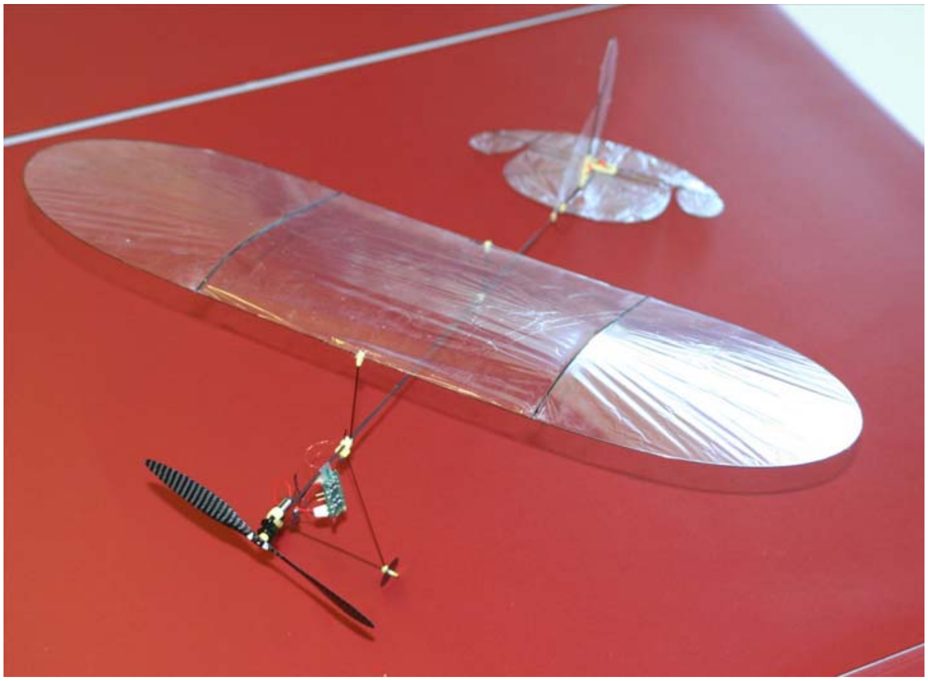
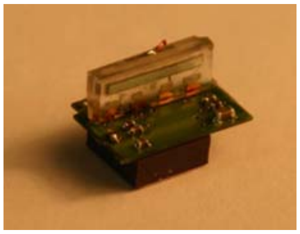
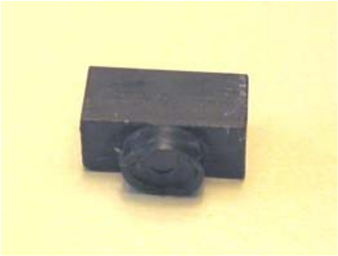
Miniature Cameras for Ultra-Light Flying Robots







E&CE Fourth Year Design Project

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Section de Génie Électrique et Électronique
Laboratory of Intelligent Systems (LIS)

E&CE Fourth Year Design Project final report

Miniature Cameras for Ultra-Light Flying Robots

Group #061

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This report is submitted as the final report requirement for the ECE.492B course. The course requirements were completed while doing a semester project at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland. The academic credits gained at EPFL for this project do not count towards a degree and will not grant me any other credits at the University of Waterloo, other than for ECE 391, ECE 492A and ECE 492B. It has been written solely by me and has not been submitted for academic credit before at this or any other academic institution, except where mentioned above.

June 20, 2005

Abstract

The Laboratory of Intelligent Systems (LIS) at the Swiss Federal Technical Institute at Lausanne (EPFL) is working on a project to create an autonomous flying robot that uses 'vision' (i.e. optical flow) to maneuver through small spaces such as corridors in a building. The navigation algorithm uses data from a linear photodiode array and a gyroscope to determine the distance of the robot from an obstacle.

This project involves the design of a light-weight vision system to be used on the flying robot. The vision system is made up of two identical modules, each one containing a linear photodiode sensor array, a focusing lens with associated plastic casing, a gyroscope, and the PCB on which the system is mounted. The first module will be pointed ahead of the robot and will be used for lateral steering, and the second module will be pointed straight down and be used to control elevation. The main design constraint is the weight of the system, which has to be below 2g for the robot to fly.

Acknowledgements

I would like to acknowledge the help of my consultant Dr. Jean-Christophe Zufferey in all aspects of this project. This project was a small part of Dr. Zufferey's ongoing research in flying robotics. His advice on every part of the project, including how to design the final prototype, was invaluable. In particular I would like to acknowledge his help in designing the PCB that was used in the final modules.

On the realisation side of the project, I would like to acknowledge André Guignard and Georges Vaucher for their work on the mechanical and electronic parts of the project. Mr. Guignard molded the casings for the lenses, machined the vision sensors to remove excess weight, and removed the lenses from their original packaging. He was also involved in many smaller mechanical tasks during the project and provided advice on the practical sides of the project. Mr. Vaucher did all the routing of the PCBs, according to the specifications given to him by myself and Dr. Zufferey. He also soldered and mounted all the electronic parts on the final prototypes, and his advice on electrical matters was much appreciated.

As secondary consultants, I would like to acknowledge Antoine Beyeler and Alvaro Fernandez Salmeron for their advice on the project.

Glossary of Terms and Acronyms

AS – Aperture Size
The aperture size is the diameter of the opening (aperture) in front of the lens of a camera.

BGA – Ball Grid Array
A semiconductor packaging technology that decreases packaging weight and footprint by placing connections underneath the chip in the form of small solder bumps that are attached to a PCB by curing in an oven

EPFL – Ecole Polytechnique Fédérale de Lausanne
A university in Lausanne, Switzerland, where this project was completed, as arranged with the University of Waterloo, Canada.

FL – Focal Length
The distance from the middle of the lens to its focal point.

FOV – Field of View
The angle in degrees from the face of the lens from which light can pass through the lens and be focused on the photodiode array on the other side, providing an image.

LIS – Laboratory of Intelligent Systems
The laboratory at EPFL where this project was completed

OF – Optical Flow
The perceived visual motion of objects as the observer moves relative to them. The cameras developed in this project provide OF data that will be used to navigate the robot.

PCB – Printed Circuit Board
A plastic board that is imprinted with one or more layers of circuitry.

VD – Vision Direction
Defined as one of three directions that must be sensed by the vision system in the project specifications. These directions are:

- **Forward-Left –** Centered at 45º left of the longitudinal axis of the plane, FOV of ~40º, minimum 20 pixels
- **Forward-Right** - Centered at 45º right of the longitudinal axis of the plane, FOV of ~40º, minimum 20 pixels
- **Down –** Pointing down parallel to the direction of flight, maximum FOV possible, minimum 20 pixels

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1 Introduction

1.1 Background

The Laboratory of Intelligent Systems (LIS) at the Swiss Federal Institute of Technology (EPFL) in Lausanne, Switzerland, is a group whose primary mission is "to understand and replicate the principles that allow living and artificial systems to self-organize, adapt and remain operational in changing and unknown environments" (http://lis.epfl.ch). As part his ongoing research project entitled "Bio-inspired Vision-based Flying Robots", Jean-Christophe Zufferey is designing a 10-15g ultra-lightweight flying robot that will be able to fly autonomously through corridors and avoid obstacles (http://phd.zuff.info).

Much like the common house-fly, this robot navigates using Optical Flow (OF) information received through a set of miniature cameras mounted on the robot. The purpose of this project is to design the vision system[1] for the robot. These cameras must at once be light-weight to accommodate the weight restrictions of the robot, fast enough to detect changes in environment with sufficient accuracy, and simple enough to fit within the processing capacity of the microprocessor.

There are two main purposes for the cameras: The first is to provide an image of what is ahead and to the sides of the robot, used in corridor-following and to avoid obstacles. The second purpose is to provide OF data on the elevation of the robot above the ground.

The eventual goal of this project is to provide insight into the construction of autonomous ultra-light robots that can be used in an indoor office environment. These robots will be used by LIS to study artificial intelligence. Lessons learned using this vision system can be used in industry to provide navigation capabilities to a variety of different flying robot platforms.

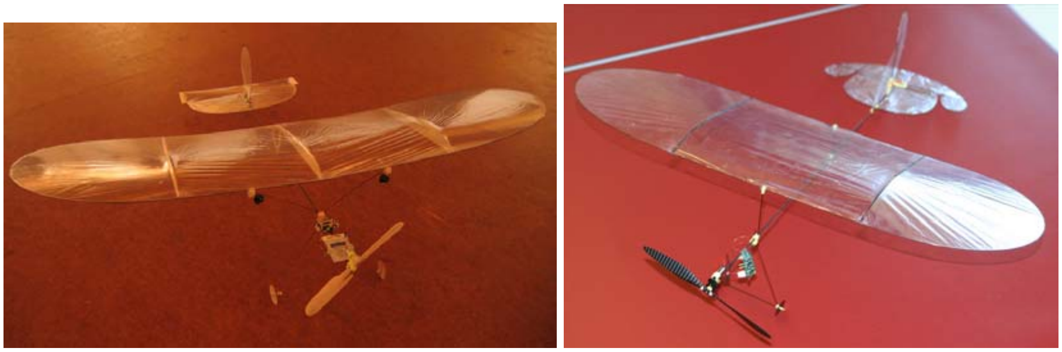
1.2 Previous Design – The F2

This project is a continuation of ongoing research in flying robotics, and much of it is based on a previous flying robot that used OF navigation called the F2 [1]. This robot (see Figure 1a) weighed 30g, had a wingspan of 86cm and had a maximum turning radius of 1.3m. It navigated using a system of two cameras, each one comprising of a horizontal TSL3301 linear photodiode arrays (TAOS inc.), an EL-20 plastic lens (Applied Optics Group) and a custom-designed lens casing. This casing and lens illuminated the centre

1

[1] The term "camera" refers to a system composed of a photodiode sensor (linear array or 2D array), a focusing lens and casing, and the PCB the system is mounted on. The term "vision system" will be used to indicate the complete OF-sensing system of the robot in all directions, which will be made up of two or three separate "cameras".

50 of the 102 pixels of the TSL3301. See Table 1 for an overview of the weight allowance of the F2.



(a) (b)

Figure 1 - The F2 (a) and miniCeline (b) flying robots

Table 1 - Weight distribution of the F2 [2]

Fuselage and tail	4.7g
Wing	4.5g
Landing gear	1.2g
Motor, gearbox, propeller	2.7g
Two servos	2.7g
Battery	6.9g
Microcontroller board with gyroscope	3.0g
Two 1D cameras with optics	2.0g
Bluetooth radio module	1.0g
Miscellaneous (cables, glue)	1.3g
TOTAL	**30g**

1.3 General Specifications

1.3.1 Vision System Weight

If the goal of navigating through an office corridor was to be realised, this robot had to be significantly miniaturised. The eventual goal was to move from the 30g F2 to a robot closer to a total weight of 10g. Towards this goal a new ultra-light-weight airplane platform was designed, the miniCeline. The miniCeline weighs only ~6.5g but cannot support more than a 5g payload. This electronics payload currently includes:

- 1g Additional battery
- 1.2g Pevopic microcontroller board
- 1g Bluetooth chip and antenna
- 1.8g Allowance for vision system and gyroscopes

This restriction not only affects the vision system directly, but also the connections between the vision system and the rest of the electronics package, and thus the design of the vision system must also take into consideration the rest of the electronics package. Integrating the vision system into the main PCB containing the microcontroller could save weight by eliminating the need for separate PCBs, connection wires and connectors. Based on experience gained on the F2, a preliminary goal of 1.5g was set for the vision system.

1.3.2 Camera Vision Directions

The function of the vision system is to provide the robot with Optical Flow (OF) data to be used to steer the robot. The vision system consists of 2-3 photodiode sensor arrays, each one pointing in one of 3 well-defined Vision Directions (VD) (Figure 2):

- **Forward-Left –** Centered at 45º left of the longitudinal axis of the plane, FOV of ~40º, minimum 20 pixels
- **Forward-Right** - Centered at 45º right of the longitudinal axis of the plane, FOV of ~40º, minimum 20 pixels
- **Down –** Pointing down parallel to the direction of flight, maximum FOV possible, minimum 20 pixels

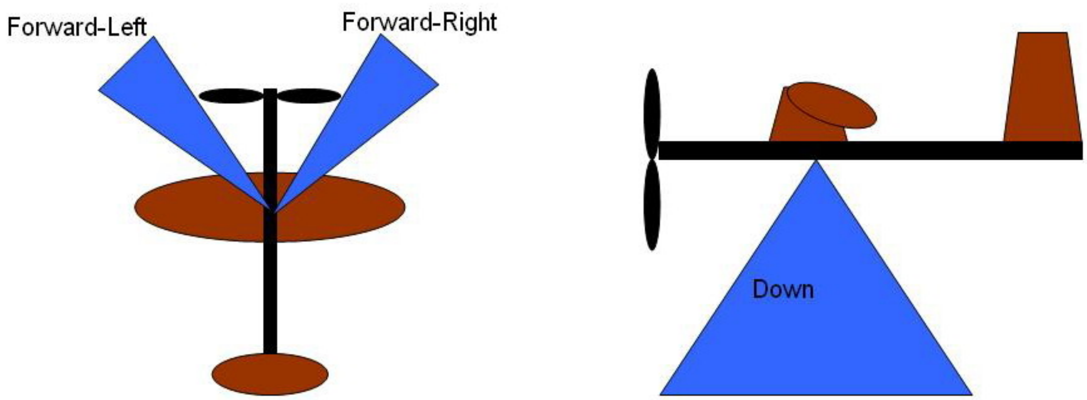
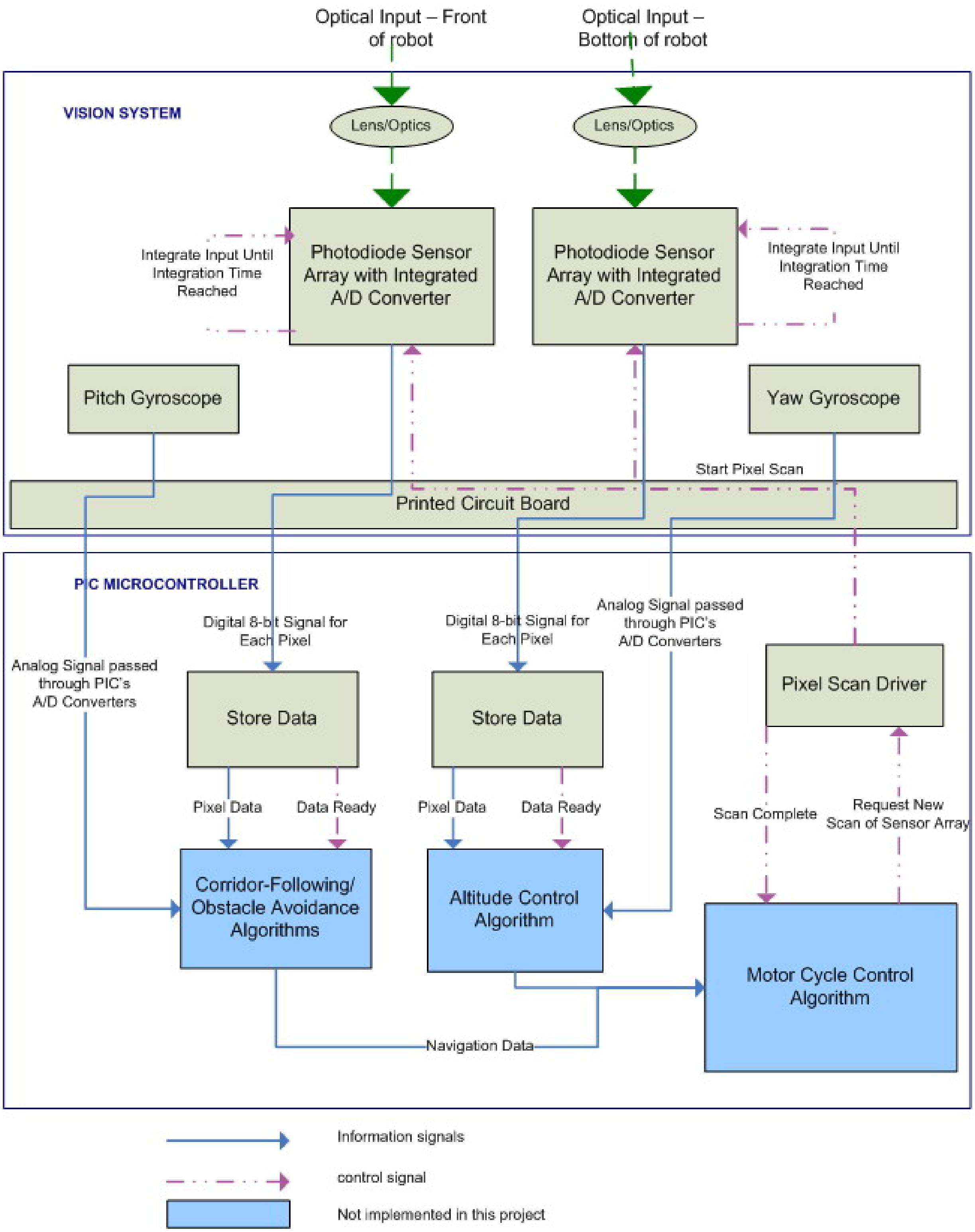


Figure 2 – Vision Directions of Vision System

The Forward-Left and Forward-Right VDs will be used for the corridor-following (CF) and obstacle-avoidance (OA) algorithms [3], whereas the Down VD will be used by the altitude control (ALC) algorithm [4].

1.4 Block Diagram

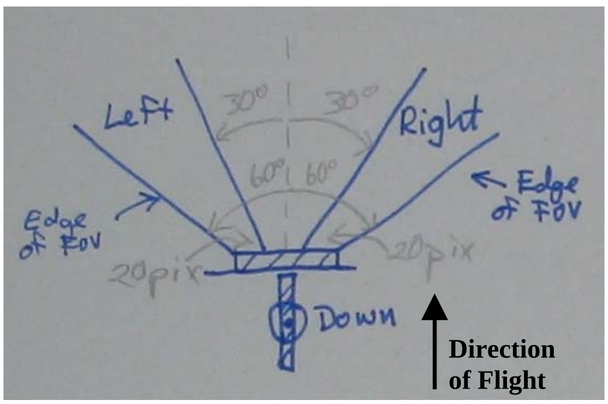


2 High-Level Analysis

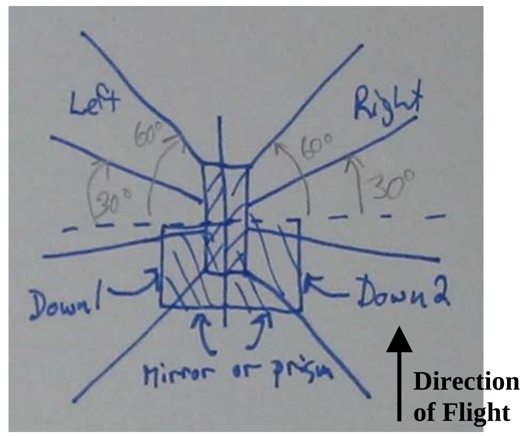
2.1 Vision System

2.1.1 Using Only 2 Cameras for 3 VDs

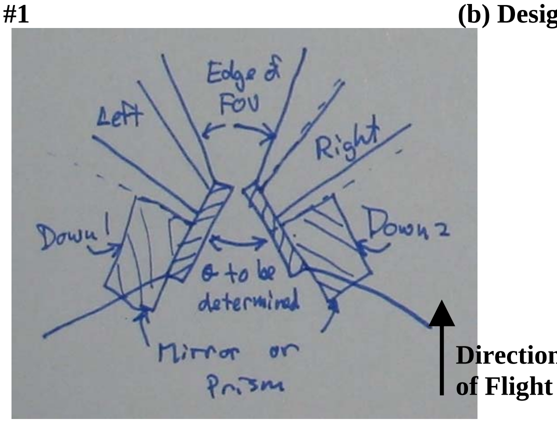
One of the main specifications of the module is weight: the weight allowance for the entire vision system, including all sensors, optics (with casings), PCBs and connectors is less than 1.5g. This stringent specification makes the idea of having a separate camera for each of the 3 VDs practically impossible, making it necessary to devise a system of only 2 cameras for the 3 VDs. 3 possible designs are presented in Figure 3.



(a) Design #1



(b) Design #2



(c) Design #3

Figure 3 - Possible designs using 2 sensors for 3 VDs (View from above the plane)

Design #1 (Figure 3a) presents the simplest solution, where 1 camera is used for both the Forward-Right and Forward-Left VDs. For this solution to be viable, an optics system must be devised that has a useful FOV of at least 120º, preferably >130º. A second camera pointing straight down would be used for the Down VD.

Design #2 (Figure 3b) shows a slightly more complicated design, where 2 cameras are mounted looking directly at either side of the plane. A mirror or prism is used to reflect light coming from below the plane, splitting the Down VD into 2 parts, one half each camera. This solution also requires an optics system with a FOV of at least 120º. Its advantage is that both cameras can be mounted on a single PCB, saving weight, however the added complexity and weight of the reflecting mirrors are a marked disadvantage.

Design #3 (Figure 3c) is a slightly altered version of Design #2, with the two sensors pointed slightly in the direction of travel of the plane. The main advantage is that the Forward-Left and Forward-Right VDs no longer need an optics system with such a high FOV. Several new disadvantages in this option, however, including the need for 2 PCBs and distortion of the Down VD, make this option a last resort.

After several experiments performed with the EL-20 lens and the TSL3301 linear array, it was established that a workable image could be taken with a FOV of >120º, given the proper lens casing parameters (see Section 2.1.3). These results made all 3 proposed camera orientation options possible. After careful consideration of all the pros and cons of each design, the straightforward orientation of Design #1 was chosen. The main factors included its construction simplicity and the clarity of the image, which did not have to be reflected by imprecise mirrors. Appendix B contains a more detailed description of the advantages and disadvantages of each design option.

2.1.2 Photodiode Sensor Array

The purpose of the sensor array is to detect an image that can be used for optical flow calculations. There are several constraints for the selection of the sensor:

- The image can be either one-dimensional or two-dimensional
- The sensor must be small and extremely light-weight
- The sensor must be capable of taking two images in quick succession, within around 5ms, one of the requirements of the OF navigation algorithm [1]
- The sensor should run on <3.3V and not require much power (the robot's battery has limited capacity), otherwise a step-up transformer would be necessary which adds unnecessary complexity, power loss and weight
- Enough pixels to provide a clear image for each VD, and possibly for 2 VDs, as described in Section 2.1.1
- The sensor should have a data stream small enough (<3840 bytes, memory of the PIC microcontroller) to avoid flooding the PIC microcontroller's memory and impede its functioning

Initial market research was conducted to find a suitable sensor to meet the above requirements. Several 2D sensors were found, but they all provided too high of a data stream to the low-power PIC. It was decided to stay with a linear 1D sensor, with several models available from TAOS inc.[5] The models to be considered are the TSL1301, TSL1401 and the TSL3301.

The TSL1301 is a 102-pixel sensor with an analog output, available in an 8-pin DIP package. The TSL1401 is a 128-pixel sensor that also has an analog output, but is available in a much smaller and lighter Ball Grid Array (BGA) package. The TSL3301 is similar to the TSL1301, but has integrated A/D converters for each pixel, as well as a gain amplifier, making it easier to use and eliminating the need for extra computation time in the PIC to do the conversion.

2.1.3 Lens System/Optics

The lens is used to focus an image on the photodiode sensor, and is a requirement of any camera system. As with the other components, the main requirement for the lens is weight. Glass lenses and multi-lens solutions provide better quality of image than a plastic lens but are much too heavy. For example, the Marshall V-4201 miniature glass less package, currently in use at LIS for other applications, has a weight of 4.5g. Light-weight plastic lenses are available on the market; in particular the EL-20 lens weighs under 0.1g (without casing).

The FOV of the lens is an important factor if only 2 cameras are to be used (as discussed in Section 2.1.1). The designs in Figure 3a and 3b, the two solutions most likely to be used, both require a lens with a FOV of 120º, the useful image for the Front -Left and Front-Right VDs being between 30º and 60º on either side. In its factory casing the EL-20 is specified for a FOV of only 56º. Tests done using the F2's vision system determined it was the cone of the plastic casing that prevented a larger FOV. A custom plastic casing was built without a cone to see if this increased the FOV. Initial tests of the EL-20 lens in a custom-designed casing suggest this is feasible (see Figure 4). Further testing is necessary to determine the exact image quality in these regions. See Appendix C for details on the experiments that were performed.

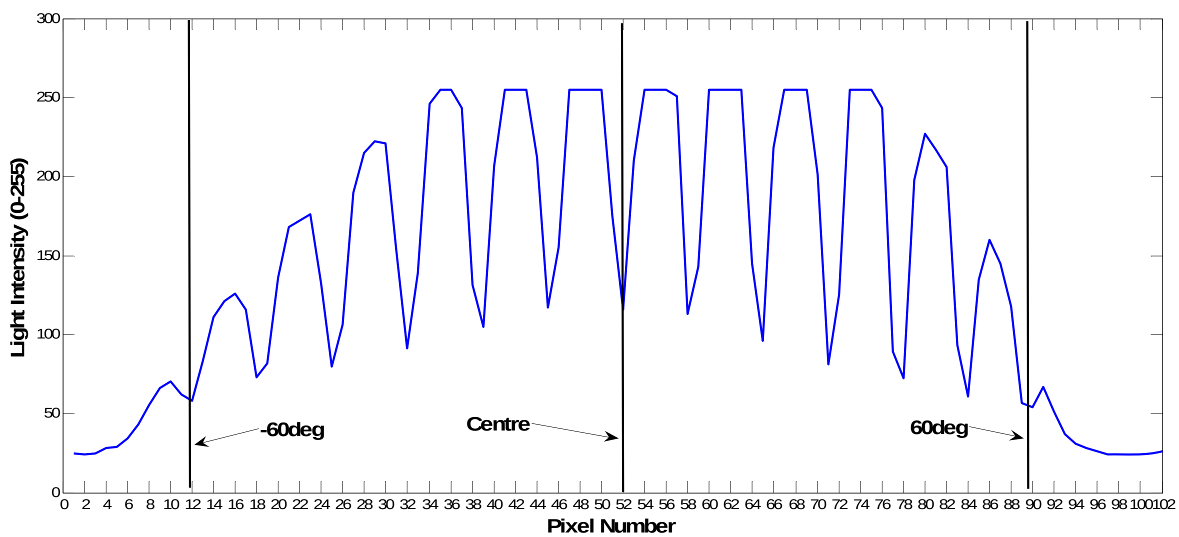


Figure 4 - Initial FOV results for EL-20 lens

EL-20 Lens tested in custom packaging with no cone. Tests were done in an arena with a circular wall covered in white paper. Black stripes were placed at 10º intervals, starting at the centre (0º), to make FOV easy to interpret. The figure demonstrates that an acceptable image is still visible at 60º on either side.

Part of the optics system includes the casing for the lens and the photodiode sensor. The lens must be held at a fixed distance above the sensor to provide proper focus. Ideally this distance should correspond to the focal plane of the lens, but given the need to use the image at the fringes of the FOV of the lens, a different focal length may be selected for the Forward camera to better focus the light in the areas of interest.

A secondary purpose for the casing is to shield the sensor from light not coming through the lens that might distort the image on the sensor. This casing should be made of a light-weight material that will not greatly increase the weight of the system. A black plastic with glass bubbles has a density of only $1.4kg/m^3$ has been successfully used in previous designs and should be suitable for the current application.

2.2 Microcontroller

The inputs/outputs of the vision system will be handled by a Microchip PIC18F6720 microcontroller.[6]

2.2.1 A/D Conversion

If either of the analog linear arrays are to be used (TSL1301 or TSL1401), the signal received from the sensor array must first be converted from an analog signal to a digital signal before being processed by the navigation algorithm. This conversion must be done quickly, since the robot has a motor cycle of ~80ms. Each motor cycle requires two images to be taken by the sensor array approximately 5ms apart. The A/D conversion must be completed within this time constraint. Tests performed at LIS by A. F. Salmeron [7] indicate this conversion time to be 2.04ms.

Many commercially-available sensor arrays, including the TAOS TSL3301 sensor array, have an A/D converter built directly into the chip. Having a digital signal arrive at the PIC would eliminate the need for the A/D conversion and would likely speed up the process of acquiring and processing images.

2.2.2 Pixel Scan Driver

Every sensor array has a specific set of control instructions that must be implemented in the PIC. Drivers are already available for several sensor array models used in previous implementations of the vision system. These can easily be modified to provide the required functionality for this project. Drivers do not take much processing power or time and can be programmed fairly quickly, and therefore do not present a large stumbling block in the project.

2.2.3 Store Data

The signal received by the PIC must be stored in the memory buffer before being used by the various navigation algorithms. The PIC currently being used only has 3840 bytes of RAM that must be shared between the program and the two images that must be taken every motor cycle. The images should not use more than 10-20% of the RAM, and therefore the size of each image should be no greater than ~350 bytes.

3 Detailed Design

3.1 Overall Design

The final design for the miniature camera system is two separate modular units each containing both a vision sensor and a gyroscope (see Figure 5). The vision sensor will be a TSL-3301 Linear 102-pixel Array, the lens will be an EL-20 plastic lens, and the gyroscope will be an ADXRS-150 Single Chip Yaw Rate Gyro (Analog Devices). The lens will be mounted in a custom-built plastic lens casing. All components will be mounted on a custom-designed PCB. The entire module is expected to weigh between 0.5-1.0 grams. Schematics included in Appendix D.

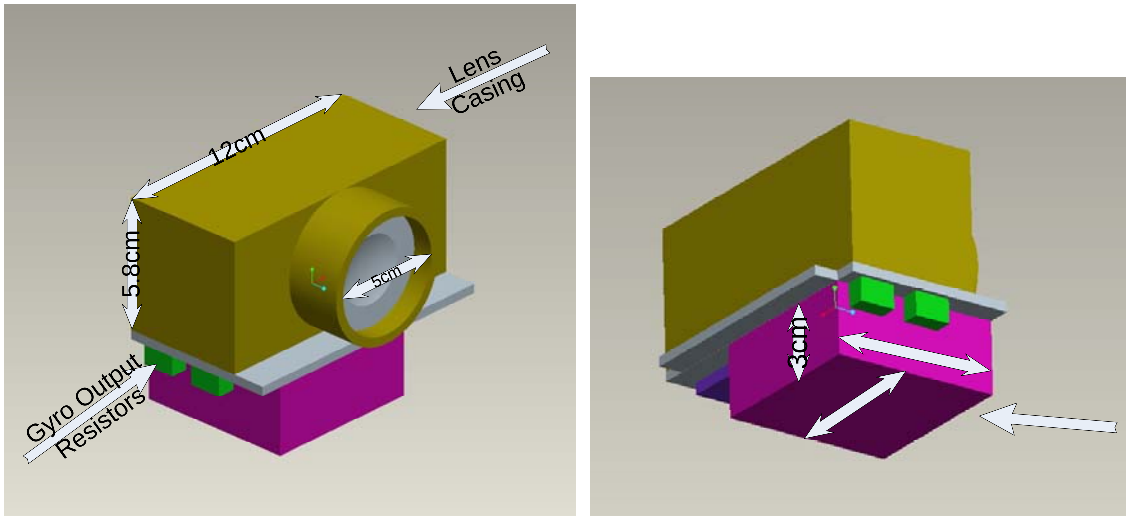


Figure 5 - Model of Final Design of the Modular Camera System

3.1.1 Inclusion of the Gyroscope in the Final Design

The flying robot's navigation algorithm uses OF acquired via the camera system. Without going into detail, this algorithm needs to know the rotation of the camera about its vertical axis to retrieve data about rotational optical flow (see [1] for more information on the algorithm). A rate gyroscope is used to measure this rotation. In the F2 the gyro was integrated into the main electronics PCB and was separate from the vision system.

Since the miniCeline will feature two cameras (one pointing forward and one pointing down), there needs to be two gyroscopes, one measuring rotation about the vertical axis (Yaw gyro) and one measuring rotation about the horizontal axis perpendicular to the direction of flight (Pitch gyro). The orientation of the gyros is important, which means there would have to be at least one gyro that cannot be mounted on the main electronics PCB and would require a separate PCB.

Late in the design process it was decided to include the gyros as part of the vision system module, instead of the main electronics PCB. Integrating the gyro into the vision system PCB eliminates the need for a separate PCB for the gyro. The gyro can be placed on the opposite side of the PCB than the camera, which does not increase the PCB's size. Since the camera is almost always used together with its respective gyro, putting both components in a single module provides an added advantage for future applications.

3.1.2 Modularity vs. Integration

Initial designs for the camera system were concentrated on integrating the system into the main electronics PCB of the robot. The idea was to save weight by eliminating the need for additional PCBs. There were, however, several problems associated with fully integrating the camera system into the main PCB:

- A new revision of the main PCB would have to be designed, built and tested
- The lens casing would create oddly-shaped and unusable spaces on the PCB, thus requiring more area on the PCB for other components and diminishing the weight advantage
- There was still a need for an additional PCB for the Pitch Gyroscope, which had to be mounted vertically parallel to the direction of flight of the robot

Creating a modular design for the camera system presented some interesting advantages:

- Two identical modules can be created, simplifying the construction process
- Modules would allow the robot to fly with all or only 1 of the modules, depending on the application, increasing the flexibility of the robot
- A gyroscope could be integrated into the module, eliminating the need for a separate PCB for the gyroscope and decreasing weight
- Navigation using the OF almost always requires a gyroscope in conjunction with the vision sensor. Having both a gyroscope and a vision sensor in a single package makes it attractive for future applications in OF navigation.

The final design opted for a modular approach because of the above-stated advantages.

3.2 Components

3.2.1 Photodiode Sensor Array

The final choice for the vision sensor was the TSL3301. This sensor was chosen for several reasons:

- The TSL3301 has a built-in A/D converter, which substantially simplifies processing of the signal and decreases processing time
- Although not in a compact solder bump package such as the TSL1401, the unit can be trimmed to be smaller by removing unnecessary plastic
- The integration time for the sensor is much lower than it’s analog counterparts (the TSL1301 and TSL1401) (based on tests performed at LIS by A. F. Salmeron) [7]
- It has been successfully used in previous vision systems, and is already in stock
- The TSL3301 can be soldered vertically, unlike the TSL1401 which needs an additional PCB to be mounted vertically

This component comes in a plastic 8-pin DIP package. Although small, it still adds a significant weight to the system (0.43g). The pins and much of the plastic can be removed without damaging the electronic components. The removal of the plastic is a delicate matter, however. The pixel array is connected to the connectors using bonded gold line, which is easily damaged when mechanically removing the plastic. Chemical removal of the plastic was investigated but was complicated and untested, and re-connecting the bonds if they broke would prove nearly impossible. Therefore the plastic will have to be removed mechanically, taking care to test the sensor for damage before it is mounted on the PCB. Since the sensor must be completely enclosed by the lens casing, removing some of the plastic also decreases the size of the required lens casing. Figure 6 compares the original DIP package to a trimmed sensor (weight of 0.12g).

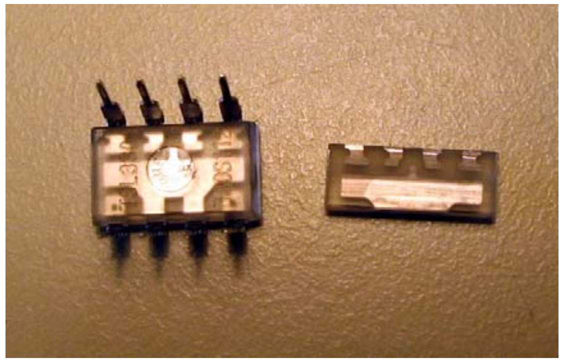


Figure 6 - Size Reduction of TSL3301 by Mechanical Removal of Plastic (from 0.43g to 0.12g)

3.2.2 Lens System/Optics

The EL-20's tested performance, along with its weight and short focal length (3.4mm), made it a natural choice for the final vision system. This lens must first be removed from its standard factory packaging before it can be mounted in the custom lens casing.

The lens casing has 2 functions: holding the lens in front of the sensor at the required focal length, and blocking all light not coming from the lens from reaching the sensor. The previous lens casing design included the option of screwing in the lens to adjust its focus. Although it is a useful feature, it greatly increases the size of the plastic, which in turn increases the necessary PCB surface and the weight of the entire system. The new design includes an opening just big enough to fit the lens itself, without any threaded components. There is some room to move the lens in or out to finely adjust focus, but once the casing is mounted on the PCB the lens can no longer be adjusted.

To determine the correct focal length, several experiments were performed. The contrast between black and white bars was compared for different focal lengths to find the best length. Although it is expected that the theoretical focal length of 3.4mm would give the best image in the centre, it was not clear whether this length would also provide the clearest image at the edges of the FOV of the lens. Experimental data showed that a focal length of 4mm provided a clearer image with higher contrast than the theoretical shorter focal length, not only for the edges of the FOV, but over the entire image. This extension of the focal length could be caused by diffraction of light as it passes through the plastic package before it reaches the photodiodes, or perhaps the focal length mentioned in the EL-20 datasheet only applies when it is in its factory casing.

Another consideration was the aperture size for the lens. Although it was clear that a bigger aperture meant more light passing through the lens and less time to acquire an image, it was not clear how this affects the quality of the image. Tests were done with 3 different aperture sizes: 0.5mm, 1.0mm and 1.5mm. The result of these experiments was that images with similar quality and contrast could be obtained by all 3 aperture sizes, but that the larger aperture sizes needed less time to provide these images. Therefore an aperture size of 1.5mm was chosen for the final camera system. Appendix C contains details on the experiments referenced in this section.

Creating the aperture for the lens was the final part of the optics' system design. The original design called for a plastic circle containing the correct aperture size to be glued to the face of the lens. This however meant more plastic parts that add to the weight of the system. The circle was replaced by a thin black plastic film that was specially designed for tiny camera systems. This film has a sticky side and can be directly applied to the face of the lens. The film is ideal because it has negligible weight and does not let any light through, except through the aperture hole.

3.2.3 Gyroscope

The gyroscope to be used in the final assembly is the ADXRS-150. This is the same device used in previous models of the robot, and meets all the requirements of the OF-based navigation algorithms.

Mounting of the gyro requires several external capacitors which are described in detail in the product's datasheet (see Figure 7). These capacitors were included in the design of the PCB. The gyro also requires a step-up voltage converter, since the robot and vision sensor run on a 3.3V battery while the gyro requires a 5V power supply. The MAX1686H by Maxim was used to provide the necessary voltage.

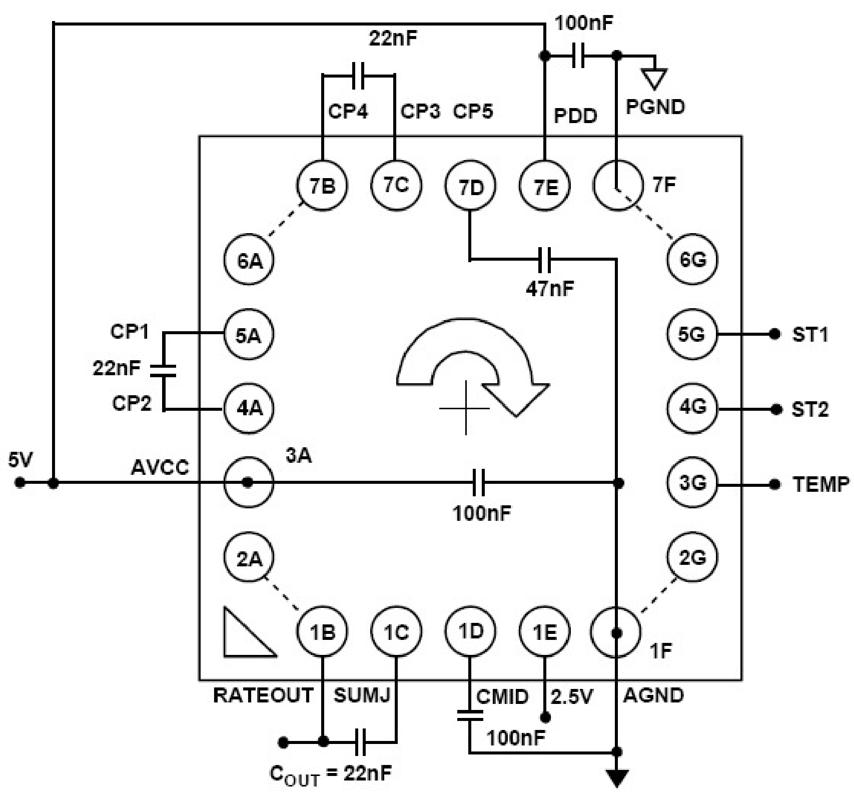
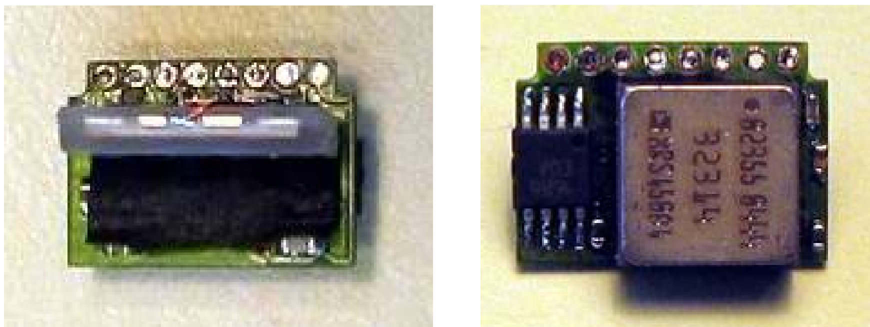


Figure 7 - Circuit Diagram for Gyroscope Connection [8]

The 5V supply of the gyro also creates a problem on the output. The gyro's output signal is an analog signal between 0-5V, with 2.5V meaning no rotation, and positive deflection indicating clockwise rotation. The PIC microcontroller however is running on a 3.3V supply, and can only receive signals smaller than 3.3V. To solve this problem, a simple voltage divider is used to cut the output voltage to required levels. See Appendix D for circuit diagrams of the PCB.

3.2.4 Printed Circuit Board

All of the above-mentioned components must be put together on a Printed Circuit Board (PCB). To conserve weight and size, components will be mounted on both sides of the PCB. Figure 8 shows the placing of the components on the PCB.



(a) **(b)**

Figure 8 - Component Placement on PCB

Figure 8a is the top of the PCB, and shows the trimmed TSL3301 mounted vertically. A black paper square is used to block any light coming through the PCB, below which are mounted several capacitors used by the gyroscope. Figure 8b is the bottom of the PCB, most of which is taken up by the gyro and the adjacent smaller step-up converter. Remaining resistors and capacitors are mounted beside the gyro.

The photodiode sensor array will be mounted vertically on the top of the PCB and then covered by the lens casing. There is some empty space inside the casing between the lens and the sensor equal to the focal length of the lens. This space will be used to place some of the capacitors and resistors needed for the gyroscope.

The bottom of the PCB will contain the gyro and the step-up converter, along with the remaining resistors and capacitors. Placing these components on the other side of the vision sensor has the added benefit of blocking some of the light that would otherwise pass through the semi-transparent PCB.

Final schematics of the PCB are available in Appendix D.

3.3 Duties/Responsibilities

Construction of the components was delegated to specialized workshops throughout EPFL. The casing for the optics system was designed by Adam Klaptocz, and was molded by André Guignard, head of the mechanical workshop at EPFL. A. Guignard also removed the lens from its original casing and trimmed the plastic off the TSL-3301. The PCB was designed by A. Klaptocz and Jean-Christophe Zufferey and was routed by Georges Vaucher at the ACORT lab. The plans were then sent to the PCB lab at EPFL for construction. All electrical components were then mounted on the PCB by G. Vaucher.

All testing of the system was be done by A. Klaptocz. This included testing of the images produced by the vision sensors and the functioning of the gyroscope. Final mounting of the modules on the robot will be done by J-C Zufferey when the rest of the electronic components are designed and built.

4 Experimental Results

4.1 Testing of Prototypes

After final construction of the 2 prototype modules, they were both put through a series of tests to make sure they were functioning as predicted.

4.1.1 Vision Tests: FOV

To test the camera system of the module, each camera was interfaced with a Khepera robot, similarly to the experiments done during the design phase, and the same experimental setup was used (see Appendix C for details on the experiments). Images were taken at different integration times, and were analysed for their contrast in the same manner as during the design phase. It was determined that the new modules performed similarly to the module used in design, more specifically they had similar average contrast on the whole 120º FOV.

Figure 9 shows images taken during initial design experiments and with one of the two modules. The 2 curves have similar contrast level in the centre 60 pixels, indicating good correlation between initial tests and the final prototypes. Near the edges the two images diverge. This is caused by slightly different focal lengths. The lens casing in the prototype camera module does not have a mechanism to precisely adjust the focal length.

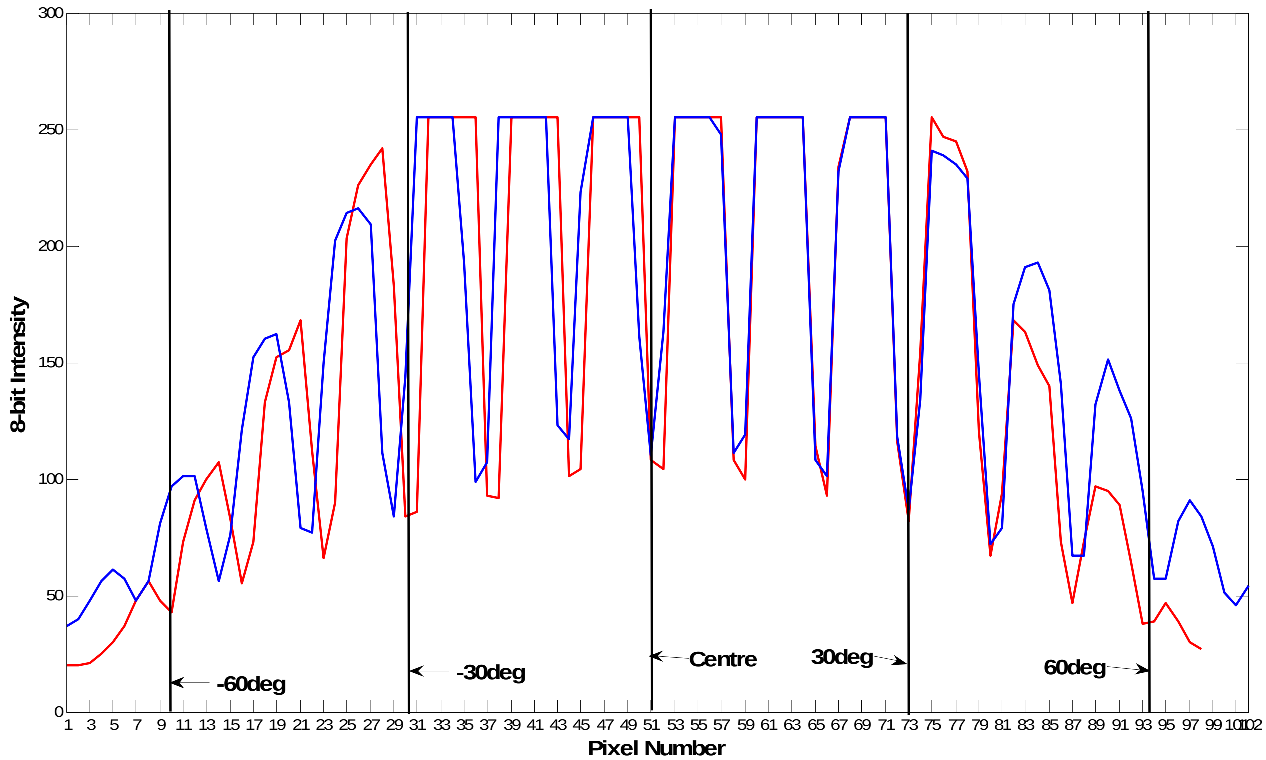


Figure 9 - Comparison Between Design Testing and Prototype Testing

4.1.2 Gyroscope Tests

The gyroscope circuit was based on a sample circuit provided in the component's datasheet, the only difference being a voltage divider on the output to scale down the output voltage maximum from 5V to 3.3V. The gyroscopes were tested using an oscilloscope and multimeter. It was determined that they worked within operating limits, although their output voltage was near the bottom bound specified in the datasheet. Table 2 summarises the operating conditions for each module.

Table 2 - Gyroscope Operating Conditions

Module 1 Gyroscope		Module 2 Gyroscope	
At-Rest Voltage	1.30 V	At-Rest Voltage	1.32 V
Min Voltage	0 V	Min Voltage	0 V
Max Voltage	2.92 V	Max Voltage	3.12 V

4.2 Deviations from Original Design Functionality and Specifications

4.2.1 Inclusion of Gyroscope in Final Design

The final design contained one major deviation from the original, which was the inclusion of the gyroscope in the prototype module, as mentioned in the Section 3.1.2. The gyroscope had several effects on the original design specifications.

Firstly, the weight of each module increased significantly. Each gyroscope weighs approximately 0.4g, and requires several external resistors, capacitors and a step-up voltage converter (the gyro runs on 5V, whereas the battery provides only 3.3V), which in total increase the weight of each module by 0.45g. Although the total weight of the vision system (2 modules at 0.84g/each = ~1.9g) did not meet the specifications of <1.5g, ignoring the weight of the gyroscopes and associated circuitry puts the weight of the vision system alone well within the original specifications. The F2 had only 1 gyroscope (unlike the 2 now included in the miniCeline), and it was mounted on the main board and was thus not included as part of the weight of the vision system. See Table 3 for a weight breakdown of the module.

Table 3 - Weight Breakdown of 1 Vision Module

Camera Components	
Trimmed TSL3301 Sensor	0.14g
Lens Casing and Lens	0.17g
Printed Circuit Board	0.08g
Camera Total	**0.39g**
Gyroscope Components	
ADXRS-150 Gyroscope	0.37g
Step-Up Converter	0.01g
Resistors, Capacitors in Gyro Circuit	0.07g
Gyroscope Total	**0.45g**
MODULE TOTAL	**0.84g**

The addition of the gyroscopes to the system also increased its total power consumption. Each gyroscope consumes 30mW during operation, and some power is also dissipated in the step-up converter and the rest of the gyro's external components. This contributes significantly to the total power dissipation of the 2-module system, which is around 100mW during normal operation. Even without the gyroscopes, the vision system's power consumption would still not have been less than 10mW, however it is still efficient enough to not be a heavy burden on the robot's battery.

4.3 Exceeded Requirements, Improvements from Previous Design

The main goal of this project was to cut the weight of the flying robot's vision system in half, and this goal was achieved. The F2 robot's vision system weighed 2g, whereas the new system weighs approximately 0.8g (not including gyroscopes and associated circuitry). Aside from the weight of the modules themselves, however, the new vision system decreased the weight of the rest of the robot's electronics by decreasing the weight added by the gyroscopes and their related circuitry and PCBs. The new system also contains several other important improvements, including modularity and the ability to run an altitude control algorithm. These improvements are presented in greater detail in Table 4.

Table 4 - Improvements in New miniCeline Vision System from F2 Vision System

Improvement	Description
Decreased weight of vision system	Total weight of the vision system was decreased from 2g (on the F2) to approximately 0.8g. Taking into account the two gyroscopes and associated circuitry, the two modules weigh a total of 1.9g.
Decreased total weight of robot	Placing the gyroscopes on the same PCB as the vision sensor eliminates the need for additional PCBs, and further decreases the total weight of the robot.
Altitude control	The F2 included could only detect Left and Right VDs and lateral rotation, data which will be detected by a single module on the miniCeline. The second module on the miniCeline will provide data on the Down VD and pitch rotation of the robot, giving it the ability to run the altitude control algorithm.
Increased Field of View for EL-20 lens	The EL-20 lens in the custom packaging designed for the F2 had a FOV of only 70º. The new casing designed for the miniCeline, along with its focus distance and aperture size, increased its FOV above 120º.
Modular Design	As mentioned in the Section 3.1.1, the modular design of the vision system provides the miniCeline with more flexibility than the F2, and is an attractive package for future OF-based navigation systems.
Increased number of usable pixels on TSL3301 photodiode array	Whereas the F2's vision system could only use 50 pixels of the 102 available on the TSL3301, the new lens/casing package creates a usable image on ~90 of the sensor's pixels

5 Discussion and Conclusions

5.1 Novelty of Design

The final result of this project was a brand new vision system that is not only a miniaturisation of the F2's vision system, but has several new interesting features that can be exploited in future research in OF navigation. The drastic reduction in weight of the system means that it can be used with the miniCeline platform, bringing closer the final goal of a 10g autonomous flying robot. Adding the Down VD to the robot makes it capable of controlling its altitude as well as its lateral direction, which shall make the miniCeline the first plane-based robot at LIS capable of complete autonomous flight.

The modular aspect of the new vision system gives it flexibility beyond the miniCeline platform. The module has already been successfully interfaced with the Khepera robot and used by several other students in their related research. As the project moves beyond the miniCeline platform, the modules can continue to be used on other robots, that is until a replacement is designed with even newer technology.

5.2 Possible Future Changes/Improvements

Available technology was the main limiting factor in this project. More than half of the weight of each module was due to the gyroscope and its associated external capacitors/resistors. A new gyroscope built in a lighter package with no need for external components could significantly reduce the weight of the module. A low-power gyroscope running on 3.3V would also eliminate the need for a step-up converter and would probably drain less power from the battery, further improving efficiency.

The photodiode sensor array also contributed to the weight of the system. Linear arrays in smaller packages are already on the market, although they do not yet meet all performance requirements. If a faster and more powerful microprocessor will become available with a similar package size and power consumption as the current model that is in use, it will be possible to move towards a 2D CMOS sensor. Such a sensor has the potential of greatly improving the navigational accuracy of the robot by providing it with more data on its surroundings.

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2 Zufferey, J.C. **Bio-inspired Vision-based Flying Robots**. Thèse n° 3194, Faculté Sciences et Techniques de l'Ingénieur, EPFL, 2005.

3 Gillet, L. **Optic-flow-based Navigation for an Ultra-Light Indoor Aircraft.** Projet de Semestre, Laboratory of Intelligent Systems, Faculté Sciences et Techniques de l'Ingénieur, EPFL, 2005.

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5 Taos inc. **Linear Array Product Line.** http://www.taosinc.com/category.asp?cateid=3, as of 20 June 20, 2005.

6 Microchip. **PIC18F6720 Product Page.** http://www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=1335&dDocName=en010315, as of 20 June 20, 2005.

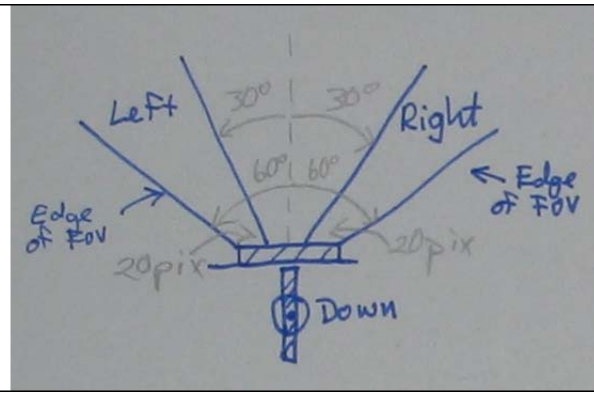
7 Salmaron, A. F. **Multi-1D Miniature Vision Sensor.** Projet de Diplôme, Laboratory of Intelligent Systems, Faculté Sciences et Techniques de l'Ingénieur, EPFL, 2005.

8 Analog Devices. **ADXRS150 Datasheet.** http://www.analog.com/en/prod/0,2877,ADXRS150,00.html, as of 20 June 20, 2005.

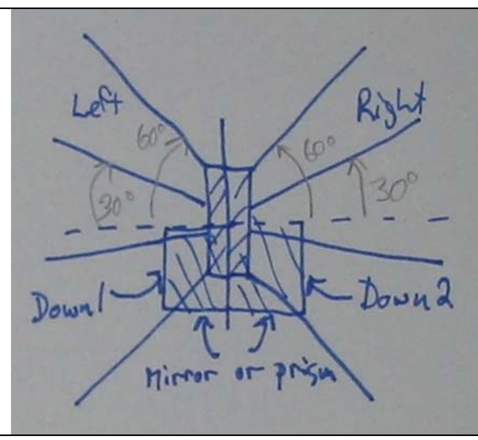
Appendix A – Updated Project Budget

Item	Manufacturer	Part No.	Source	Price
Characterization Setup material (used for characterization experiments for camera and lenses				
Custom PCB for mounting sensor used for testing	ACORT lab at EPFL	Custom	EPFL in-house PCB workshop	50chf
Digital sensor array	TAOS	TSL 3301	Advanced Electronics	11.70chf
Khepera Robot (used as base for testing)	K-Team	Khepera-I	Provided by LIS	N/A
2 Lenses	Applied Optics Group	EL-20	Advanced Electronics	4.60chf
Prototype Material				
4 Linear Sensor Arrays	TAOS	TSL 3301	Advanced Electronics	46.80chf
2 Lenses	Applied Optics Group	EL-20	Used from charac. experiment	N/A
Custom PCB for mounting camera system	ACORT lab at EPFL	Custom	EPFL in-house PCB workshop	150chf
Celine Flying Robot	DIDEL	mini-Celine	Provided by LIS	N/A
2 Gyroscopes	Analog Devices	ADXRS-150	Advanced Electronics	110chf
Various Other Expenses				
Computer Workstation		N/A	Provided by LIS	N/A
Various Electronic Parts (such as connectors, cables, resistors, etc.)	Various	Various	Provided by LIS	50chf
			Total	423.10chf

Appendix B – Camera Orientation Comparison

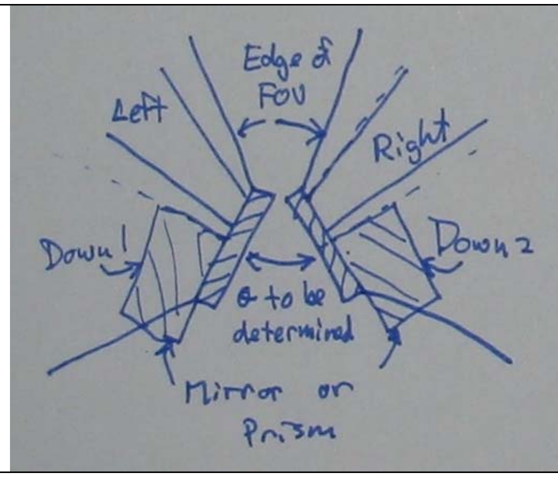
<table>
<tr>
<td>Design #1: One camera in front, one looking down</td>
<td>
</td>
</tr>
<tr>
<td>Advantages:

Simplest solution, requires only 2 cameras and 2 lenses with no need for additional optics
Down image has full FOV of entire camera, pointed parallel to the direction of travel of the robot
Requires only 1 additional PCB (for Front Camera)
</td>
<td>Disadvantages:

Left and Right images will not be very clear because of the wide angle, resulting in blurring, low light intensity and long integration time
Left and Right images each have only 20 pixels of data available
</td>
</tr>
<tr>
<td>Design #2: Two cameras pointing 90º left and right from direction of travel, with mirrors or prisms reflecting light from the ground</td>
<td>
</td>
</tr>
<tr>
<td>Advantages:

Requires only 2 cameras
Possibility to adjust mirrors/prism to provide slightly different angle of ground for each Down image
Requires only 1 additional PCB
</td>
<td>Disadvantages:

Left and Right images have same FOV as in Design #1, and thus have same problem of blurring, etc.
Down image not as clear because of distortions caused by optics
Down image split into 2 separate images, each providing only half the amount of pixels and FOV
Added weight and complexity of mirrors/prisms
</td>
</tr>
</table>

Design #3: Two cameras pointing at an angle <90º left and right from direction of travel, with mirrors or prisms reflecting light from the ground	
Advantages: - Requires only 2 cameras - **Left and Right images clearer than in Design #2 because of decreased angle from centre of camera**	Disadvantages: - Down image not as clear because of distortions caused by optics - Down image split into 2 separate images, each providing only half the amount of pixels and FOV - **Down image no longer parallel to direction of travel** - Added weight and complexity of mirrors/prisms - Requires 2 additional PCBs

Appendix C – Design Experiments

C.1 Complications with the Experimental Setup

The first experiment that was conducted to measure the FOV of EL-20 lens in its new casing involved placing it in front of black-and-white striped wall and counting the number of stripes visible on the photodiode array (Figure C-1 is a picture of this setup). Since the width of the stripes was known, the width of the wall seen by the sensor could be calculated. This width, along with the distance of the sensor from the wall, could then be used to calculate the FOV of the lens.

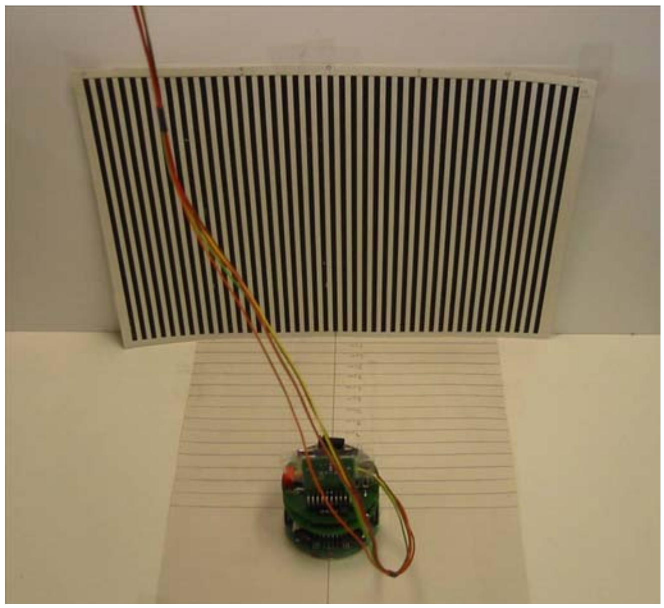


Figure C-1 - Original Flat-Wall Experimental Setup

This setup provided several problems. The focus of the lens was set to provide a good image at its centre. Since the distance to the wall increased as the angle from the centre increased, the image coming from the outer edges of the lens' FOV was blurred. The images of the black and white bars were also much thinner at higher angles from the centre because they were farther away than the bars in the centre (see Figure C-2).

Figure C-2 - Typical image from experiment #1, with thin and blurred lines on outside edges

These problems were solved by creating a new test bed with a circular wall (see Figure C-3). This new setup guaranteed an equal distance between the sensor and all points on the wall. Angles were drawn directly on the test board to ease the measurement.

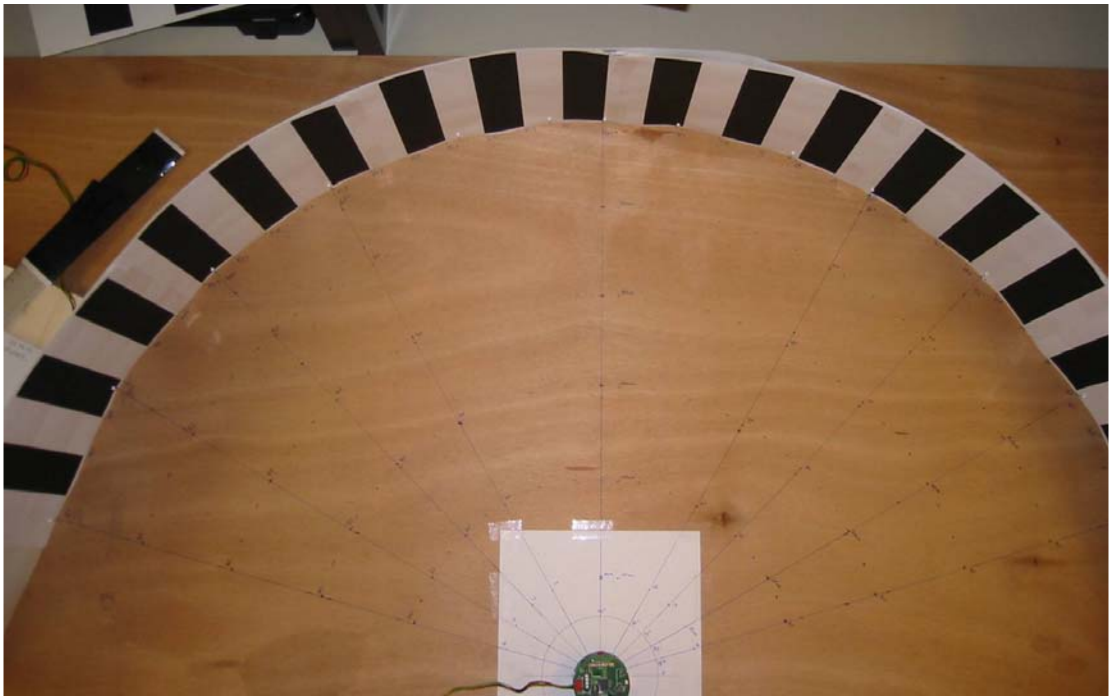


Figure C-3 - Circular-Wall Experimental Setup

C.2 Determining Focal Length and Aperture Size

The optimal Focal Length (FL) and Aperture Size (AS) were two important characteristics that had to be determined before the design of the lens casing. Unlike the old threaded system in the F2, the new lens casing had an opening just big enough to fit the lens, not giving much leeway in adjusting the focus of the lens. The theoretical focal plane of the EL-20 lens lies at 3.4mm, however it was not evident whether this length would provide the best image near the edges of the lens' FOV. Diffraction through the plastic casing before the light reaches the photodiodes may also affect the focal length. As for the aperture size, intuition suggests that the bigger the aperture size, the more light coming into the sensor and thus the shorter the integration time. It is not clear however whether a large aperture size will result in a lower-quality image because of a change in diffraction through the aperture.

The Circular-Wall Experimental Setup shown in Figure C-3 was used for the FL and AS experiments. The wall was white with black bands at 10º intervals, making it easier to analyse the images from the camera. Images were taken while the integration time was incremented by 200µs. 3 different aperture sizes were used: 0.5mm, 1.0mm and 1.5mm. Each of these aperture sizes was tested with 1 of 3 focal lengths: 3.0mm, 3.5mm, and 4.0mm. The intensity values of each pixel at each integration time were then analysed using Matlab and Excel.

The main factor used to judge image quality was contrast, defined as the difference between a white and a black band. For the Down VD the contrast was averaged over the middle 60º (middle black band and three black bands to either side) to determine the FL and AS with the highest contrast. For the Left and Right VDs, the contrast of the image between 30º and 60º on either side of centre was used as the deciding factor. Figures C-4 and C-5 show intensity plots that have the maximum contrast values for the Down VD and the Left/Right VDs, respectively.

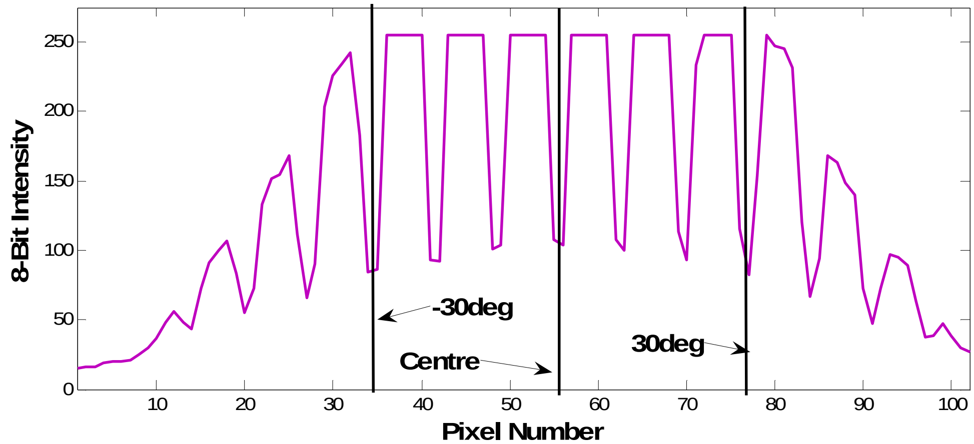


Figure C-4 - Highest Contrast for Down VD (1.5mm aperture, 4mm FL, int time 100us)

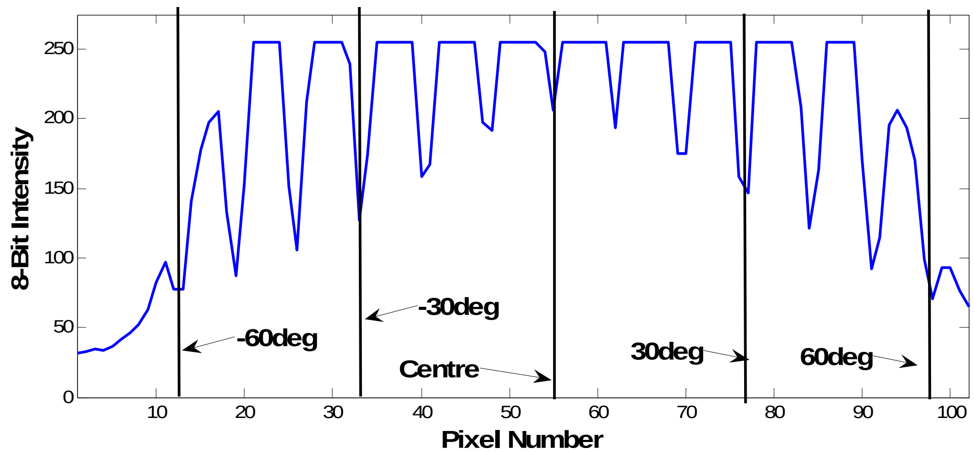


Figure C-5 - Highest Contrast for Left and Right VDs (0.5mm aperture, 4mm FL, int time 800us)

The results of the experiment showed that, as predicted, bigger aperture sizes led to shorter integration times to have similar images. There was however no significant blurring caused by the increase in aperture size. This was the case for all three VDs, and thus an aperture size of 1.5mm was chosen as the aperture size of the prototype modules. Figure C-6 shows two images with some of the highest contrast values taken with 2 different aperture sizes. The blue curve (1.5mm aperture) was taken with an integration time of 200μs whereas the red curve (0.5mm aperture) was taken with a 600μs integration time.

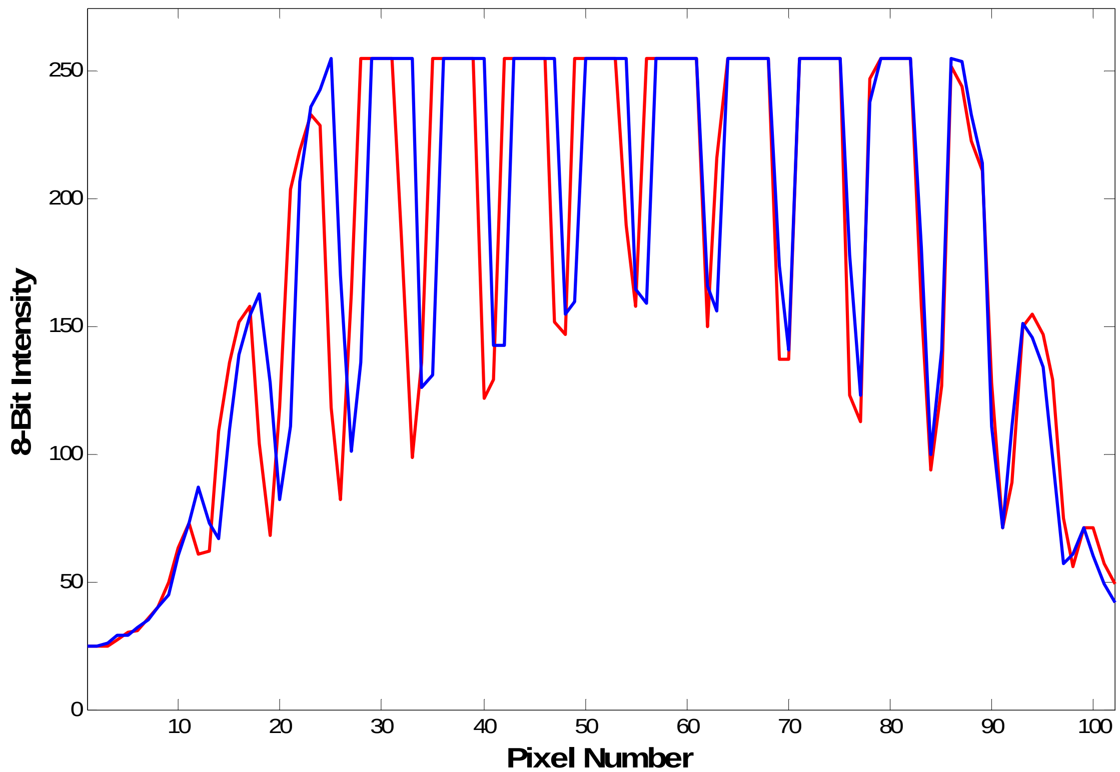
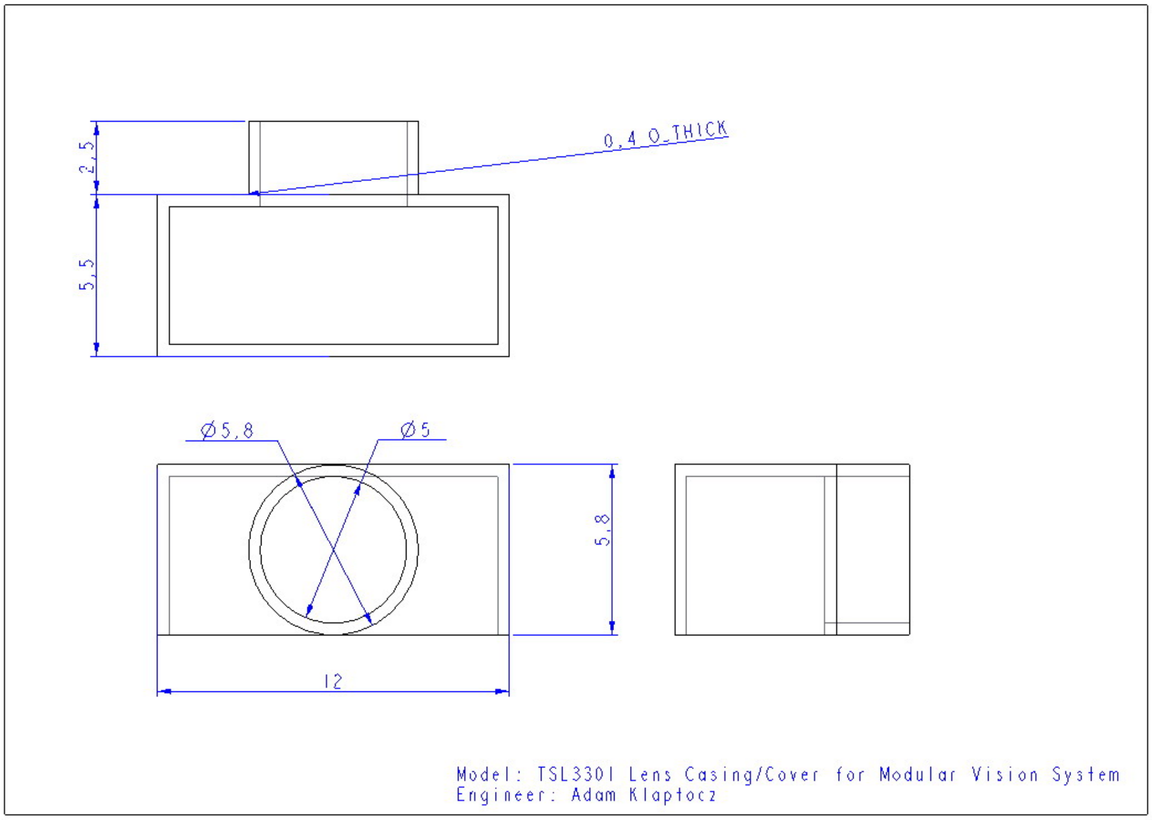


Figure C-6 - Image taken by 1.5mm aperture (blue) and 0.5mm aperture (red)

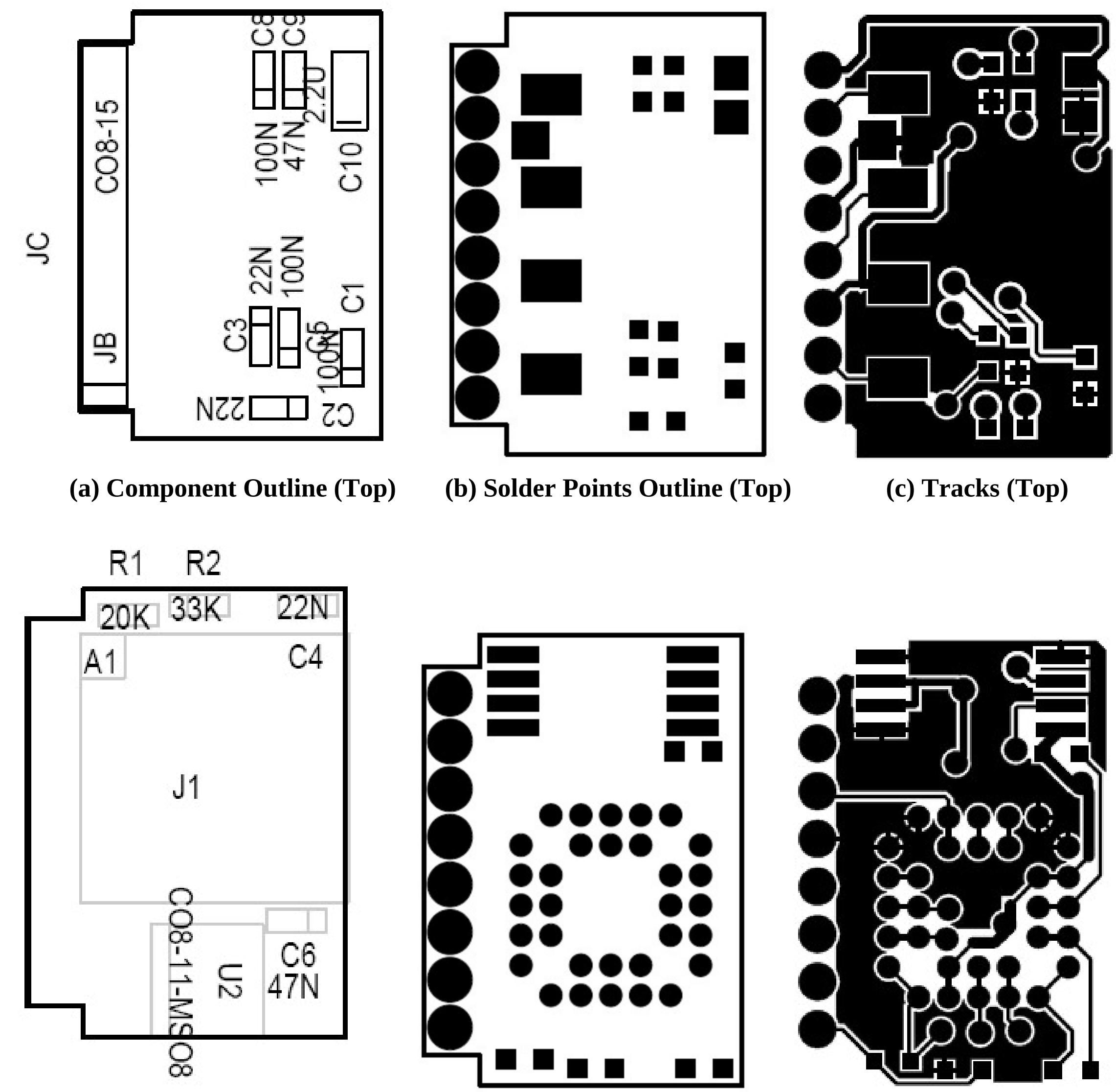
Experimental results also showed that the greatest contrast was achieved with a 4mm focal length for all 3 VDs. This suggests that light is slightly refracted as it passes through the plastic package of the TSL3301, or that the characteristics stated in the data sheet are no longer accurate when the lens is removed from its factory casing. A 4mm focal length was integrated into the design of the lens casing.

Appendix D – Overall Design Schematics

D.1 Lens Case Schematics



D.2 PCB Schematics



(a) Component Outline (Top) **(b) Solder Points Outline (Top)** **(c) Tracks (Top)**

(d) Component Outline (Bottom) **(e) Solder Points Outline (Bottom)** **(f) Tracks (Bottom)**

Figure D-1 - Component, Solder Points and Tracks Outlines for Top and Bottom of PCB

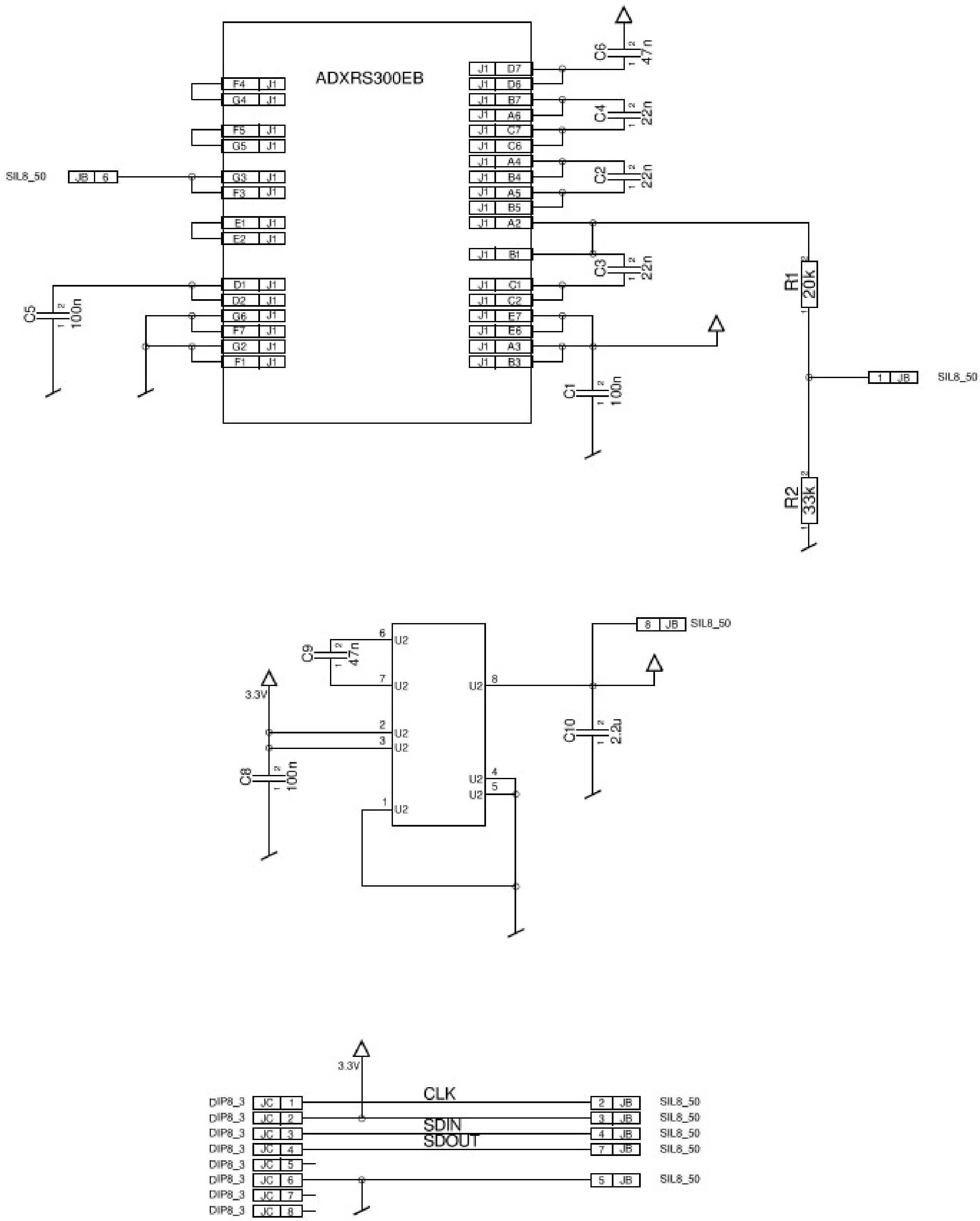


Figure D-210 - Connection Diagram for PCB

Appendix E – Vision System Specifications

E.1 Camera #1 (Red Cables)

Table E-1 - Pixel/Angle Relationship - Camera 1

Angle	Pixel Number	Angle	Pixel Number
-75	N/A	05	56
-70	N/A	10	59
-65	6	15	62
-60	8	20	66
-55	13	25	69
-50	15	30	74
-45	20	35	76
-40	23	40	81
-35	27	45	83
-30	30	50	88
-25	34	55	90
-20	38	60	95
-15	42	65	97
-10	45	70	101
-05	49	75	102
00	52		

Table E-2 - Electrical Characteristics - Camera 1

System Characteristics	
Current Draw*	14.58 mA
Power Consumption*	48.7 mW
Gyroscope	
At-Rest Voltage	1.30 V
Min Voltage	0 V
Max Voltage	2.92 V

*at Rest (ie. no rotation of camera) using Khepera robot power supply, mean value of supply voltage is 3.34V with a Peak-Peak noise of 280-400mV.

Table E-3 - Left and Right VDs Pixel Numbers and Average Contrast Values

	Left Side				Right Side			
Red	Number of Pixels, -60deg - -30deg	Average Contrast (-60 - -30)	Average Contrast (-55 - -35)	Average Contrast (-50 - -40)	Number of Pixels, 30deg - 60deg	Average Contrast (60 - 30)	Average Contrast (55 - 35)	Average Contrast (50 - 30)
95	23	109.17	112.75	124	22	102.83	123.75	136.5
80	23	104.33	104.75	106	22	102.17	118	120.5
90	23	108.33	111.75	120.5	22	101.67	122	131
85	23	106.83	109	114	22	101.00	118.75	125
105	23	108.17	113.25	128	22	100.17	122.75	134
100	23	108.33	114.25	129.5	22	100.00	122.25	134
75	23	97.83	98.5	99	22	95.17	108.75	108.5
110	23	101.67	106	117.5	22	94.83	117.75	125.5
115	23	101.67	105	114.5	22	92.83	115.5	121.5
70	23	93.33	94	95	22	89.67	102	100.5
120	23	101.33	104	111	22	88.33	110.75	115
130	23	95.00	96.75	100.5	22	85.33	109	109
125	23	95.17	97.5	102	22	85.17	108.25	108.5
65	23	84.83	85.75	87.5	22	82.33	93.75	92
135	23	91.17	91.75	93	22	78.83	101.5	101.5
60	23	79.33	79.25	79.5	22	77.00	88.25	86
140	23	91.00	91.5	91.5	22	76.17	98.5	98.5
55	23	75.67	75.75	75.5	22	74.33	85	83
50	23	68.83	69	70.5	22	66.50	76	74
45	23	62.67	62.75	64	22	63.17	71.75	71
40	23	55.83	56.25	58	22	55.17	62.75	61
35	23	49.00	50	51.5	22	50.83	57.5	57
30	23	45.50	46	47.5	22	44.00	50.25	49.5
25	23	38.83	38.5	38	22	38.83	44.5	43.5
20	23	33.17	33	34	22	33.00	38	38

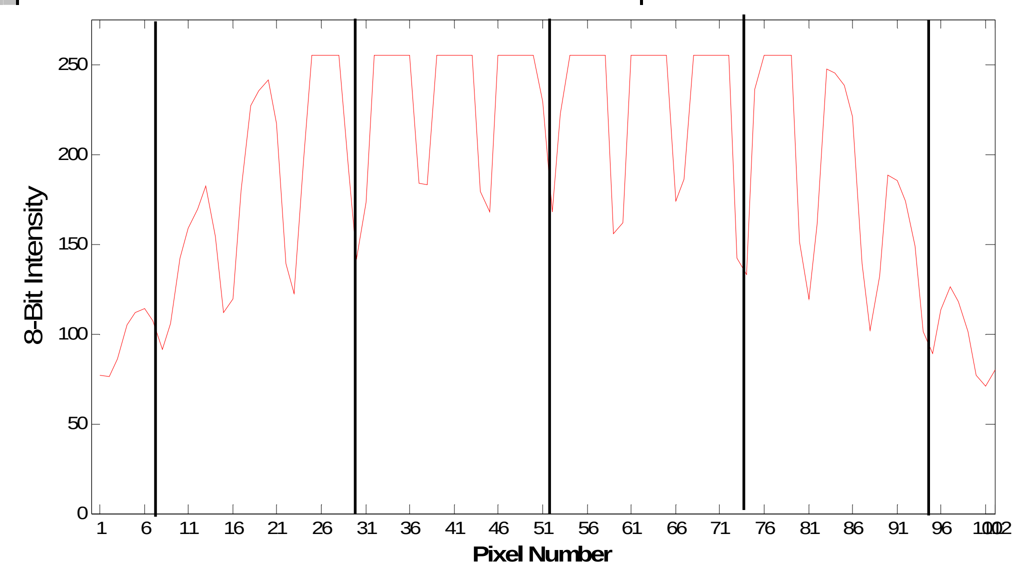


Figure E-1 - Maximum Average Contrast for Left and Right VDs (int time 950us)

Table E-4 - Down VD Pixel Numbers and Average Contrast Values

Red	Number of Pixels, -30deg - 30deg	Number of Pixels, -40deg - 40deg	Average Contrast (-40 - 40)	Average Contrast (-35 - 35)	Average Contrast (-30 - 30)
65	45	59	133.875	135.0714	138.75
60	45	59	131.8125	134.0714	138.9167
70	45	59	130.5	129.7857	131
75	45	59	128.4375	126.1429	125.6667
55	45	59	128.125	130.5	135.3333
80	45	59	121.3125	117.2143	114.0833
50	45	59	116	118.1429	122.75
85	45	59	113.5625	109	105.8333
45	45	59	108.5625	110.5	114.5833
90	45	59	106.125	101.2857	98
95	45	59	99.4375	94.42857	90.58333
40	45	59	96.9375	98.92857	102.9167
100	45	59	88.4375	83.28571	79.33333
35	45	59	88.0625	89.71429	93.08333
105	45	59	85.3125	79.85714	75.58333
30	45	59	75.25	76.57143	79.33333
110	45	59	73.75	68	63.75
115	45	59	68	62.14286	57.58333
25	45	59	66.5625	67.85714	70.41667
120	45	59	60.8125	54.57143	49.91667
20	45	59	55.875	56.92857	59.08333
125	45	59	51	44.57143	40.16667
130	45	59	48.125	41.28571	36.33333
135	45	59	39.4375	32.57143	27.41667
140	45	59	34.75	27.57143	22.41667

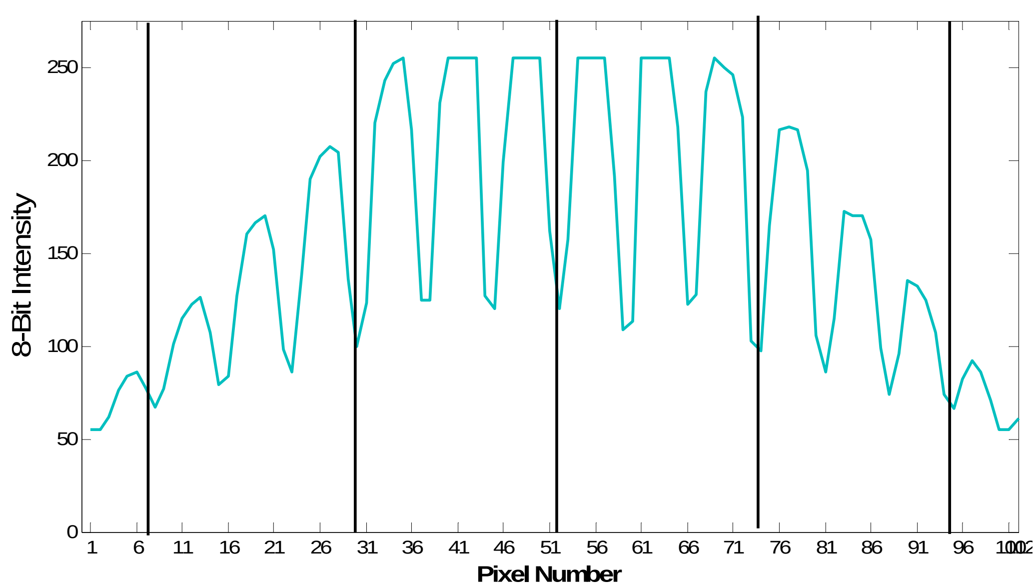


Figure E-2 - Maximum Average Contrast for Down VD (int time 650us)