RamanFlex

Post Mortem

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The Fine Print

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1 Project Goals

As outlined in our initial project proposal, our long term goal was to design an inexpensive gas analyzer that provides near-instant feedback on gas molecular content. Our targeted sales cost for the production model was between $1,000 and $2,000.

Our short term goal, covered within the scope of this project, was to build a proof of concept device which would demonstrate the feasibility or futility of building a gas analyzer using Raman spectroscopy. We initially had a four month timeline and a budget of $2500 for this effort. The timeline was later extended to 8 months.

With a project as technically ambitious as this one, we did not expect to produce a conentional prototype. Instead, we intended to complete the exploratory phase to a point at which we could begin the design of a fully functional prototype device.

For this proof of concept, we set out to build the following modules:

- A laser, providing a powerful, stable, consistent, and monochromatic light source.
- A sample chamber to contain the gas to be analyzed, and optics to maximize the efficiency of the collection of the Raman scattering.
- A sensor module, which would separate the Raman scattering from the background and laser based noise, and provide a frequency spectrum of the Raman scattering.
- A control module which would control the light source and sensing module, as well as providing a PC compatible data output method.
- An analysis and user interface program which would run on a PC.

In the proposal document, we presented an initial budget as shown in 1.

Equipment	**Estimated Cost**
Laser	$500.00
Sensor	$500.00
Optics	$200.00
Microprocessors	$100.00
Cavity	$100.00
PCB	$200.00
Discrete components	$200.00
Subtotal	**$1800.00**
Contingency	$700.00
Total Cost	**$2500.00**

Table 1: Budget Estimation

2 Accomplishments

As the project progressed, it became apparent that we were not going to be able to complete our goals within a 4 month timetable. We were accomplishing and learning a great deal, however, and therefore we were allowed to extend our project to an 8 month term.

At the end of this extended term, while we have still not achieved our initial goals, the data that we have at this point suggest that these goals are not unreachable. Rather, our experience suggests a strong likelihood that the long term project goals are achievable.

2.1 Technical Achievements

At the end of our 8-month 305/340 terms, we produced a sensitive and accurate spectrograph. With our prototype, we were able to produce the following spectral profiles:

- Laser Characterization
- Incandescent Light Profiles
- Bandpass Filter characterization
- LED characterization
- TFT screen colour curves

There are some additional encouraging results. The circuit board and components have proven themselves highly functional, reliable, and stable; indeed, the board itself was left on for weeks at a time with no adverse effects.

We have achieved a high integration time ceiling of approximately 30s. Our sensing module is extremely sensitive, and has a good SNR. Also, we have observed very little crosstalk interference in data transfer.

The current status of each component is summerized below and expanded upon later in section 4.

Light source

We were able to obtain, at no cost, a laser which was suitable for our initial testing, and may be suitable for our final prototype should we be able to limit the light entering our sample chamber to a single wavelength.

Sample Chamber

At this point our prototype sample chamber seems to be creating more problems than it solves. We will likely have to use ray tracing software to model a better sample chamber. Particularily if it operates at high pressure (which is extremely desirable), we will need to hire a professional machinist to produce a prototype to our design specs.

Sensing Module

Any complaints we have with the sensing module are trivial. For example, a re-design would place the sensor closer to the edge of the board. Apart from technical headaches with the PIC, we see no problems at this time with completing our current objectives using the current prototype.

As mentioned above, we are extremely impressed with the stability and reliability of the electronics. We would, however, like to integrate some of the filtering or averaging directly on the board to reduce the amount of data transferred over RS-232.

We would like to obtain a new CCD, without a crack in the glass.

Control module

A more ideal control module might allow us, for example, to rapidly pass or block the laser beam. However, while such strategies would allow us to better characterize some sources of noise, they likely will not provide as great an improvement to the signal as other strategies could.

We do not foresee spending a great deal of time refining control mechanisms in the immediate future.

Analysis and user interface module

Our current analysis and interface module is written using the MATLAB mathematical analysis package. We have found that this package contains flaws which causes it to periodically consume all of the available memory in the computer and halt execution. We have also encountered several timing problems when feeding realtime data to this software. While we feel that it is an excellent analytical tool, and we will likely continue to use it as such, we forsee having to redesign the realtime data I/O as a seperate software package.

The direction taken by the project so far suggests a number of additional phases before a production-quality prototype could be constructed. These are explained in further detail in a later section.

2.2 Budget In Review

To this point, we have incurred the following expenses vis a vis our initial budget as summarized in Table 2.

Equipment	**Estimated Cost**	**Cost To Date**
Laser	\$500.00	\$0.00
Sensor	\$500.00	\$80.00
Optics	\$200.00	\$40.00
Microprocessors	\$100.00	\$0.00
Cavity	\$100.00	\$4.00
PCB	\$200.00	\$500.00
Discrete components	\$200.00	\$200.00
Subtotal	**\$1800.00**	**\$824.00**
Contingency	\$700.00	
Total Cost	**\$2500.00**	**\$824.00**

Table 2: The Budget, in Hindsight

It should be noted that expenses were kept low through various scrounging, begging, pleading and borrowing activities. However, a number of the components which we used because of their convenience or availability are inappropriate for a production prototype. Lowering the cost of the components is an important refinement which is best left until the exploratory phase is complete and Raman scattering in gases has been observed.

2.3 Individual Contributions

Table 3 summarizes the areas in which each teammember feels that they have made a substantial contribution.

Item	**Bernard**	**Graeme**	**Jon**	**Simon**
Firmware				
Microcontroller				
Development		✓	✓	
Debugging		✓	✓	
FPGA				
Development		✓		
Debugging		✓		
Integration		✓	✓	✓
MATLAB software				
Prototyping		✓	✓	
Development		✓		✓
Hardware				
Electronics				
Design & Parts Selection	✓	✓		✓
Schematic Layout	✓			✓
Place & Route	✓	✓		✓
Debugging	✓	✓	✓	✓
Optics				
Experimentation	✓	✓	✓	✓
Design	✓	✓		✓
Scrounging	✓	✓	✓	✓
Machining & Integration		✓	✓	✓
Research	✓	✓	✓	✓
Documentation				
Proposal	✓	✓	✓	✓
Functional Specifications	✓	✓	✓	✓
Design Specifications		✓		
Presentation	✓	✓	✓	✓
Post-Mortem	✓	✓	✓	✓

Table 3: Individual Contributions, Summarized

3 Lessons Learned

Over the course of this project, we learned a great deal from our successes and, perhaps even more from our difficulties. As with any broad project, the breadth of subjects covered allowed each of us to cover a large amount of new ground. And as with any challenging project being undertaken while other major demands are being made on everyone's time, there were also a number of group dynamics, project management, and planning obstacles to overcome and learn from. Some of the challenges are listed below.

- Surprisingly enough, high density SMD devices proved a good choice. We will not be so nervous about using them in the future.
- Our choice of analysis techniques enabled us to learn a great deal about Raman spectroscopy, a topic previously unknown to us.
- The high costs of our board fabrication runs showed us the importance of not making any mistakes, and the value of having the fab company review the board layout prior to fabrication.
- We learned about how crucial regular meeting times and co-operative lab work times are.
- The ambitious nature of our project, made more difficult by external circumstances, taught us about proper project management and risk assesment.
- Our experiences with parts scalpers emphasized the importance of establishing proper supply channels and designing with obtainable parts.
- The length of our development cycle, without testable milestones showed us the importance of regular, achievable, measureable short term goals in maintaining group morale.
- Our experiences with the PIC, in particular, have demonstrated how difficult it is to work with beta silicon and development software.
- Our difficulties with naïve optical experimentation clarified the benefits of careful modelling of light collection and integration systems. Above all else, however, optics requires a great deal of experience and intuition.

4 Implementation Details

The electronics design and optical path of our prototype have been described several times before; most recently, in our presentation. The following headings present the most salient information about their strengths and flaws for our application.

4.1 Light Source - Laser

We had two lasers: a 300 mW Nd-YAG, circularly polarized, 532.8 nm (green) laser and a 10 mW linearly polarized He-Ne (red) laser. We chose to use the green laser due to its much higher power output.

Neither laser proved to be tightly monochromatic; the green laser, in particular, exhibited strong multimoding and at least one harmonic signal within our sensors' range.

Also, neither laser was capable of modulation, which would have enabled us to increase the signal to noise factor by allowing the use of a phase locked amplifier/filter on the digital signal.

The circular polarization of the green laser proved to be an impediment because Rayleigh and Raman scattering from a circularly polarized laser travels along the direction of the incident beam, and not at a 90 degree angle to it. This caused some problems in the separation of the scattered light from the incident light. Had the laser been linearly polarized, a significant portion of the scattered light would have been at an angle of 90 degrees to the incident beam, and thus more easily extracted for analysis.

Additionally, before looking for the very weak Raman scattering, Rayleigh scattering provides an excellent indication that the optics are sensitive and tuned enough. Rayleigh scattering is several orders of magnitude stronger than Raman scattering; however, Rayleigh scattering is emitted at the same wavelength as the laser.

Because, for us, the Rayleigh scattering is emitted mostly along the same axis as the laser, it is impossible to separate from the incident beam itself. A linearly polarized laser might provide a measurable Rayleigh signal.

4.2 Sample Chamber

For the sample chamber, we found that it is very important to have a well characterized light path for the incident beam, with a light trap at the end of the path to prevent the incident beam from reaching the collection/integration optics. While reflecting the beam repeatedly between mirrored surfaces in a random manner did provide a much greater path length, it also produced a large number of 'point sources' within the sample chamber, which were then picked up by the collection integration optics and prevented the focusing of the light exiting the sample chamber on a small area of the diffraction mirror. This effect would have been further minimized by the insertion of a post-filter between the sample chamber and the collection/integration optics to block the incident light frequency from exiting the sample chamber.

Without a well defined light path, a light trap, and a post chamber filter, we found that the use of a reflective sample chamber caused an unmanageable increase in the optic noise. We therefore made the decision not to use a sample chamber until such time as a solution to the problem of incident light removal is implemented.

The sample chamber was mirrored through an aluminum spattering process, which produced reflective surfaces of very low optical quality. Had we used vapour deposition or another process better suited to producing mirrors, the scattering mentioned above would have been much more manageable.

4.3 Collection/integration Optics

We were greatly hindered in this area by the lack of proper experimental optics equipment (lenses, mirrors, mounts). We strongly recommend that a multi-purpose optical bench with a variety of high precision lenses, mirrors and proper mounting equipment capable of macro and micro adjustments be obtained for further experimentation in this area. Proper optical modeling software might also aid the design of better collection/integration optics.

4.4 Analysis Optics

The holographic mirror which we used provided a reasonably good match with the CCD. It required that the sensor board be placed quite close to the grating; indeed, a grating with a slightly lower groove density would have been preferable.

The major concern with the grating is its blaze wavelength: that is, the incident beam for which it provides the greatest amount of throughput. The blaze wavelength for our grating was far into the infrared, indicating that the grating has a much lower efficiency in the visible range.

We were also hampered by a lack of proper mounting hardware for the grating; however, we were able to use a makeshift mount.

4.5 Light to digital data conversion

Due to the difficulty and delay in obtaining our chosen linear CCD array, the use of a different part with similar characteristics should be investigated. Our CCD, the TCD1304AP, required large-quantity orders at a 16-week manufacturer lead time; therefore, we ended up using a second-hand part at significant mark-up.

4.6 Control, Storage and Data Routing

Working with our microcontroller proved quite difficult, and we have found that it is not well suited to our needs. There is a C compiler for this PIC currently in development by Microchip, and while it was not ready in time for us to use it for our current programming, it may be usable in the near future. This would enable us to avoid several architectural disasters in this chip.

The FPGA used proved to be a good choice for the task, however, we believe that a better choice overall would be to use a larger FPGA capable of containing an embedded processor, and sufficient RAM memory to buffer our data sample (32K). By using an embedded processor and FPGA based RAM memory, we could eliminate both the external micro-controller and the RAM chip from our design, lowering fabrication costs, as well as providing for more future flexibility through the use of a more advanced FPGA. An external UART/Line driver chip would then be used in place of the current line driver for RS-232 communications.

The use of an embedded processor would also provide a platform for the control of the laser modulation, if it proves neccessary.

Altera makes two suitable products: the NIOS soft-core CPU, and the Excalibur, which combines an ARM microprocessor, RAM blocks, and a large FPGA on a single chip.

4.7 Data Analysis

While MATLAB did provide us with a large number of very useful mathematical tools for data analysis and storage, we found that we were running into problems caused by a gradual increase in the amount of memory used by a running program. MATLAB seems unsuited to long-term, real-time data collection, and this prevented us from being able to produce analysis software which was stable for more than a few hours. For our purposes it was not a major difficulty, but in the future we will want to separate the data input and storage layer from the analysis layer, perhaps with a custom program which reads the samples from our system and saves them to disk. MATLAB is an invaluable analysis tool; we do not anticipate replacing it entirely.

5 Requirements for Completion

During our presentation, we introduced a number of improvements that would help us complete this project. A few of them, in particular, pointed towards signal intensity or SNR improvements of several orders of magnitude.

These improvements are described in more detail below. To each, we have tried to attach an approximate price.

5.1 Laser Line Interference Filter

Our lasers, as mentioned above, are not truly monochromatic. In particular, the green laser produces a broad signal at 532.8 nm, and several harmonic signals. One of these harmonics occurs in the neighbourhood of 800 nm, which is still within the range of our sensor and optical setup. In addition, a great deal of light sprays in a conic profile from the nozzle of the laser.

All of these imperfections result in a noisy optical path which is extremely difficult to characterize. The obvious solution is to prefilter the laser so that the light entering the optical path is clean and tightly monochromatic.

Oriel optics produces a family of laser line filters. The most appropriate of these is model 52700, a 1-inch-diameter interference filter at 532.0nm, which has a 3nm bandwidth and costs USD $217.00.

A less expensive option (USD $100.00) exists with a broader passband. However, it is vital that the passband of this filter be entirely contained within the stopband of the following notch filter. A tight passband is much more likely to meet this requirement.

5.2 Holographic Notch Filter

One of the primary sources of noise in our system was the laser itself. The Raman effect produces a signal so weak that it is handily drowned out by the laser in a number of ways. Just like film, the CCD has a limited dynamic range, and cannot measure a very weak signal on one pixel when exposed to a very strong signal on another. Secondly, the optics are not perfect; a small proportion of the incident beam will not land where it is supposed to, and may be scattered anywhere throughout the analytical optics. The incident beam is powerful enough that this stray light can also drown out the Raman signal.

Once again, Oriel produces an appropriate filter. Model 53683 would exceed requirements, and costs USD $1300.00.

It is possible that a more conventional longpass filter could do an adequate job of this task. However, for prototyping purposes, it would be safer to use a holographic notch filter. Relaxing component tolerances is best done after we have successfully measured Raman scattering.

5.3 Ruled Diffraction Grating

The holographic diffraction grating we used worked admirably for strong signals. However, it is optimized (blazed) for a frequency well beyond the visible range; it may not be nearly as efficient for the wavelengths of interest to us.

A suitable part might be the Edmund Optics NT46-067, which costs approximately USD $130.00. This is a transmissive grating, and while it would be much preferable to use a reflective grating, we have not yet found a more appropriate part. It is also a great deal smaller and more convenient than the grating we used.

5.4 Machining and a Pressurized Sample Chamber

The intensity of scattered Raman light off of a given volume of sample gas increases linearily with the pressure of the sample. It is extremely desirable, therefore, to bring our gaseous sample to the operating pressure of a compressor, which varies between 200 and 300 atmospheres.

Machining such a sample chamber is beyond both the Engineering metal shop and our expertise. Outsourcing the machining of a steel sample chamber with the appropriate mounts would likely cost several hundred dollars.

In addition, we will need to build a number of mounts for our board and sample chamber. Ideally, these would be fairly heavy aluminum, blackened to minimize light scattering. We can likely scrounge scrap metal.

5.5 Proper Optical Prototyping Equipment

Apart from our initial lack of experience, the major problem hampering our development of the optical platform was the lack of a proper optics workshop. A good stock of lenses, mirrors, and above all else, mounting hardware would prove invaluable. Optics equipment will expand to consume any available budget; we cannot, of course, provide a dollar figure.

6 Future Plans

Although much was accomplished during the 8 months spent on the project, there are still many milestones left on its path to completion. Simon and Graeme hope to address several of these objectives during a directed studies course in May 2003 under the supervision of Dr. Rawicz.

The specific goals of this directed study have not been finalized, but they are sure to include the incorporation of optical pre-/post-filters into the design, the construction of a stable mechanical system, and further refinement of the system model and device characterization. It is hoped that by reaching these milestones in a timely fashion that it will be possible to observe Raman scattering from known, strongly scattering substances. These substances will likely be liquids or solids so as to increase the intensity of the Raman scattering and thus our desired signal.

After the completion of the directed study, Graeme is considering continuing work on the project as his undergraduate thesis. This work would include the profiling of gases under pressure and further refinements of the optical system as well as the signal processing system.

After the completion of the proof-of-concept prototype of a gas analyzer using Raman Spectroscopy, it may be possible to complete of a production prototype, one which would both be manufacturable and usable in the desired application of SCUBA gas analysis. This would require a reconfiguration of the optical and mechanical systems, the development of a user interface usable by the average SCUBA filling station attendant, and indepth reliability analysis. Of course, such a model would have to meet the stringent requirements set for the Phase 3 prototype described in detail in the Requirements Analysis; its eventual development depends on a good deal of luck and hard work.

7 Individual Perspectives

At the completion of the postmortem, we felt that it was necessary to devote some space for each group member to provide a personal opinion on the project. These sections are included below.

7.1 Jon Jolivet

It has been said that nothing truly worth doing is easy. If this is true, then this project definitely qualifies as something that was truly worth doing. While it may be true that we would have achieved more in the way of a functioning system had we chosen a less ambitious project, we probably would not have learned anywhere near as much as we did with this one. That said, our successes with this project were far from trivial. I believe that we have all come away from this project with a much better understanding of both the technical issues of the technologies we used, and the dynamics of personal interactions in group projects.

As in all group projects, there was a varying degree of committment, interest, enthousiasm, and available time amoung the members of the group. At various times throughout the 8 month duration of the project, some members of the group were unable, or less able to dedicate large portions of their time to the effort. This is to be expected in the normal course of any long term project that is being done concurrently with other, sometimes higher priority, tasks. The linear nature of our development cycle, together with the impacts of scheduling and knowledge distribution problems, sometimes led to inequities in workload. That said, I believe that each member of the group contributed to the project to the best of their abilities. This belief notwithstanding, I would be remiss in not acknowledging the leadership effort and exceptional contribution to the project made by our team lead, Graeme. This was a very ambitious project, much more so than most, and I believe that each member of the team put in an above average effort, but I believe that the effort made by Graeme was far and away above that made by the other members of the group, myself included.

The very nature of our project and the resources we had available to us drove us to learn a great deal about improvisation, recycling of old equipment, and flexibility of design. I believe that had we had unlimited resources, we would not have been forced to be nearly as creative. I believe that this project also showed our group the importance of learning to work together, towards a common goal, rather than as a group of individuals. I also believe that through our non-trivial group dynamics difficulties we each were able to further develop our style of group interaction to best suit our individual personalities, knowledge bases, and learning objectives.

On the technical side, this project had a great deal of breadth and depth. We covered material in the domains of chemistry, atomic interactions, lasers, optics, CCD arrays, D/A conversion, the use of FPGAs in prototyping, microprocessor programming, machining, PCB design, PCB fabrication, surface mount technology, and many other areas to a lesser degree.

I believe that the way to learn the most is to attempt to do more than you can easily do, to do so with less than you anticipate that you'll require. It may not be the strategy that leads to the most success measured in terms of the functionality of the finished product, but I believe that this strategy leads to much greater personal intangible benefits than taking the easy road.

I encourage others to do as we did, and to not be afraid of failure, as it is not through success easily achieved that we learn to extend our limits. Reach for the ceiling, and you'll get there; reach for the stars, and you'll get to the moon.

7.2 Simon Laalo

Although the goal of producing a working product is of no small importance, it should not be forgotten that the objective of this course was to gain experience in a self-guided, team-developed, design project. I believe that a great degree of progress was achieved in both these regards. The product is well on its way to completion and the experiences I gained and lessons I learned extended well beyond the core concepts of the two courses.

During work of the project, I learned much of the first stages of the product development lifecycle. First and foremost, I learned that over-ambitious project planning does little good. This is not to say that work on an ambitious project was detrimental but that by placing unrealistic development deadlines, one may guarantee that those deadlines will soon become meaningless and will loose all effect as motivational milestones. These sliding deadlines combined with over-ambitious goals necessitated the lengthy extension of the development timeline. Secondly, I learned a great deal about the importance of proper risk assessment and analysis of the critical design path. This stems from extremely sequential nature of the critical design path of the project which allowed for little parallel work. This necessitated a fair amount of risk assessment and the consideration of contingencies to minimize the effects of a risk coming to fruition. Lastly, I believe the budgetary constraints placed on the project both by target market and pocketbook enforced the "do as much as possible for as little as possible" nature of the engineering design process.

Team dynamics was also an issue at the forefront of the project. I acquired new techniques for conflict resolution, further risk management, and teamwork. These were acquired through dealing with issues such as distribution of workload, poor scheduling, and, most importantly, knowledge transfer. It was the acquisition of this last skill that allowed for better teamwork through minimizing productivity ”ramp up” time. This skill became even more important when Bernard had to leave for his co-op position at NRC. The experiences gained from working on the RamanFlex team not only strengthened my interpersonal skills but also allowed my to discover how I function within a team and how to improve myself.

Academically, this project has thrust me into many experiences not generally encountered during the standard engineering program at SFU. Through my research, I learned not only of Raman spectroscopy but also many other techniques of chemical analysis. Also, by working with the CCD and familiarizing myself with lasers, I gained knowledge and experience with photonics. Through my close work with Graeme on the analysis of data, I learned a lot about signal analysis. Finally, from my experimentation with the optical system, I gained experience not only with optical systems but also mechanical design for assembly and machining.

Overall, work on the RamanFlex team and project has been a positive experience. Although the project was ambitious and took 2 terms to reach its current state of completion, I would not discourage others from attempting their own ambitious projects for two major reasons. This first is that an ambitious project brings forward all the issues of the first stages of product development to a degree that they cannot be ignored; it is easy to ignore team dynamics, budgetary constraints, and planning when a project is simple. Secondly, the experiences gained through work on an ambitious project far outweigh the hard work, stress, and sleep deprivation that come along with them.

7.3 Graeme Smecher

While I have gained tremendously useful technical experience as a direct result of this project, I consider the management experience to be more valuable.

A functioning team consists of a great deal more than a collection of individuals with complementary skills. A team that is united and driven towards a coherent goal can accomplish almost anything. A team which is confused or lacks confidence in the project bears little chance of reaching its goals on time. At different points throughout the project cycle, we fell into either category.

We have achieved some very impressive technical accomplishments. In hindsight, however, I'm confident that we could, much more rapidly, produce a vastly improved version. That fact alone speaks volumes about the technical experience and insight we've gained over the past 8 months.

The same applies to the managerial hurdles which we've either overcome or accepted.

The next project I undertake will certainly not proceed without any hitches; however, many of the dynamics problems we experienced this time are easily avoided with a little foresight and experience. As group management, and as a group member, I suspect that avoiding some mistakes basically amounts to having made them before.

I remain dissatisfied with the balance of contributions throughout the project. Uneven division of labor is a fact of life; however, the degree of imbalance should be minimized both by individual effort and by managerial oversight. It was, and remains, the responsibility of both the group and its management to address any such problems — and we tried. However, we failed to check these imbalances early enough to allow an equitable resolution.

That said, I'm thrilled to have the opportunity to pursue this project to its completion. I'm proposing a Directed Studies course this summer, which should allow some more formal development of the optical path. Should that prove successful, I'm considering following through with my undergraduate thesis. Our goal, though it has certainly receded, remains achievable.

7.4 Bernard Smit

This project being very ambitious, and challenging, brought out the best, and the worst, out of everyone on the RamanFlex Team. Certain problems plagued us through the entire development of this project, and compounded with our own inexperience, and demanding commitments (Ie. courses), proved to establish a hellishly stressful environment: personal relationship were strained, and scholastic performance was certainly put at risk. I feel everyone should be commended, simply for having the determination to see this project through, and for the increase, decrease, and loss of grey hair, hair in general, and life expectancy, respectively.

During the short time I was able to work with the RamanFlex Team I was fortunate enough to have dealt with a number of the technical challenges presented by the project. The lessons on project management, design, risk assessment, and industry relations, that I am now able to derive from my experiences, have certainly shaped me into a better engineer. It has been a far more effective, and rewarding experience than sitting in front of even the best lecturer could ever be.

The nature of this project was such that it required expertise from a number of different fields. Areas in which we were underqualified we saught expert advise, and for the most part, taught ourselves the neccasary knowledge in order to achieve our goals. From this I've learned perhaps the most valuable lesson: That in order to be successful, one must be always be ready to learn, and should never let fear get in the way of your ambitions.

In the end, my involvement with this project has been a positive experience. I am pleased with the technical accomplishments we have achieved, and am sure that it is possible to achieve our final goal. I wish Graeme, and Simon the best of luck in their future endeavours with this project; as I have accepted an extension on my coop at NRC I will be unable to collaborate with them in the immediate future. I do, however, look forward to working with them again at some later date.

8 Thanks, acknowledgements, and references

Of course, no project is completed without a good deal of theft, scrounging, and begging. We would like to thank the following people, without whom we would not have been able to achieve as much, or learn nearly as much:

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