  Buffer[7] = (uint8_t)((width >> 24) & 0xFF);

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

  file_write_buf(Buffer, DIBHEADERSIZE);

  for(i = 0; i < height ; i++ )
  {
    for(j = 0; j < width ; j++)
    {
      //Copy the data across.

      /*Buffer[j] = Image[i*width + j];*/
      Buffer[(2 * j) + 1] = (uint8_t)(Image[i*width + j]);
      Buffer[(2 * j)] = (uint8_t)(Image[i*width + j] >> 8);
    }
    if(file_write_buf(Buffer, width * 2) != (width * 2))
    {
      print_dbg("\n\rFile write error.");
```

```
    }

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



  free(Buffer);
  file_close();
}

#define BMP_HEADER_FILESIZE_OFFSET    2
#define BMP_HEADER_OFFSETTOARRAY_OFFSET 10
#define DIB_V5_WIDTH_OFFSET       4
#define DIB_V5_HEIGHT_OFFSET      8
#define DIB_V5_BITCOUNT_OFFSET      14
#define DIB_V5_IMAGESIZE_OFFSET     20

int ReadBigEndian(uint8_t *Buffer, int Offset, uint size)
{
  int retVal, i;
  retVal = 0; //initialise value
  for(i = 0; i < size; i++)
  {
    retVal |= Buffer[Offset + i] << (i * 8);
  }
  return (Buffer[Offset]) | (Buffer[Offset + 1] << 8) | (Buffer[Offset + 2] <<
     16) | (Buffer[Offset + 3] << 24);
}
void ReadBitmap(char *Filename, Image_t *image)
{
//  Image_t image;
  int i, j, FileSize, OffsetToArray, temp, BitCount, ImageSize;
  uint8_t Buffer[128];
  nav_filelist_reset();
  if(nav_filelist_findname((FS_STRING)Filename, false) == false)//if the file
    doesn't exist
  {
    print_dbg("\n\rFile ");
    print_dbg(Filename);
    print_dbg("\n\r does not exist;");
    return;
  }
  nav_setcwd((FS_STRING)Filename, false, false);
  file_open(FOPEN_MODE_R);
  //Read Header
  file_read_buf(Buffer, BMPHEADERSIZE);
  //Check for BM to confirm it is a Bitmap
  if((Buffer[0] != 'B') || (Buffer[1] != 'M'))
  {
    print_dbg("\n\rBitmap Parse Fail 'BM';");
    return;
  }
  //Extract file size and offset to pixel array
```

```
  FileSize = ReadBigEndian(Buffer, BMP_HEADER_FILESIZE_OFFSET, 4);
  OffsetToArray = ReadBigEndian(Buffer, BMP_HEADER_OFFSETTOARRAY_OFFSET, 4);

  file_read_buf(Buffer, DIBHEADERSIZE);
  temp = ReadBigEndian(Buffer, 0, 4);
  if(temp != 0x7C) //check it is a V5 BMP DIB Header
  {
    print_dbg("\n\rBMP Parse: DIB Header not V5;");
    return;
  }
  image->Width= ReadBigEndian(Buffer, DIB_V5_WIDTH_OFFSET, 4);
  image->Height = ReadBigEndian(Buffer, DIB_V5_HEIGHT_OFFSET, 4);
  BitCount = ReadBigEndian(Buffer, DIB_V5_BITCOUNT_OFFSET, 2);
  ImageSize = ReadBigEndian(Buffer, DIB_V5_IMAGESIZE_OFFSET, 4);
  print_dbg("\n\rBitmap Width = ");
  print_dbg_ulong(image->Width);
  print_dbg("\n\rBitmap Height = ");
  print_dbg_ulong(image->Height);
  print_dbg("\n\rBitmap File Size = ");
  print_dbg_ulong(FileSize);
  print_dbg("\n\rBitmap Offset to Array = ");
  print_dbg_ulong(OffsetToArray);
  print_dbg("\n\rBitmap Image Bitcount = ");
  print_dbg_ulong(BitCount);
  print_dbg("\n\rBitmap Image Size = ");
  print_dbg_ulong(ImageSize);

  file_seek(OffsetToArray, FS_SEEK_SET);
  j = 0;
  image->ImagePtr = mspace_malloc(sdram_msp, image->Height * image->Width);
  for(i = 0; i < ImageSize; i += 2)
  {
    image->ImagePtr[j++] = (file_getc()<<8) | (file_getc());
  }
  file_close();
  nav_filelist_reset();
  return;
}
```

D.1.1.16 TWI.c

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

```
/*
 * TWI.c
 *
 * Created: 27/02/2013 10:51:19
 *  Author: hslovett
 */

#include "CustomDevices/CustomDevices.h"
#include <asf.h>

#define TARGET_ADDRESS      0x0             //! Target's TWI address
```

```
#define TARGET_ADDR_LGT     3               //! Internal Address length
#define VIRTUALMEM_ADDR     0x123456        //! Internal Address
#define TWIM_MASTER_SPEED   50000           //! Speed of TWI


void twim_init (void)
{
  int8_t status;
  /**
  * \internal
  * PIN 2 & 3 in Header J24 can be used in EVK1104
  * PIN 1 & 2 in Header J44 can be used in UC3C_EK
  * \endinternal
  */
  const gpio_map_t TWIM_GPIO_MAP = {
  {AVR32_TWIMS0_TWCK_0_0_PIN, AVR32_TWIMS0_TWCK_0_0_FUNCTION},
  {AVR32_TWIMS0_TWD_0_0_PIN, AVR32_TWIMS0_TWD_0_0_FUNCTION}
  };

  // Set TWIM options
  const twi_options_t TWIM_OPTIONS = {
    .pba_hz = FOSC0,
    .speed = TWIM_MASTER_SPEED,
    .chip = TARGET_ADDRESS,
    .smbus = false,
  };
  // TWIM gpio pins configuration
  gpio_enable_module (TWIM_GPIO_MAP,
      sizeof (TWIM_GPIO_MAP) / sizeof (TWIM_GPIO_MAP[0]));

  // Initialize as master.
  status = twim_master_init (&AVR32_TWIM0, &TWIM_OPTIONS);

}
```

Appendix E

PCB Design

E.1 PCB Top Side

E.2 PCB Bottom Side

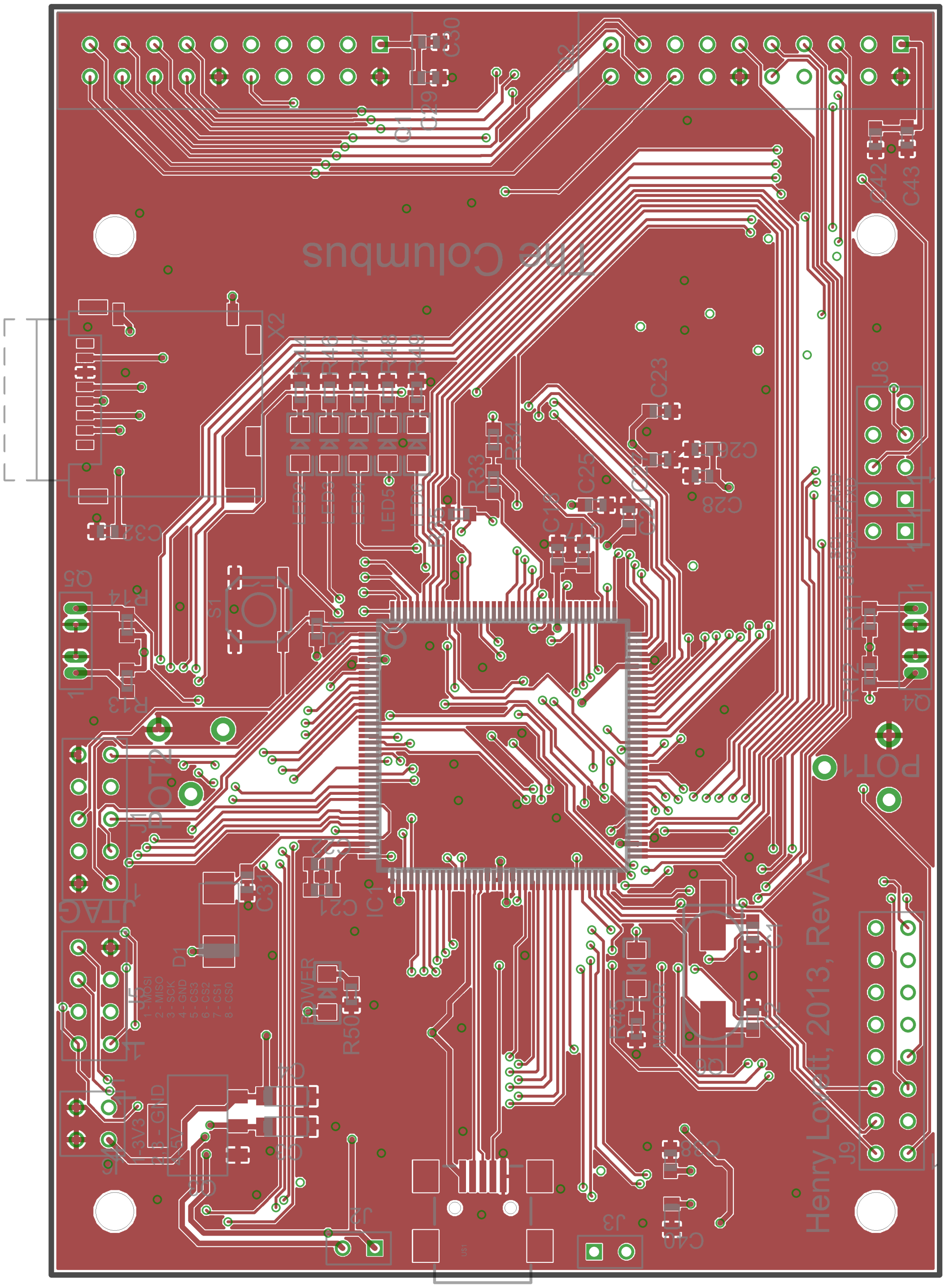


Figure E.1: The Top side of the CAD Design of the PCB

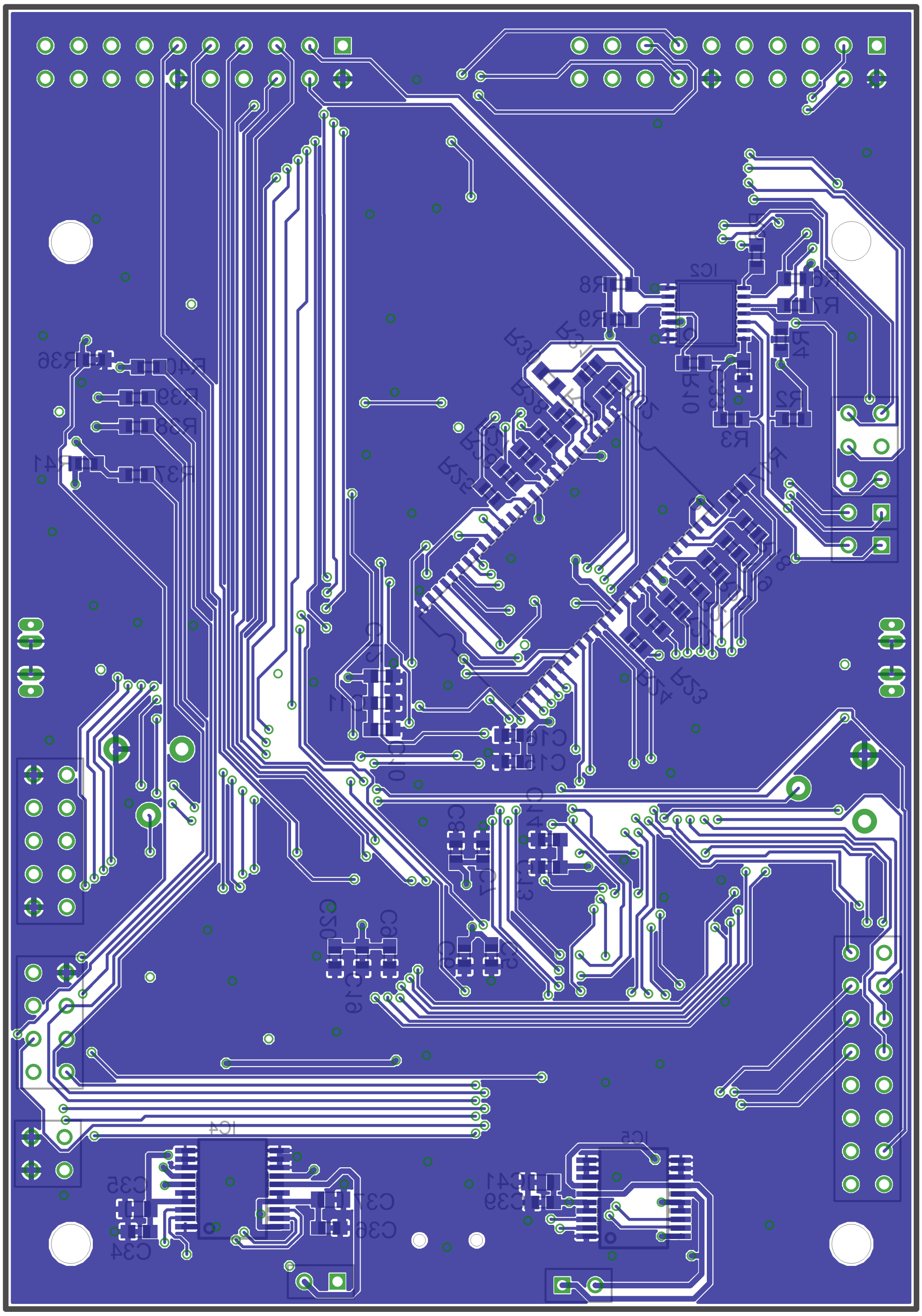


Figure E.2: The Bottom side of the CAD Design of the PCB

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