Department of Electrical Engineering and Electronics, UMIST

Third Year Project Report

Sensor Head for Diffusion Imaging System

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Abstract

The knowledge of blood flow is an increasingly important factor in modern medicine. This report details using a diffusion imaging system to map the position of blood vessels below without the requirement of surgery, concentrating on the design of a suitable scanning head.

The method employed uses an LED emitting at 880 nm as the light source and an a pair of instrumentation photodiodes as a differential measurement system. Source and backscattered light is guided between the scanning head and the scanning site be means of optical fibres. The system designed has a thermal stability of $\pm 0.606\,\%\mathrm{K}^{-1}$ and an overall noise level under constant temperatures of $\pm 0.213\%$.

The blood vessel maps produced by an imaging system such as this could be used in the diagnosis and monitoring of various physiological conditions to help identify the boundary between healthy and damaged tissues.

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Chapter 1

Introduction

1.1 Diffusion imaging

When a collimated beam of light is incident upon a layer of skin tissue, much of the light is reflected or absorbed by the skin. Some of the light, however, will pass into the skin and undergo multiple scattering [3]. Some of this light reaches the skin surface again, where the intensity of the light can be detected.

If the light passes through a blood vessel whilst being scattered, most of the light will be absorbed due to high levels of attenuation in the blood flowing through the vessel. As a result, the optical power detectable at the surface will be reduced.

The distance between the incident light beam and the detection site affects the effective scanning depth [3], as shown in figure 1.1 on the following page.

1.2 Project specification

The aim of this project is to reproduce a diffusion imaging system described in a recent research paper [3]. This paper described a method for using optical diffusing imaging to map the position of blood vessels under the skin using a system comprising of a small sensor head with a light source, detector and a small mechanical mounting, a scanning mechanism to move the mounting over the scan site and a computer program to analyse the detected light levels and product a visual map of blood vessel positions.

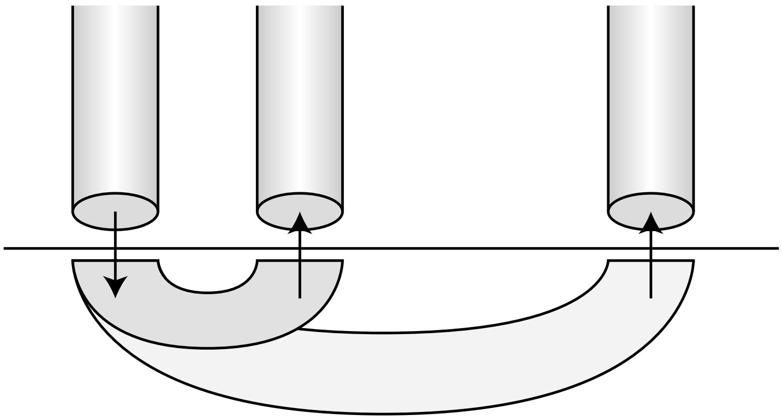

Figure 1.1: Graphical representation of how changing the source-detector distance affects the effective scanning depth

The aim of this project is to produce an equivalent sensor head without the need for an optical power meter. The design should meet or exceed the specification of the original. The design should provide an approximately collimated incident beam and a directional detector.

1.3 Ultimate Goal

The aim of my project is to produce a working scanning head equivalent to the one described in section 1.2. Two other projects are being carried out concurrently to produce both an equivalent scanning mechanism for moving the scanning head and some computer software to analyse the signals returned by the scanning head.

The secondary target for these projects is to bring together the individual modules after their completion and form a single system that can automatically scan an area of skin and produce an image mapping the blood vessels below this area.

As such, the interfaces between the modules must be defined to ensure that once the individual components are completed, they can be brought together to successfully operate as a single system.

1.4 Previous work

1.4.1 Background

The specification that has to be matches is described in a research paper entitled "Optical non-invasive technique for vessel imaging" (Phys. Med. Biol. 45 (2000) 3765-3778). This paper uses a near infrared LED emitting light with a wavelength of 890nm. This light is guided to the scanning site by means of an optical fibre.

The reflected light is guided from the scanning site to the detection hardware through an identical optical fibre. The detection hardware used in this system was a dedicated optical power meter. A microcomputer and program was used to graphically display spatially resolved reflectance at the surface of the skin.

1.4.2 Limitations

The main disadvantage of using such a system is the high cost of the optical power meter. The model specified is a Newport 835 power meter, which has a single unit cost of around £2 000. One of the main aims of this project is to find an alternative detector that does not compromise the overall effectiveness of the system.

The original system uses a single-ended optical power detection system. If there are any changes in source light levels, for example from fluctuations in the power supply to the LED, these would get directly translated into readings at the detector. Similarly, the single-ended system provides limited compensation for the thermal instabilities of the devices used in the scanning head.

Chapter 2

Design

2.1 System specifications

Since this project is attempting to meet or exceed the performance of a previously designed system, the specifications of the original system needed to be understood in order to check that the requirements are being met.

2.1.1 Light source

The light source used in the original system was a Hamamatsu L2690 890 nm LED. Light from this device was passed through a Melles Griot SELFOC gradient index lens and into an Ensign-Bickford HCPM 1000 T-10 optical fibre.

2.1.1.1 LED

The Hamamatsu L2690 LED has the following characteristics:

- 890 nm wavelength light output.
- 14 mW radiant optical flux (at 50 mA current).
- 1.45 V forward voltage (at 50 mA current).
- 0.4×0.4 mm square emission size.
- Non-reflective packaging.
- 0.28dB optical power output change per 10 °C temperature change.

2.1.1.2 Optical fibre and lens

Information on the exact optical fire used, which is described as "HCPM 1000 T-10, NA=0.37, Ensign-Bickford Optics Company, USA" is difficult to obtain. It is stated in the report that a 1 mm diameter fibre was used, indicating that a 50/125 or 62.5/125 fibre would have been used as these types often have an outside diameter of 1 mm.

The light generated by the LED is passed through a 0.25 pitch Selfoc lens to increase the collimation. This is a gradient index lens that will focus collimated light onto a point source right at the edge of the lens.

Similar lenses are built into the packages of a number of commercially available LEDs. For these devices, the angular distribution of the light emitted from the device is around 10-15°.

2.1.2 Light detector

The light returning from the skin was passed along a similar optical fibre as was used in the source. This was coupled to a Newport Corporation 835 optical power meter. This product is now discontinued, and little information is available about its specifications.

As a comparison, the specifications for the similar Newport 819-IR optical power meter have been included in the component specification comparison tables in section 2.2 on page 25.

2.2 Sensor head arrangement

The blood vessel mapping method used by this project requires that a collimated beam of light is projected onto the skin. The reflected light is then detected by a device a known distance away from the light source.

The separation distance determines the effective depth at which the device will be scanning for blood vessels as described in section 1.1 on page 7, so the separation of the light source and detector must be adjustable to be able to scan for blood vessels at different depths.

This is the only external requirement placed on the sensor head itself. Any method could be used to guide and position the light before it comes into contact with the skin. Some possible arrangements are discussed below.

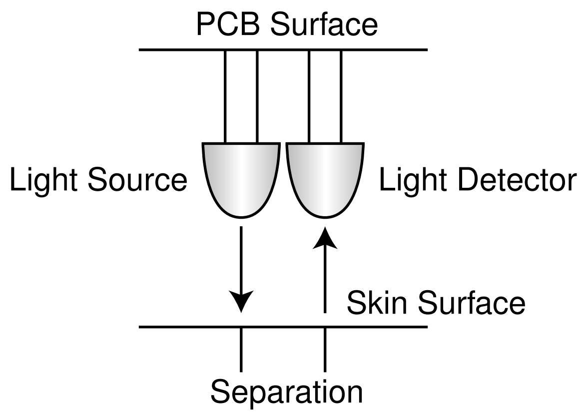

Figure 2.1: Direct positioning arrangement

2.2.1 Direct positioning

The light source and the detectors could be positioned directly above the skin surface, as shown in figure 2.1. The beam created by the light source assembly is projected directly onto the surface, and the reflected light is measured directly. This would be the simplest arrangement, providing benefits in the form of low costs and reduced sensor head complexity.

The main problem with this approach is getting the source and detector close enough to each other to allow shallow scanning depths. The source and detector would need to be as close as 2 mm from each other for the most shallow scans [3].

Another potential problem with this approach would be connection to the rest of the scanning system. At the very least, wires would have to run from the controlling circuitry to the light source and detector, which would have to move about in the Earth's magnetic field as the head moves. An estimate of the noise EMF that would be induced this way can be calculated as in equations 2.1 to 2.3:

$$B = \frac{\Phi}{A} \tag{2.1}$$

$$\varepsilon = \frac{d\Phi}{dt} \tag{2.2}$$

$$\varepsilon = \frac{d(BA)}{dt} \tag{2.3}$$

Where:

A Area bounding the moving wire.

B Earth's magnetic field strength, approximately $50\,\mu$T.

t time to move across one scan line, approximately 1 s.

Φ Magnetic flux.

ε Induced noise EMF (V).

If we assume that the head will be moving at a constant velocity, and that 50 cm long wires are used for connection, remaining perpendicular to the Earth's magnetic field, we can calculate the approximate induced noise EMF based on a 3 cm scan line as in equations 2.4 to 2.6:

$$\varepsilon = \frac{\Delta(BA)}{\Delta t} \tag{2.4}$$

$$\varepsilon = \frac{50 \times 10^{-6} \times 0.5 \times 0.03}{1} \tag{2.5}$$

$$\varepsilon = 7.5 \times 10^{-7} \tag{2.6}$$

Giving an approximate amplitude for magnetically induced noise of $0.75\,\mu$V. In the case of a phototransistor or an integrated photodiode and amplifier circuit, changes in light level as low as 1 mWcm^{-2} would provide an output changes of significantly greater than $0.75\,\mu$V. However, photodiode current changes would be much smaller, meaning that their signals could get lost in the noise generated by the environmental magnetic field.

2.2.1.1 Laser diode direct positioning

If a laser diode was to be used as the light source, the light output from the device would be collimated very well, allowing the device to be positioned further away from the skin than for an LED whilst still achieving acceptable collimation at the scanning site.

This allows by laser beam to be shone close to the edge of the detector's packaging, allowing for closer positioning of the source and detected beams. It does not, however, eliminate the problem of electromagnetic noise or the large, heavy packaging of a laser diode module.

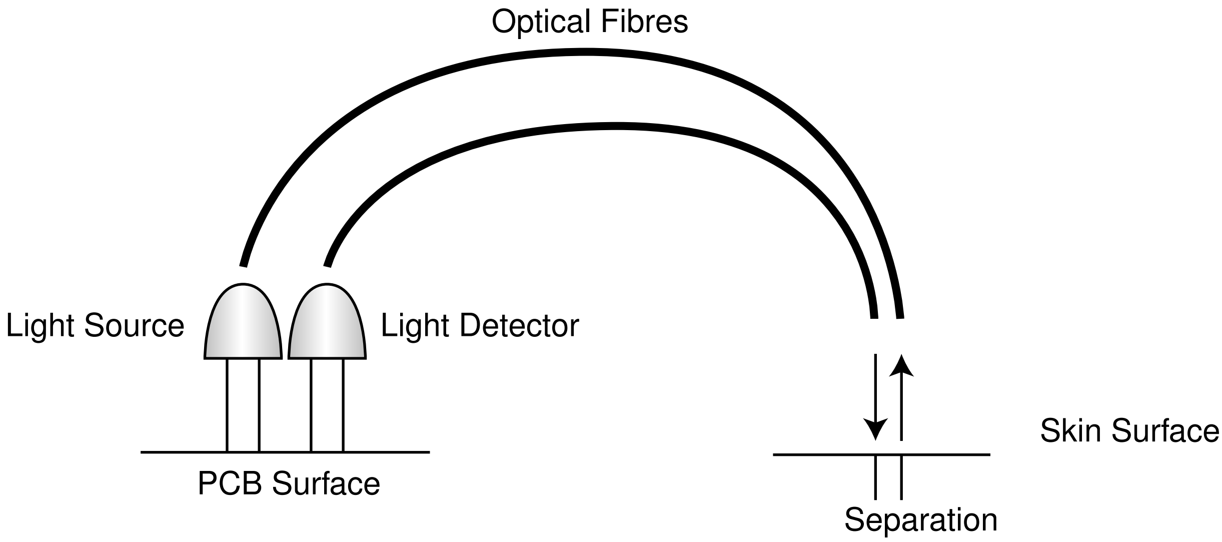

Figure 2.2: Optical fibre positioning layout

2.2.2 Mirror positioning

Collimated beams of light could be reflected off a rotating mirror onto the source and back again. This would allow the source and detector positions to remain constant, reducing electromagnetic noise without using optical fibres.

This approach, however, would require the mirror to be rotated through two axes, which would be a difficult task to achieve, especially within the accuracy and precision bounds demanded by this project. Using a single mirror approach would also alter the angle of incidence of the light beam onto the skin, which should remain constantly perpendicular to the skin surface throughout the whole scan.

The latter problem could be resolved by using an array of two or more mirrors moving as a system to reposition the beam. There are significant complexities involved with moving the mirrors which would take too long to work around, rendering this idea impractical in the given time scale.

2.2.3 Optical fibre positioning

It would be possible to position the light source and detector in a location separate from the scanner head itself, and use optical fibres to guide the light to and from the head assembly, as shown in figure 2.2. Since if using this method there would be no metallic conductors to be moved around, no EMF would be induced by moving the optical fibres.

In order to be able to position the centre of the source and the detector 2 mm away from each other, and without using a laser diode, some form of guidance such as optical fibres must be used because of the size of the packages of the source and detector components.

2.3 Losses

2.3.1 Causes of light loss

2.3.1.1 At the scanning site

The main loss of power in a diffusion imaging system such as this will be between the end of the light guidance system from the source, absorption in and under the skin and in the atmosphere between the skin and the detection light guidance system. If we assume no losses between the light source and the detector apart from at the scanning site, we can estimate the maximum optical power to be detected.

If absorption in the skin is ignored, we can consider all the power incident upon the skin to be available to be detected. As the light gets scattered, however, it will radiate in all directions. This can be modelled as a point source of light on the surface of the skin [3].

Optical power will dissipate in an approximately spherical manner. The output power will be spread across the surface area of this virtual sphere, which will have a curved surface. For simplicity, if a section of the surface area of a sphere is considered to be flat, at any point away from the point source the optical power will be:

$$P_d = \frac{P_s A_d}{4\pi r^2} \tag{2.7}$$

Where:

P_d Detectable power per unit area at the point in question (Wm^{-2}).

P_s Power dissipated by the point source (W).

r Distance from the virtual point source (m).

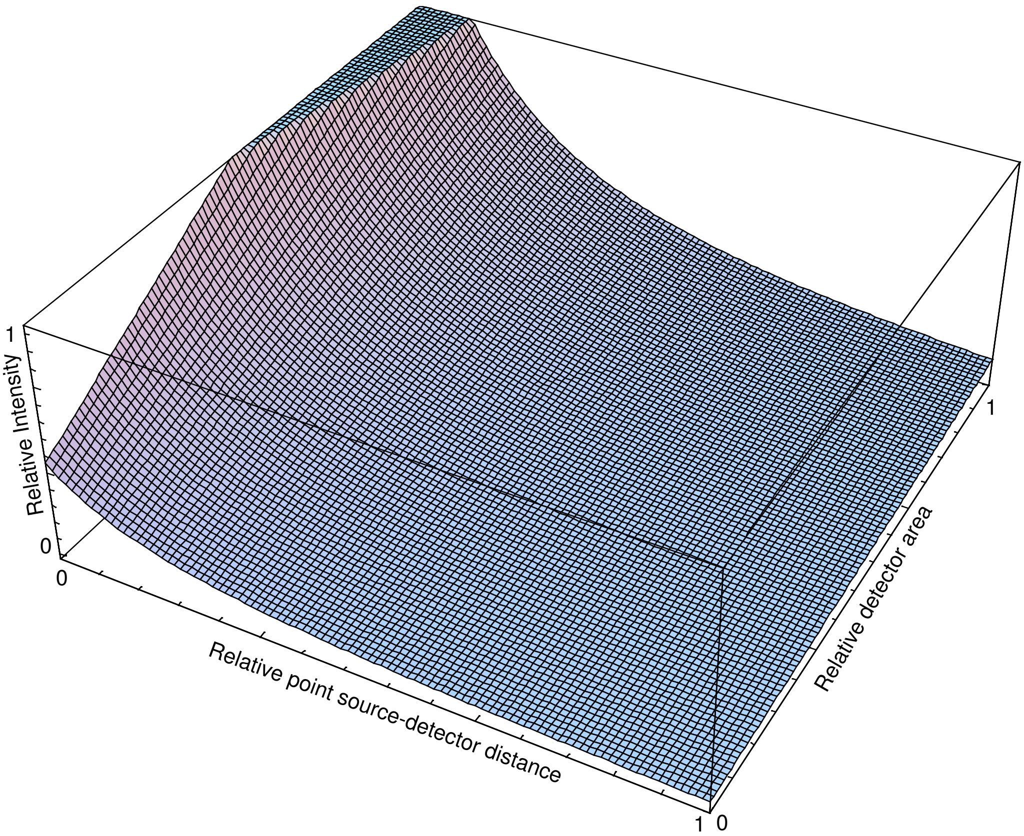

Figure 2.3: Light loss graphical illustration

A_d Detection area (m^2).

This relationship is illustrated graphically in figure 2.3 on the preceding page.

As an example, if the light source was emitting 7 mW of optical power, and the detector was positioned 2 mm away from the surface of the skin, the detectable optical power can be calculated by applying equation to give equations 2.8 and 2.9:

$$P_d = \frac{7 \times 10^{-3} A_d}{4\pi \times (2 \times 10^{-3})^2} \quad (2.8)$$

$$P_d = 139 A_d \quad (2.9)$$

Which is a power per unit area of 139 Wm^{-2}. Taking a photosensitive device with a circular photosensitive area of 1mm diameter, A_d and therefore the maximum power at the detector can be calculated as shown in equations 2.8 to 2.12:

$$A_d = 2.5\pi \times 10^{-7} \quad (2.10)$$

$$P_d = 139 \times 2.5\pi \times 10^{-7} \quad (2.11)$$

$$P_d = 1.09 \times 10^{-4} \quad (2.12)$$

So for this arrangement, the optical power at the detector will be about 0.109 mW, 1.56% of the power of the source.

2.3.1.2 Light guidance

The above assumptions will give a maximum optical power at the detector assuming the only loss is at the scanning site. This would be an acceptable model if the source and detector were to be directly positioned on the head close to the scanning site.

The effect of light dispersion along an optical fibre is to reduce the bandwidth of the fibre. Scanning a line of 100 data points was expected to take around 1-2 seconds, giving a worst case scanning frequency of 100 Hz. Because optical fibres have a bandwidth-distance product of hundreds of thousands of MHz.km, dispersions in the fibres can be considered negligible in this case.

Assuming optical fibres are used to guide the light from the source to the scanning site and then back to the detector, the attenuation of the fibre must be taken into account. In the near infrared region, attenuation in an average optical fibre will be in the order of 1-2 $dBkm^{-1}$. For this system, the fibres would need to be no longer longer than about a metre, leading to very small losses in light power from the attenuation of the optical fibres.

The main loss in optical fibres will be at the ends of the fibres as the refractive index of the material the light is travelling through changes. A typical loss due to reflection and refractive index change would be about 0.6 dB, allowing approximately 85% of the optical power to pass.

2.3.2 Optical power levels

2.3.2.1 Direct positioning

With direct positioning, the point source model will give an upper bound for the optical power level to be detected at the photosensitive element. As calculated in section 2.3.1.1 on the preceding page, the relationship between power at the detector, power at the source, area of the detector and distance from the point source to the detector can be modelled as:

$$P_d = \frac{P_s A_d}{4\pi r^2} \tag{2.13}$$

This assumes that the detection area is small relative to the surface area of the sphere, ie the curvature of the sphere's area can be ignored.

If the optical power emitted by the source is constant, the optical power incident on the detector will increase linearly with the area of the detector, and decrease linearly with the square of the distance the detector is positioned from the source.

For a typical detector with a circular 1mm diameter area, it was shown that about 6.25% of the optical power emitted from the source would be present at the detection area. For a typical light source providing 7 mW of optical power, this would cause a maximum of 0.437 mW of power to be incident on the detector.

Thus, this component arrangement, a detector with a 140 Wm^{-2} dynamic range is required.

2.3.2.2 Light guidance

If optical fibres are used to give the light from the source to the scanning site, then from the scanning site to the detector, additional losses will occur

Light source
↓ [1]
Source guidance fibre
↓ [2]
Scanning site
↓ [3,4]
Detection fibre
↓ [5]
Light detector

Figure 2.4: Positions of light loss in a fibre-guided scanning head

at the boundary between each stage, as indicated in figure 2.4 on the next page.

The losses at each transition can be summarised as follows:

1. Reflection and loss on light entering the source optical fibre (85% transmission efficiency).
2. Reflection and loss on light leaving the source optical fibre (85% transmission efficiency).
3. Light dispersion at the scanning site as described in section 2.3.2.1 on the facing page (6.25% transmission efficiency).
4. Reflection and loss on light entering the detection optical fibre (85% transmission efficiency).
5. Reflection and loss on light leaving the detection optical fibre (85% transmission efficiency).

This can be modelled as for the direct positioning system, but with an adjusted power output at the point source. The power of the detector would have to be multiplied by 0.85^4 to account for losses at the ends of the optical fibres. This would allow us to estimate:

$$P_d = \frac{0.52 P_s A_d}{4\pi r^2} \tag{2.14}$$

If we assume a typical set of components as for the direct positioning arrangement, ie a light source emitting 7 mW of optical power as for the direct positioning system described in section 2.3.2.1 on the preceding page, and an optical fibre placed 2 mm away from the scanning site, based on equation 2.14 we can say:

$$P_d = \frac{0.52 \times 7 \times 10^{-3} \times A_d}{4\pi \times (2 \times 10^{-3})^2} \quad (2.15)$$

$$P_d = 72A_d \quad (2.16)$$

Thus, in this case a detector with a 75 $\mathrm{Wm^{-2}}$ dynamic range is required.

2.4 Device considerations

2.4.1 Light source

2.4.1.1 Choice of device

Many different light sources are available, however the system requires close to monochromatic light in either the red, or near infrared wavelengths. Two types of light source seem suitable for this application at first glance:

- LEDs
- Laser diodes

Both devices will produce light of a narrow wavelength range, with the laser providing a narrower range of output wavelengths than the LED.

2.4.1.2 Collimated output

A major concern for the light source is obtaining a collimated beam. With most commercially available laser diode modules, the output light beam spreads at a very narrow angle, generally less than 1°. LEDs, however, can be modelled as emitting light in all directions.

Various manufacturers produce LEDs with lenses built into the package to produce a beam with a spread angle of 10-15°. These should provide a similar level of collimation to adding a 0.25 pitch Selfoc lens to the outside package of an LED. If a more collimated beam was required, an external lens would be required.

Using a spherical lens with a focal length equal to the distance between an LED and the end of its package would cause all light emitted from the LED through the lens to be collimated, assuming the light was emitted from a clearly defined point source. [5]

Since an LED emits light in all directions, many packages reflect light to point towards the front of the device to maximise light output. This would affect the focusing if an external lens were to be used. LEDs are available in non-reflective packages, such as the Hamamatsu L2690 as used in the original experiment [3]. This would greatly restrict the effective light source, allowing the lens to more accurately collimate the beam.

Collimating lenses are available for standard laser diode modules with a cost that is generally only slightly higher than that of a stand alone lens, as would have to be used with LEDs.

2.4.1.3 Output power

The absolute intensity of light emitted at the source has no effect on the percentage change of light intensity at the detector [3], so exact matching should not be required. This makes either an LED or laser diode suitable light sources in terms of the supplied optical power.

It would be interesting to look at how varying the incident light power affects the images produced by the system. This requires a method of limiting the output power of the source device in the circuitry for the sensor head. Such a mechanism could be easily implemented for either an LED or laser diode using current limiting resistors.

Throughout the duration of any scan cycle, a stable optical power output from the light source is important, so a stable current source would be required as the supply to the light source device.

2.4.1.4 Packaging

If the device were to be directly mounted onto the scanning head, it must be small and light enough so as to not impair the function of the overall system. The scanning unit itself will use precision actuators for the positioning of the head, so the head must be small and light enough that inertia does not cause a problem for the actuators.

LEDs are available in a variety of different packages and generally weigh very little. Laser diode modules are normally packaged in much larger containers, and weight considerably more than LEDs.

2.4.2 Light detector

2.4.2.1 Choice of device

There are many light detectors commercially available. The major groups are:

- Light dependant resistors.
- Photodiodes.
- Phototransistors.
- CCD arrays.
- Photovoltaic cells.

As mentioned in the feasibility report, included as appendix A on page 40, light dependant resistors and photovoltaic cells are not particularly suitable for very sensitive applications such as this. They are too non-linear and slow to respond to environmental changes.

CCD arrays at a basic level are arrays of photodiodes or photo MOS capacitors. Since this project is only interested in a single column of light that is being diffused through the skin, an array of detectors is unnecessary.

Photodiodes are normally put in circuits reverse biased, so under normal conditions negligible current would flow through the diode. However, the PN junction of the diode is exposed, and light falling on the junction will cause the generation of charge carriers, allowing larger currents to flow through the device.

Phototransistors work in a similar manner to photodiodes, except that the base of a bipolar transistor is exposed to light. This affects the current flowing through the base of the transistor, which is amplified as for a “normal” transistor to allow a current to flow from collector to emitter.

In terms of general device characteristics, photodiodes and phototransistors are most suitable for this application, and were the subject for further investigation.

2.4.2.2 Thermal stability

Almost all electronic devices change their characteristics along with their temperature. Since all electronics create heat, even controlling the ambient temperature will not completely eliminate this problem.

In many circuits, thermal changes are not a major concern. However, since the aim of the sensor head is to look for some very small changes against a much larger background field, thermal changes could conceivably be interpreted as a signal.

This problem is particularly important for the light detector. Any errors introduced here will be amplified in later stages, and could easily drown out the wanted signal. It is therefore necessary to use components with particularly stable thermal characteristics.

2.4.2.3 Drive requirements

The unit will be connected to a voltage-based analogue to digital converter (ADC). Ideally, such a device should have an infinite input impedance, but in practice a an input impedance of at least $10\,\mathrm{M\Omega}$ can be expected. At $10\,\mathrm{V}$, this would give a current of $10^{-5}\,\mathrm{A}$, which all listed light detection devices should be able to source.

Because of the small variations in signal, the signal from the light detector is needed to be amplified with respect to an adjustable reference voltage. This effectively allows the signal to be extracted from the background field.

One potentially useful side effect of such an arrangement is the low output impedance of an operational amplifier, which should be able to drive much higher loads. As mentioned above, this is not a significant factor for this particular project, but may be useful if the scanning head is ever used with different controlling and load hardware.

2.4.2.4 Device types

Phototransistors are particularly suited to low light level situations, as the current generated by the light would be amplified to more usable levels. The background light level for this application will be relatively high, which the changes in light level being important. Because of this, a photodiode would probably be more useful than a phototransistor.

Table 2.1: Light source specification comparison

Parameter	Hamamatsu L2690	Honeywell SE5470	Sharp GL514	Vector 785nm LD	DeHarpporte Red LD	Unit
Angular distribution	10	10	7	0.3	0.5	°
Aperture	1.0	3.4	3.0	4.5	—	mm
Wavelength	890	880	950	785	650	nm
Power output	14	7.0	3.31	3.0	<5	mW
Thermal stability	-0.028	-0.040	-0.040	-0.015	—	$dB.K^{-1}$
Package diameter	4.2	4.1	4.7	15	12	mm
Unit cost	—	3.16	3.73	131.58	19	£

Photodiode devices are available in integrated circuits containing integral amplifiers. This approach should reduce the overall system complexity. Noise picked up by external or PCB track runs will be reduced, and the number of voltage drops from interconnections will decrease.

2.5 Device specifications

2.5.1 Light source

The characteristics of some possible light source devices are summarised in table 2.1.

2.5.2 Light detector

The characteristics of some possible light detection devices are summarised in table 2.2 on the facing page.

Table 2.2: Light detector specification comparison

Parameter	Newport 818-IR Power Meter	Sharp PT510	Honeywell SD5443	Burr Brown OPT301	IPL 10530 DAL	Unit
Thermal stability	0.1	0.5	0.5	0.02	1.0	$\%K^{-1}$
Sensitivity	±2%	$2mA.cm^2mW^{-1}$	—	$0.24AW^{-1}$	$60V/\mu Wmm^{-2}$	—
Dynamic range	3	10	5	0.5-15	—	$mW.cm^{-2}$
Acceptance angle	90	6	10	40	10	°
Peak wavelength	850-1700	800	870	770	950	nm
Package diameter	3.0	4.7	4.8	9.4	8.3	mm
Unit cost	518	3.88	1.45	20.60	17.70	£

2.6 Component choice

2.6.1 Physical arrangement

Section 2.2 on page 11 gives details of some different positionings for the active components on the scanning head. The two most practical arrangements are the direct positioning and the light guidance by optical fibre arrangements.

The main problem with the direct positioning method is allowing the centre of the light source and the detector to get close enough to each other. To meet the specification of the original system, the centres of the active areas need to be as close as 2 mm to each other.

The smallest source device package has a diameter of 4.1 mm, and the detector (apart from the Newport power meter which is not acceptable for this project) is 4.8 mm. This gives a centre-centre separation of 4.5 mm as a minimum, without considering the need for shielding the devices to stop light leaking directly from the source to the detector.

Without using moving mirrors, which would create a lot of extra complexity, another option was to position the source and detector components away from the scanning head. Light could then be guided to and from the head using optical fibres.

This option creates the problem of having to couple the fibres to the light source and detector. Devices are available commercially to couple active optoelectronic devices and optical fibres, such as the Sweet Spot dry non-polished system, but only for a limited range of devices. Nonetheless, the optical fibre light guidance method was chosen for this project because it offered close proximity scanning without adding unsurmountable complexity.

Coupling arbitrary devices, in this case the light source and detectors, to the fibres was achieved by taking a block of solid plastic, and drilling a hole with a diameter equal to that of the device part of the way in to the block. The drill bit diameter was then changed to the diameter of the fibre to continue the drilling, the device and fibre could be held in close contact. A small amount of glue at the holder interface can be applied prevent the devices working their way loose.

This fixed termination approach is not suitable at the scanning head, as to meet the specification of being able to scan for blood vessels at different depths, the relative position of the source and detector fibres needs to be adjustable.

Various methods were considered to accommodate this requirement. The simplest method would be to have a series of holes the exact diameter of the fibre drilled into a sheet of material mounted on the scanning head. One of the fibres could be fixed in place, whilst the other could be positioned in any of the available holes. Similarly, a groove could be provided for one of the fibres to allow positioning anywhere within a certain range of positions. Each of these methods is hampered by the requirement to hold the fibre steady without increasing its effective outside diameter.

The method that was eventually chosen was to clamp both fibres at the sides and create a positioning system for the clamps themselves, providing a larger area to hold steady. The relative position of the clamped fibres can be adjusted to anywhere between 2 and 35 mm apart. Figure 2.5 on the following page and figure 2.6 on page 29 are photographs of the top and bottom side of the clamping mechanism.

2.6.2 Light source

The model described by equation 2.7 on page 15 shows that for a typical arrangement using optical fibres to guide the time between the source, the scanning site and the detector, an optical power density of around 72 Wm^{-2} would be present as a maximum at the detector. The detectors shown in table 2.2 on page 25 have dynamic ranges of between 0.5 and 15 Wm^{-2}.

It is also sown in equation 2.7 that several factors influence the power at the detector (assuming all others factors remain constant):

- The detector power is directly proportional to the detector area (area of the optical fibre in this case).
- The detector power is directly proportional to the source power.
- The detector power is inversely proportional to the square of the distance between the detector fibre and the scanning site.

The easiest way to reduce the power levels at the detector, if required, would be to reduce the source power levels. The original experiment found that the percentage change in power levels at the detector was approximately constant as the incident power was varied, so adjusting the power output of the source should not affect the sensitivity or range of the system.

A typical laser diode from RS is listed in table 2.2 on page 25 which has excellent specifications for this application, but the price makes it prohibitive.

Figure 2.5: Fibre clamps: top view

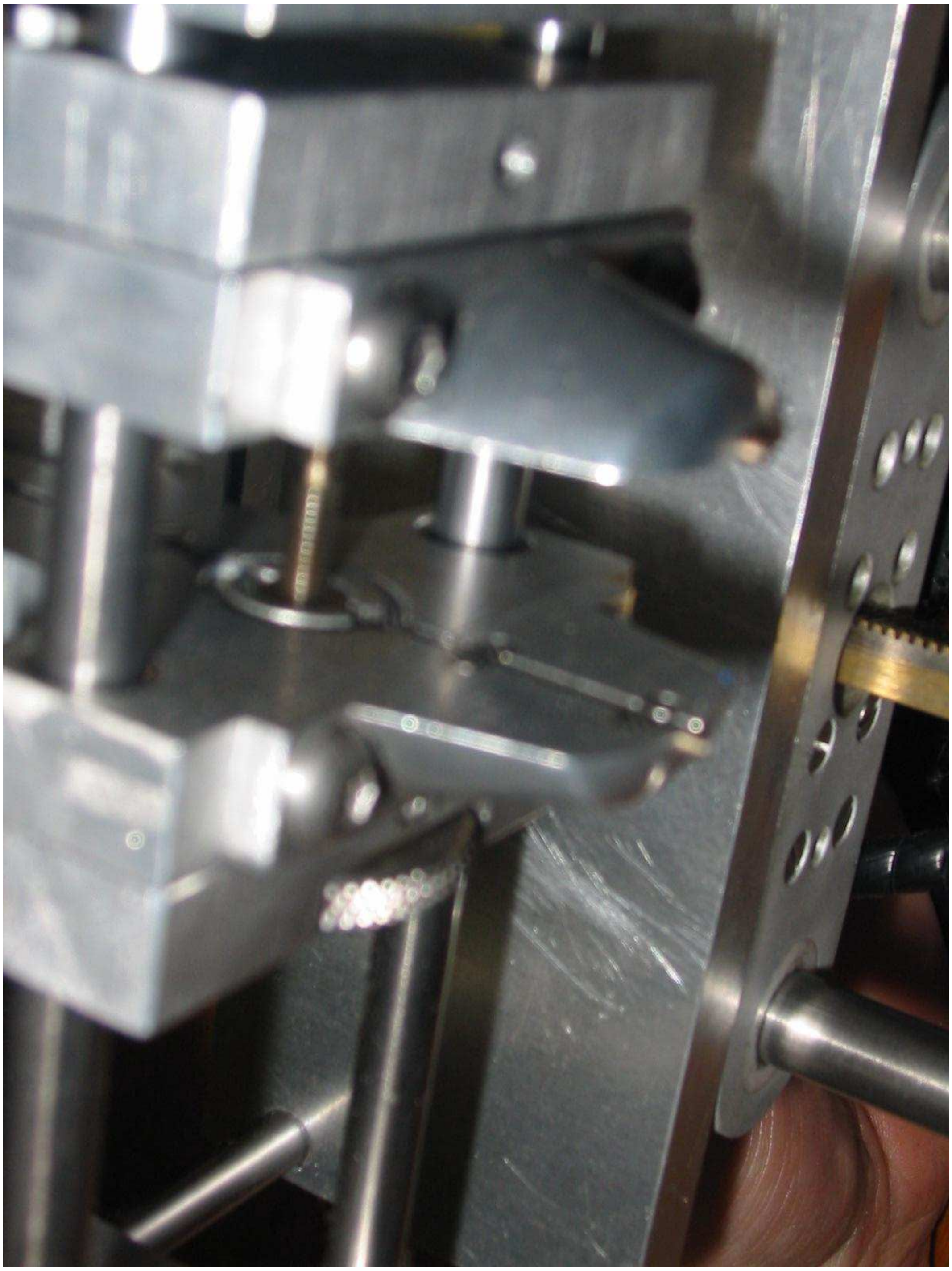

Figure 2.6: Fibre clamps: bottom view

A cheaper laser diode module is also listed, but specifications on the device are unavailable. It appears to be a device pool, as the suppliers cannot even guarantee who will manufacture the module.

The remaining possibly was to use a NIR LED. Using one of the devices with a built-in lens would solve the problem of attaching a lens at the appropriate position with respect to the LED, simplifying the connection to the source optical fibre.

This left a choice between the Sharp and Honeywell LEDs, both of which are similarly specified. For scanning efficiency, the Honeywell SE5470 LED was chosen as it has an output wavelength closer to that of the blood vessels to be mapped, which will increase the absorption when scanning over the blood vessels [3].

2.6.3 Light detector

Of the devices shown in table 2.2 on page 25, the Newport power meter is unacceptable for this project because of the high cost of the unit. It is listed as a reference for the other components, as it is similar to the power meter used in the original system.

Little information is available form the manufacturer or suppliers about the IPL 10530 DAL integrated photodiode and amplifier. Since it was required to look for components to meet a tight specification, this renders the component unsuitable.

Of the remaining components, I chose to use the Burr Brown OPT301 integrated photodiode and amplifier. It offers 2.5 times the temperature stability of the other remaining devices, and has a dynamic range adjustable by way of a resistor, which can be tuned to account for oversimplifications in the design of the models in section 2.3.

Using this combination of components, the power at the detector could change by 1.82%. Assuming a the environmental temperature could change by 1 °C during scanning, combined with a detector temperature stability of $0.02\,\%\mathrm{K}^{-1}$, this could lead to a 1.84% error due to local short-term changes in thermal conditions, for which an 8-bit A-D converter would be quite acceptable.

2.7 Circuit design

Once the major components had been decided upon, the sensor head circuit design was started. Rather than using a single-ended system as described in section 2.4.2.3 on page 23, it was decided that a differential detection system should be used. The light from the source would be guided to both the scanning site and an additional reference light detector.

The output from the reference detector would be higher than the output from the scanning site detector as it is not undergoing attenuation at the scanning site. Using a simple potential divider arrangement between the output of the reference detector and the inverting input on a differential amplifier would allow for any fluctuations in source optical power, perhaps due to fluctuations in the power supply, to be compensated for in the scanning head before passing the signal on to the ADC.

A differential light detection circuit is suggested in the data sheet for the Burr Brown OPT301 [2, figure 11 page 10]. This was used as the basis for the differential light measurement system for this scanning head. The example circuit included a logarithmic output as well as a linear differential output, but was not required for this project so was not built into the final circuit.

After the output of the reference detector had been passed through the potential divider, it was then fed through an operational amplifier in a buffer configuration. A Maxim OP37 amplifier was used in this project as samples were freely available. Most low-cost amplifiers could be used in place of the OP37, as in buffer mode any offsets in the device will have a gain of unity, leaving them in the range of a few microvolts. This buffer was included to provide a low output impedance so as not to affect the precision resistor network in the differential amplifier.

The final circuit design is included in appendix D as figure D.1 on page 57. After finalising the circuit for the scanning head, the PCB layout had to be designed, for which the Protel 99 design software was used.

The main requirement for the physical layout of the PCB was to light from the source to be guided to the reference detector by means of an optical fibre with a minimum bend radius of 20 mm. In order to accommodate this requirement, the light source and reference detector were placed in the PCB first with a separation of 41 mm.

The other components were then placed on the PCB, and the pin connection net was created from the circuit diagram. Using the automatic routing

Figure 2.7: Finished PCB with components

facility in Protel 99, most of the tracks were created without problem, and the remaining four tracks were placed by hand. The resulting PCB layouts are shown in figures D.2 and D.3 on page 58. The finished PCB is shown in figure 2.7.

Chapter 3

Results

3.1 Tests performed

Three tests were performed on the scanning head to check that the design meets the project specification:

1. Thermal stability test.

   This test required the the light from the source was guided through an optical fibre straight to the scanning site detector. The potentiometer for the reference detector was then adjusted so that the output after amplification was fixed towards the 5 V maximum output expected by the ADC attached to the computer.

   The assembly was then heated, with the output of the scanning head measured for every 0.1 °C change in temperature. This test was performed over a 2 K temperate range around room temperature. This is temperature deviation is larger than would be expected due to draughts and natural temperature variations in a room over the 150 s period that a scan is expected to take.

2. Noise test.

   The noise test also involved coupling the light from the source directly back to the scanning site detector. The potentiometer for the reference detector was then adjusted until the output of the scanning head was reading 5.00 V.

   The unit was then left until constant environmental conditions for a period of fifteen minutes, much longer than the 2.5 minutes that a single blood vessel scan should take. The output was measured every fifteen minutes to see how environmental noise affected the scanner head.

3. Linearity test.

   For this test, the light from the source was again guided directly to the scanning site detector through an optical fibre. The light to the reference detector was blocked off completely, so the device is effectively operating in single-ended mode.

   The potentiometer limiting the current flowing through the LED was then adjusted through its full range with the output being measured at various points. This should show how linear the scanning head behaves between the light source and the detectors.

3.2 Analysis of results

The raw results obtained for all tests described in section 3.1 are included in appendix B, starting on page 51.

3.2.1 Thermal stability

Figure 3.1 on the facing page is a plot of how the output voltage from the scanner head varies as the temperature of the scanning head is altered, assuming other parameters are kept constant. A linear approximation to the observed points is also shown on the graph, along with its equation.

This line of best fit shows the temperature stability of the system at 21 °C to be 0.0303 VK^{-1}. The ADC attached to the controlling computer is being operating in 8-bit mode on a 0-5 V input range.

Equation 3.1 shows that for a 1 K temperature variation during a scanning session, the value received by the computer would fluctuate by ± 2 out of 256 potential values. This gives a thermal stability of $\pm 0.78\%$ for a 1 K temperature change..

$$\left\lceil \frac{0.0303}{5} \times 2^8 \right\rceil = 2 \tag{3.1}$$

In order to determine the stability for any temperature chance, one must consider that $\frac{5}{256}$ V is required to move from a 0 to a 1 output after analogue to digital conversion for an 8-bit ADC. The thermal change required to produce

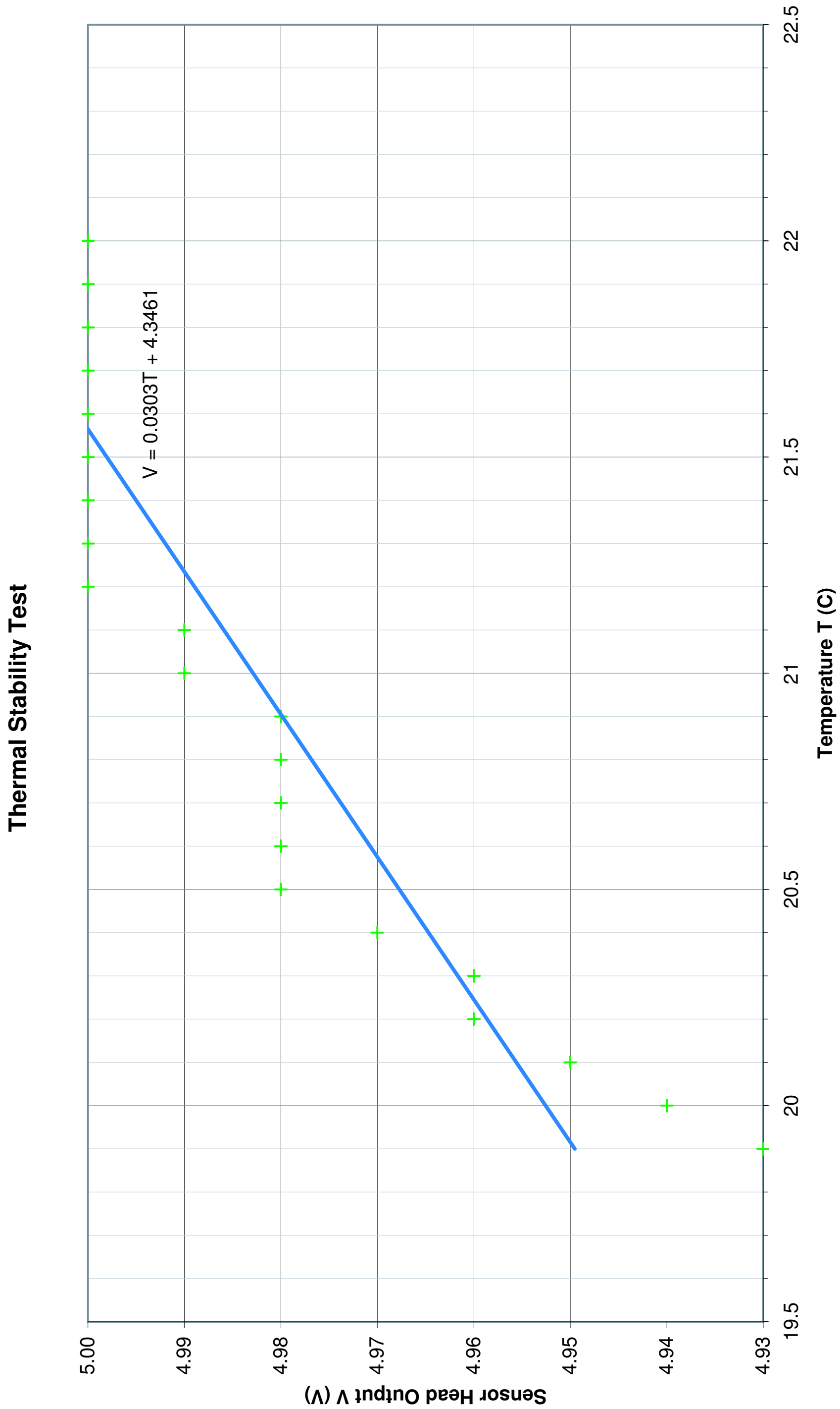

Figure 3.1: Output voltage against temperature of the scanning head

effect this can now be determined. Equation 3.2 shows that a change of 0.645 K is required to change the output by $\frac{1}{256}\%$, or a single quantisation unit.

Equation 3.3 shows that the overall thermal stability is $\pm 0.606\,\%\mathrm{K}^{-1}$. The larger error calculated for a 1 K temperature change above takes into account the fact that this error may be quantised upwards by the 8-bit ADC.

$$\frac{5}{256 \times 0.0303} = 0.645\,\mathrm{K} \tag{3.2}$$

$$\frac{100\%}{256 \times 0.645} = 0.606\,\%\mathrm{K}^{-1} \tag{3.3}$$

3.2.2 Noise test

By taking the raw data from the noise test shown in table B.2 on page 53, it can be shown that the average value obtained from the scanner head, $\bar{V}$, was $\frac{3757}{750} = 5.009\dot{3}$. The maximum deviation was $\frac{8}{750} = 0.010\dot{6}$. Calculating this deviation as a percentage gives a noise figure of ±0.213%, as shown in equation 3.4.

$$\frac{8}{750 \times 5} \times 100\% = \frac{16}{75}\%$$

$$\frac{16}{75}\% = 0.21\dot{3}\% \tag{3.4}$$

3.2.3 Linearity test

Figure 3.2 on the facing page is a graphical representation of the observed output voltage as the LED current is varied. A linear regression approximation to the observed points is also drawn in the graph, along with the R^2 value. The high R^2 value of 0.9984 indicates the the scanner head has good linearity.

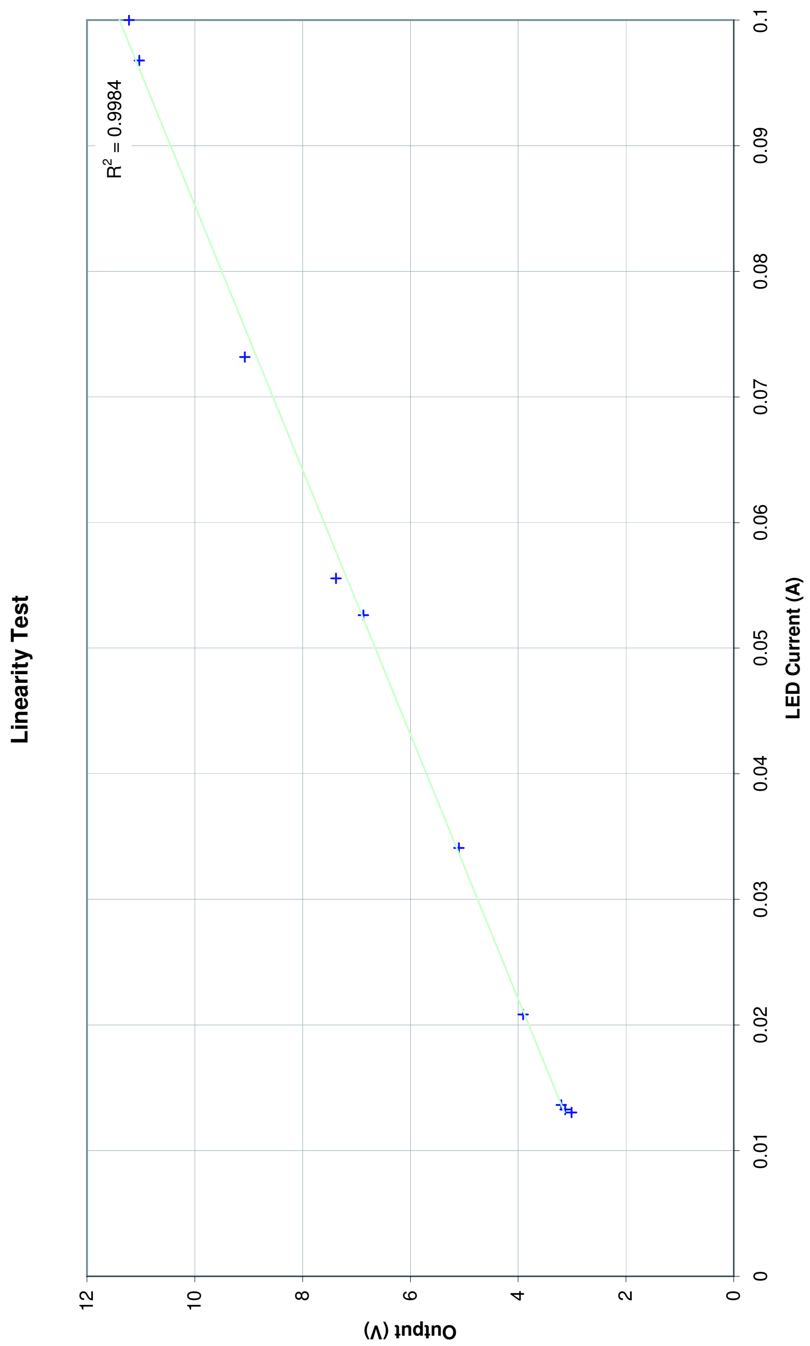

Figure 3.2: Output voltage against LED current

Chapter 4

Summary

4.1 Conclusions

The system test results documented in section 3.2 indicate that the system is suitable for use as a low-noise scanning head in a diffusion imaging system as described in section 1.2 on page 7.

With a thermal stability of $0.606\,\%\mathrm{K}^{-1}$, environmental thermal instabilities may change the picture produced by the imaging system, but as a 25% relative intensity change can be expected when a blood vessel is present under the scanning site [3], the vessel mapping process should not be effected by such errors. Similarly, noise within the system and the test environment has been shown to be 0.213%, which again should not affect the mapping process.

4.2 Suggestions for further work

As mentioned in section 1.3 on page 8, this project is one of three related projects running concurrently. The secondary objective for the project was to bring together these three aspects to form a complete, self-contained blood vessel diffusion imaging system.

Due to time constraints, this systems integration stage could not have been attempted. However, if the other two projects meet their specifications, systems integration should be a straightforward operation.

Apart form the source-detector separation as described in section 1.1 on page 7, the relative angles of the source and detection fibres should also affect the scanning width. If light is incident upon the skin at a non-perpendicular angle, the effect will be similar to starting the scan at a different position below the skin, after multiple reflections. The result is a change in the maximum photon flux path. Investigating this path in relation to incident and detection angle could lead to the ability to scan at precise depths below the skin surface.

4.3 Knowledge gained

This project has been a valuable learning experience, allowing me to experience a variety of methods used in industry. Many of the new experiences were challenging, but should provide a good foundation and valuable experience in an industrial situation.

This is the first major project I have undertaken involving large amounts of independent work. It has helped improve my research skills and techniques from a variety of sources, which could provide invaluable in the future projects.

Because the scanning head had to match a tight specification, data sheet reading and component selection took up a large amount of the project time. This is the first time the exact specifications of a set of components have been so important in an electronics project I have been involved with. The component choice experience gained in this project is likely to be very useful in future situation where thigh specifications need to be met.

Before this project, I have not had to design a PCB. Taking the production cycle from conception, circuit design, through PCB layout to manufacture and testing has provided a thorough insight into the manufacture of electronic devices. One problem encountered with my design was that the tracks were fragile and tended to lift from the PCB surface. Increasing the track width could aid this problem, and will be something I will take into account in future PCB designs.

On a similar note, heavy wires were originally soldered directly though the holes onto the PCB. Because of the weight of these wires and the fact that they are often moving, the brittle solder joints easily cracked, damaging the joints and sometimes the PCB track. This has been solved in this case by lighter wires inside the box connecting the PCB to external modular connectors. In future, PCB the possibility of using PCB pins to attach wires will be carefully considered to avoid these problems.

Appendix A

Feasibility

A.1 Project aims

A.1.1 System overview

This project is inspired by a research paper which describes a method for mapping blood vessels under the skin's surface. The aim is to produce a two dimensional map of where blood vessels are located using non-invasive diffuse light reflectance measurements, over a 27×27 mm area [3].

The system can be broken down into three main areas:

1. Computer hardware and software controlling and processing the data returned by the scanning arrangement.
2. Scanning control unit concerned with the positioning of the scanner head.
3. Scanner head concerned with emitting light and detecting the reflected light and passing the information to stage 1.

A.1.2 Sensor head

This project is concerned with the development of the sensor head for the blood vessel scanning system described above.

A.1.2.1 Physical size

The head itself must be physically small to ease integration with the scanning control unit. Large heads would be difficult to manoeuvre over a plane, but the complex shape of the human body makes this requirement even more important.

A.1.2.2 Detection and output

An optical power meter was used in the original specification. The stability and dynamic range of the photosensitive device used in the head is important, as changes in the optical intensity will be relatively small in these tests.

The output must be in a standard form, for example 0-10 V, in order to simplify interfacing with the controlling computer and any other systems.

A.1.3 Medical advantages

The circulatory system is distributed throughout such a large range of the body that information about blood flow is useful in most areas of medicine, both directly and indirectly [6].

Knowledge of the position of blood vessels and flow through them is essential for this, and non-invasive methods are almost universally preferred over invasive techniques, especially for diagnosis of ailments such as deep vein thrombosis and arteriosclerosis.

A.2 Milestones

- Preliminary paperwork submission.
- Circuit specification approved.
- First signal generated by the scanning head observed on an oscilloscope.
- Presentation delivered.
- Project report submitted.
- Creation of an image mapping blood vessels in a test subject by the system described in § A.1.1 on the facing page.[1]

[1] Image creation is dependant on the interfacing stage.

A.3 Implementation

A.3.1 Light source

The original paper described an 890 nm LED in combination with a gradient index lens as the light source for the sensor [3]. An alternative approach would be to use a laser as the light source, which would provide an approximately collimated beam without a lens.

The use of the laser over the LED would probably be preferable to maintain the simplicity of the system, although the cost of laser diode may be prohibitive.

A.3.2 Light guidance

The original system used a fibre optic system to guide the light from the source to the scanning site and then back to the detector [3]. Although this provides one possible method of implementation for the sensor head, there are many complications introduced by using optical fibres, for example matching refractive indices and physical device coupling.

An alternative approach would be to mount the source and the detector directly onto the scanning head. This would eliminate the problems associated with the fibre optics, but would require a sensor and detector that are contained in physically very small packages (see § A.1.2.1 on the page before).

A.3.3 Orientation

The orientation of the light source and detector must be adjustable in order to control the effective depth below the skin at which the scanning takes place. This adds further complexity to the idea of mounting the source and detector on the head itself, however assistance from the EEE mechanical workshop would be available.

The orientation could be adjusted either manually or by the controlling software. Because of the time allowed for the project and other commitments, and since this is secondary to the objective or mapping blood vessels, it would be more useful to manually adjust the orientation. An automated adjustment system could be added at a later date if required.

A.3.4 Light detector

The device chosen for the light detector must not be influenced by daylight. A highly selective frequency response matched to the source would help here. The dynamic range of the detector is also important, as small changes in intensity must be noticeable against a much larger background intensity.

The angular sensitivity of the detector is also important, as directional detection is important for diffusion imaging.

A.3.5 Original system

Since the specification for this project is to meet or exceed the specifications of a similar project, the exact specifications of the original system need to be determined.

- Hamamatsu L2690 high output power LED [4, 3].
  - Resin-potted package without reflector.
  - 0.4 mm emission size.
  - 890 nm peak wavelength emission.
  - 14.0mW radiant flux under 50 mA forward current.
- Ensign-Bickford Optics fibre, HCPM 1000 T-10, NA=0.37 [3].
- Melles Griot SELFOC® 0.25 pitch gradient index lens [3].
- Newport Corporation 835 optical power meter [3].
  - This product appears to be discontinued and little data is available on its specifications.

A.4 Requirements and costing

A.4.1 Light source

It can be shown that the skin is an approximately linear system in terms of light diffusion. This property is useful, as the approximate percentage change of incident light appearing as a light change on the output will be roughly constant if the absolute power of incident light is varied [3, §3].

There are several advantages of using a laser diode over the LED method chosen in original report. The light will already be collimated, negating the need for an additional collimating lens. Also, the output power of a laser diode is normally higher than for an LED, so the signal to be detected will have a larger range, reducing the constraints on the detector.

Another consideration would be that the laser light would be completely monochromatic, so a highly frequency selection light detector could be used to reduce ambient noise.

Using a laser diode, however, would result in a much more expensive solution than if an LED was used as the light source. Since the exact specification of the original system cannot be completely determined because of lack of information on obsolete products, some experimentation with different components will be needed. The high cost of laser diode modules (around £100) may be prohibitive in this case.

The cost of using an LED in combination with a collimating lens as the light source would be around £15-£30, with the lens being the most expensive part of the system.

A.4.2 Light detector

The project specification requires that "the function of an optical power meter must be met using some sort of photosensitive element". Four common light-sensitive devices are available:

- Light defendant resistors
- Photodiodes and CCDs
- Phototransistors
- Photovoltaic cells

A.4.2.1 Passive detectors

Light dependant resistors and photodiodes are passive components. They will allow different amounts of current to flow through them depending on the amount of light incident upon them. CCDs are basically arrays of photodiodes or photo MOS capacitors. Since only a single measurement will be taken at once, CCD arrays will not be required [1].

Because they would be required to detect very small changes in light intensity against a much larger background level, the changes in current would also be very small. These small changes could be lost in background noise generated by the components themselves and from ambient conditions [7].

A.4.2.2 Active detectors

Phototransistors are active components rather like standard bipolar transistors, except conduction in the base region is controlled by the incident light on the device. The current passing through the device would be amplified, but approximately proportional to the optical intensity incident on the phototransistor's base region.

With careful biasing to set the transistor into its active region for the ambient light level, small changes in the light level could be made to produce a significant change in output current which could be process further either in hardware or software before constructing any images.

Photovoltaic cells have a relatively low resistance, and create a potential difference between their two poles. The short-circuit current is approximately linear as compared to the incident luminance

A.4.3 General requirements

Ambient conditions should affect the system as little as possible, especially as relatively small changes are being measured by the device. In order to increase the accuracy and noise rejection of the system, several points have to be considered:

- Wavelength/frequency selection
- Directionality
- Stability and dynamic range

A.4.3.1 Wavelength/frequency selection

Ambient light has components with many different wavelengths, the exact mix of which depend on levels of natural light combined with the levels and types of artificial lighting in the room along with reflections from nearby objects. The type of ambient light cannot be accurately and precisely determined in advance.

However, if the wavelength of the light emitted by the source is known, using a highly selective detector should cut down on the noise produced by the ambient light, by only recording the small component of ambient light that exists in its sensitive region.

A.4.3.2 Directionality

Ambient light will fall onto the detector from a range of angles, but the position of the scanning area will be known in advance. The detector should only be influenced by light levels in from a set direction to reduce noise from ambient light levels.

A.4.3.3 Stability and dynamic range

The detection device must be able to react to a relatively small change in intensities, which must lie somewhere within the device's dynamic range. For a device such as a transistor, the dynamic range can be adjusted with biasing.

There is no need to include zero to the maximum brightness in the dynamic range, as this would create very small changes in the output of the detector. In order to give the maximum change in output, the dynamic range of the detector should match the variation of light intensities that it will be measuring.

In most components, slight variations in operation over time are acceptable. However, with equipment sensitive to small changes such as for this project, small changes in the parameters could dramatically affect the system, so stable components will be required.

External factors can also affect the stability of a device. Ambient light and temperature will be factors affecting the operating parameters of a device. If control of these factors is not practical, a high degree of rejection in the device will be required.

A.4.4 Conclusions

Cost constraints make justification of a laser difficult, so a red, NIR or IR LED would probably be the best light source (<£5) along with an appropriate lens system (£10-25).

Since few details of the original optical power meter are available, I would suggest obtaining a selection of photodiodes and phototransistors which properties similar to those required for the project (£1-£5 each). A final decision could be made after testing by prototyping.

A.5 Time scale

A full time plan is included in the form of the attached Gantt chart.

- Project deadlines

17 March 2003	Presentation week.
12 May 2003	Report submitted.

- Other milestones

11 November 2002	Preliminary paperwork submission.
25 November 2002	Circuit design approval.
15 December 2002	First signal observed.
2 March 2003	System produces first image.

A.6 Risk Assessment

A.6.1 Laser

This risk assessment has been compiled from guidelines set forward by UMIST and the University of Leeds [9, 8].

A.6.1.1 Risk to eyes

Even weak laser beams entering the eye can cause partial or complete loss of sight in the affected eye. This risk is also present for stray reflections of the laser beam.

A.6.1.2 Risk to skin

Powerful lasers can burn the skin, with increased risk from ultra-violet lasers which can produce an effect similar to accelerated sunburn.

A.6.1.3 Electrical properties

Most lasers will use high currents and/or voltages internally, which could potentially be hazardous if misused.

A.6.1.4 Minimising risk

Risks cannot be completely eliminated when working with lasers. They can be substantially reduced by following some simple guidelines

- Use the lowest practical laser output.
- Use shields to constrain the laser beam.
- Designate and restrict access to the laser area whilst in use.
- Remove all reflective surfaces not required for the scanning system, eg wristwatches.
- Always follow the manufacturer's guidelines on operating lasers.

Appendix B

Raw Test Data

B.1 Temperature stability test

Voltages obtained on the output of the scanner head unit with the light source looped directly into the detector as the head was heated are shown in table B.1 on the following page.

B.2 Noise test

Voltages obtained on the output of the scanner head unit with the light source looped directly into the detector are shown in table B.2 on page 53.

B.3 Linearity test

Total resistance limiting the current through the LED along with the current flowing through the LED are shown against the voltages observed for this current whilst operating in single-ended mode in table B.3 on page 53.

Table B.1: Temperature stability test raw data

Temperature (°C)	Output (V)
19.9	4.93
20.0	4.94
20.1	4.95
20.2	4.96
20.3	4.96
20.4	4.97
20.5	4.98
20.6	4.98
20.7	4.98
20.8	4.98
20.9	4.98
21.0	4.99
21.1	4.99
21.2	5.00
21.3	5.00
21.4	5.00
21.5	5.00
21.6	5.00
21.7	5.00
21.8	5.00
21.9	5.00

Table B.2: Noise test raw data

Time (minutes)	Output voltage (V)
0	5.00
1	5.01
2	5.02
3	5.01
4	5.01
5	5.01
6	5.01
7	5.01
8	5.01
9	5.01
10	5.01
11	5.01
12	5.01
13	5.01
14	5.01

Table B.3: Linearity test raw data

Resistance, R_{LED} (Ω)	Current, I_{LED} (A)	Output voltage, V (V)
1150	0.0130	3.01
1130	0.0133	3.13
1100	0.0136	3.20
720	0.0208	3.91
440	0.0341	5.10
285	0.0526	6.87
270	0.0556	7.38
205	0.0732	9.07
155	0.0968	11.03
150	0.1000	11.22

Appendix C

Costing

C.1 Cost estimate

The main expense in the project is the cost of the components used in the scanning head circuitry. Other costs arise from production of the PCB and the cost of materials for building the optical fibre clamps. The estimated costs for for project are summaries in table C.1 on the next page.

The project budget was set to £100, so the estimated total cost of the project of under £80 indicates that the project was completed with funds spare. If components had been damaged during the manufacture process, this excess may have been used to purchase additional components, but no such problems arose.

Table C.1: Estimated costs

Quantity	Description	Cost Each	Line Cost
2	Burr Brown OPT301 Amplified Photodiode	£20.60	£41.20
1	Honeywell SE5470 880 nm LED	£3.16	£3.16
1	Maxim OP37 Op Amp (Free Sample)	£2.66	£0.00
1	Burr Brown INA106 Differential amplifier	£9.20	£9.20
2	1 kΩ and 10 kΩ Linear potentiometer	£0.80	£1.60
1	PCB Manufacture	£5.00	£5.00
1	Scanning site fibre clamps	£10.00	£10.00
1	5-pin DIN plug and socket	£2.61	£2.61
2	Potentiometer knobs	£0.31	£0.62
1	ABS box with lid	£1.50	£1.50
1	Miscellaneous small components	£5.00	£5.00
—	Total	—	£79.89

Appendix D

Electronic layout

D.1 Circuit diagram

Figure D.1 on the facing page shows the final design of the circuit diagram for the scanning head. The components shown in the diagram are described below:

R_1	LED current limiting resistor, 150 Ω.
R_2	LED current adjustment potentiometer, 1 kΩ linear.
R_3	Reference detector offset adjustment, 10 kΩ linear.
D_1	Honeywell SE5470 880 nm NIR LED.
D_2, D_3	Burr Brown OPT301 amplified instrumentation photodiode.
U_1	Maxim OP37 low noise precision operational amplifier.
U_2	Burr Brown INA106KP differential amplifier.

D.2 PCB Layout

Figure D.2 on page 58 shown the final PCB layout as viewed from the top of the circuit board. Silk screening labels are also shown in this figure, although they were not placed on to the physical PCB because of lack of facilities. The PCB layout without these markings is shown in figure D.3 on page 58.

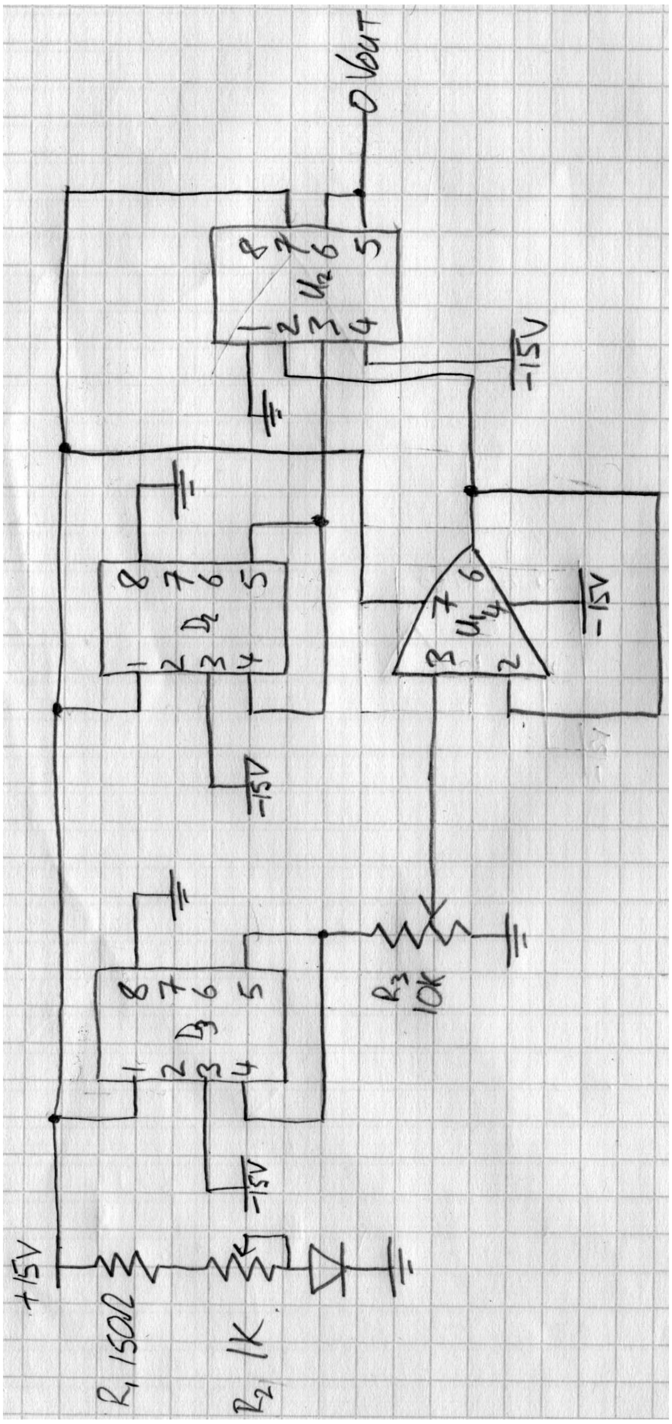

Figure D.1: Final circuit diagram

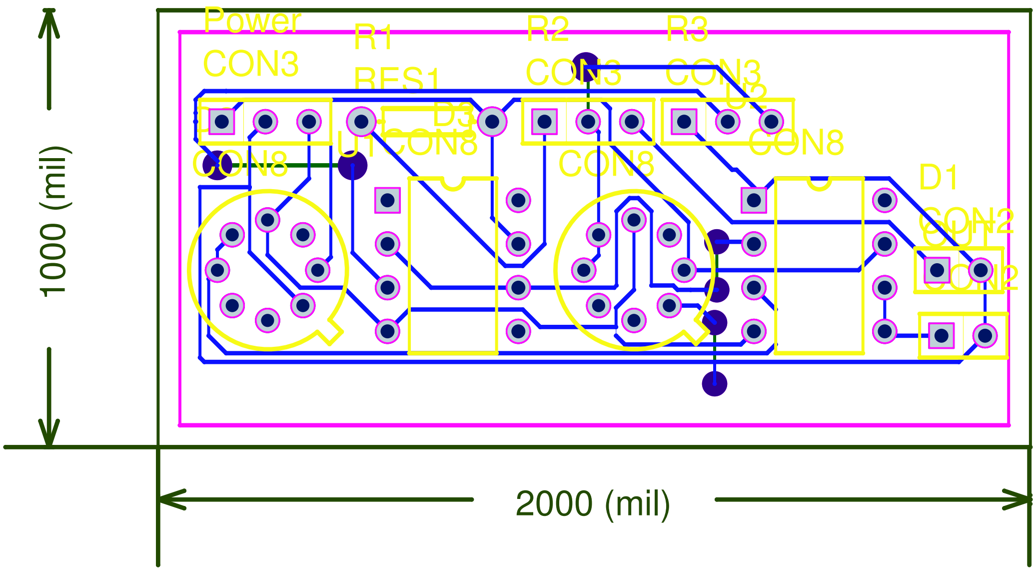

Figure D.2: PCB layout including silk screening labels

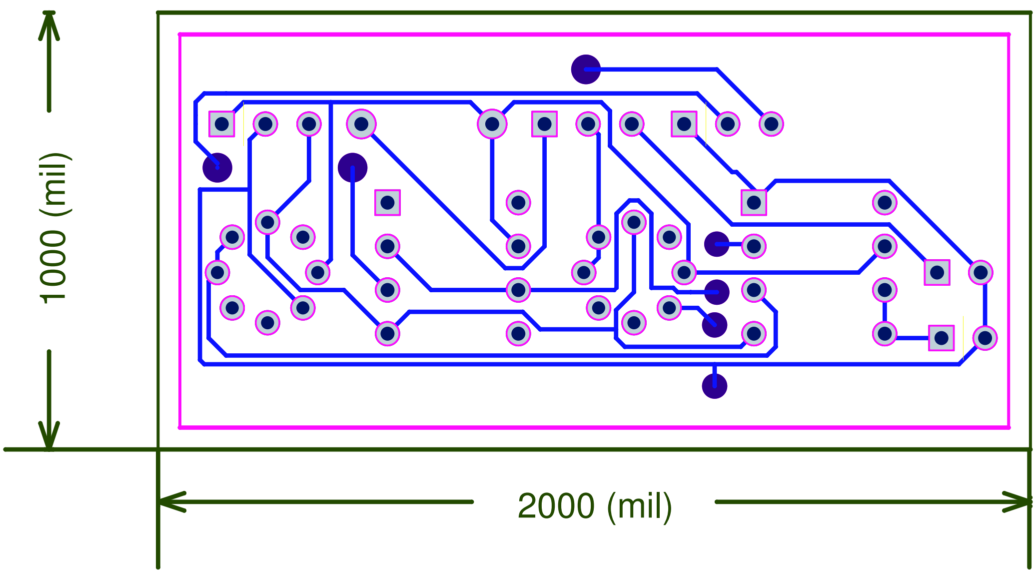

Figure D.3: PCB layout without silk screening labels

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