ROGUE AVIONICS
"Tomorrow's Innovations Today" ™
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May 4, 2009

Dr. Patrick Leung
School of Engineering Science
Simon Fraser University
Burnaby, B.C. V5A 1S6

Re: ENSC 440 Project Post-Mortem for a Virtual Piloting System

Dear Dr. Leung

Attached is the post-mortem report for Rogue Avionics' ENSC 440 Capstone project. Our project goal consists of the design and implementation of a wireless unmanned helicopter control system. This system will allow for a pilot to operate the aircraft from the ground as if he/she was physically inside the cockpit.

This document is written to describe the current state of the device, as well as, provide details regarding project deviations and future plans. In addition, budget and time constraint details will also be given. The final sections will include personal reflections by each team member discussing the various technical and non-technical hardships and successes experience during the project development phases.

Rogue Avionics consists of a team of four members: Jyh-Yuan Yeh, Isaac Chang, David Guo, and Xiaofeng Jin. Our company may be in its infant stage but the aspiration, innovation, and skill of its members are undeniable. If you have any questions or concerns about our port-mortem, please feel free to contact the team at *Rogue.Avionics@gmail.com*.

Sincerely,

JyhYuan Yeh

Jyh-Yuan Yeh
Chief Executive Officer
Rogue Avionics

Enclosed: Virtual Piloting System: The Post Mortem

VIRTUAL PILOTING SYSTEM

THE POST MORTEM

Project Team: Jyh-Yuan Yeh
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1 Introduction

During the past 15 weeks, the Rogue Avionics team has seen their proposed project of an unmanned helicopter control system come to life. This post-mortem is meant to summarize the current state of the project, what deviations were undertaken, and where the project will go in the future. Of course on this path to success, each team member has experienced varying degrees of difficulties whether it be team dynamic or technically related. Each member's experience will also be discussed at part of a self-reflection of the entire project development process.

2 Current State of Device

Currently, Rogue Avionics' Virtual Piloting System (VPS) boasts five main features: Remote Flight Control, On-Board Video, Virtual Cockpit Perception, Real-Time Flight Information, and Wireless Communication. The current state of each feature will be described in the following sub-sections.

2.1 Remote Flight Control

One of the main goals for the VPS is to give pilots aircraft control capability. In this context, the current control system, although not perfect, has fulfilled its objective. Using remote joysticks, the pilot is able to use the VPS to control the helicopter in all directions: forward, backward, left, and right. Directional control is accomplished with the use of two servomotors whereby motor turn is controlled using pulse width modulated (PWM) square wave signals. Throttling and rotational capability were accomplished by four brushless motors. These motors are control using similar PWM signals. Various calibration features were also added to the original control design for testing purposes. Overall, the general design principles of the VPS control system did not deviate from the original proposed design and specifications.

2.2 On-Board Video

In order for the pilot to fly the helicopter remotely, a video feed was needed from the helicopter. The VPS offers the feature using a video transmitter and receiver pairing. An on-board CCD camera records flight video that is transmitted to the base station and display to the pilot. Size, weight, and power considerations limited the flexibility of the overall video system. A small, lightweight, and power saving transmitter was needed on the helicopter along with a similarly constrained camera. Carefully selected video hardware and a 1/3" camera served this purpose.

2.3 Virtual Cockpit Perception

We believe the Virtual Cockpit Perception capability of VPS is one of the standout features of the system. As proposed, the VPS allows for pilots to enjoy a mimicked cockpit view using Motion Sensing Goggles (MSG). In essence, the feature matches pilot head movements with camera movements to create 180-degree views in two-dimension.

A dual-axis gyroscope is utilized to give the goggles motion-sensing capabilities. We knew that a gyroscope is able to output angular velocity information. To determine pilot head positioning, angular position information is needed. Thus, integration of the gyroscope signal is needed. Using timer triggers, samples are taken from the gyroscope and sum to generate an approximate Reimann summed integration. This result is then used to tell the camera servomotors to sway the camera accordingly. The integration process required quite a bit of processing power. The consequences of this constraint will be discussed in a later section.

2.4 Real-Time Flight Information

As with any modern cockpit, the VPS virtual cockpit needed to relay flight information to the pilot. There were many flight data that the team found important including battery life, air speed, distance from base, and altitude. After considering hardware and time constraints, however, the team elected to limit our flight information to throttle power and lateral orientation for our proof-of-concept prototype.

The generation of lateral orientation information required the use of a tri-axis accelerometer. The accelerometer allowed use to determine the angle of vertical offset of the helicopter during turning maneuvers. This offset was determined using simple trigonometric properties among the tri-axial information given by the accelerometer.

The display of both the throttle and orientation data is made possible by overlaying the information using a serial overlay module. The ultimate challenge of the feature was providing this information in real-time. After testing several possibilities using a shared PIC, the final design required the use of a dedicated PIC. This was done so to give flight information high priority and immediate processing capability in order to achieve real-time updating.

2.5 Wireless Communication

To achieve unobstructed flight, the VPS required data transmission to be completed wirelessly between the aircraft and base station. This proved to be a great challenge. A total of 3 different wireless transmission devices were tested before the final Zigbee module was chosen. The previous device fail to meet our requirements for many reasons such as noise, reliability, power, and ease of use constraints.

Once the right transmission module was chosen, an effective transmission protocol was needed. Our main concerns were the efficiency and reliability of the transfer of data. Any transmission delay, missed data, or improper data would ultimately result one of our many features failing. In severe cases, a bad control data stream would result in the pilot to lose control of the aircraft. Our final data packet design consisted of two separate packet orders: one for brushless motor control data and one for all other peripheral data. Having two separate data configurations allowed for each type of data to be transmitted efficiently. Indicator bytes within each code stream were also used to ensure the transmitted data is accurately and properly received.

3 Device Deviations

3.1 Flight Stability

Comprises made in signal processing meant that we were not able to achieve ideal flight control and stability results. The lack of processing power, limited the number of control signals we were able to process from the ground station. This ultimately limited our directional control resolution to approximately 6 steps. Thus, with the current setup, we are unable to calibrate and finely control the direction of the helicopter. Flight stability is, therefore, not to our original expectations. It is, however, important to indicate that even with the factory system that came with our remote controlled helicopter, stable flight was already hard to achieve. The complex flight dynamics of a helicopter makes it nearly impossible to for us to develop an equally complex system for stable flight in the short timeframe. Since, our first prototype is a proof-of-concept model, the current system, although a deviation in design, is still functionally sound and serves our purpose.

3.2 Signal Processing

Reducing the directional control resolution to 6 steps does affect overall flight control. However, trading off resolution for faster results only hinders the pilot's ability to make high precision flight changes. The more critical issue is how these results are processed and transferred between the ground station and aerial vehicle. It is counterproductive to sacrifice control resolution for faster results, if the system is unable to transfer and process those results in an efficient and real-time manner.

Our original conceptual design only placed one PIC at the ground station and onboard the helicopter. The lack of processing power forced our team to take two drastic measures. The first measure was that our algorithm had to be partitioned carefully, and programmed into several separate PICs. Our final completed system was equipped with at total of 5 PICs. Each PIC's operating sub-system is outlined below in *Table 1*. By splitting the algorithm correctly, it means that multiple calculations and processes can execute in parallel. This effectively increases the overall processing power of the whole system. However, much time and effort was devoted to constructing the communication links between each PIC in order to achieve successful parallel processing.

	PIC	Sub-System	Communication Link	Clock Speed
Helicopter	1	Accelerometer and Display Processing	**TX** (*XBee*) **RX** (*XBee*)	20 MHz
	2	Camera and Servo Control	**RX** (*XBee*)	8 MHz
	3	Main Brushless Motor Control	**RX** (*XBee*)	20 MHz
Base Station	4	Dual-Joystick and Flight Processing	**TX** (*XBee*) **RX** (*PIC-2-PIC*)	20 MHz
	5	Gyroscope Integral and Video Output	**TX** (*PIC-2-PIC*) **TX** (*Video Overlay*) **RX** (*XBee*)	20 MHz

***Table 1**: Division of PIC operations within the VPS system.*

The second measure was to boost most of the PICs with an external high-speed oscillator. The complexity of the helicopter's onboard circuitry and power systems required one of the PICs to run off its internal clock. The discrepancy of the clock signals introduced a couple of new issues. Two different scalar coefficients had to be calculated for the high and low speed clocks in order to produce serial baud rates that are synchronized. If all the PICs ran off the same 8MHz internal clock signal, we could simply program each PIC with any scalar coefficient. As long as the coefficients are the same, the baud rates will match.

Both *PIC2* and *PIC3* had to generate PWM signals with extremely short periods. To compensate for the slower clock speed of *PIC2*, we could not simply replicate the same PWM code from *PIC3* to be used for *PIC2* as originally planned. We had to utilize two extra timers for *PIC2*. A smarter algorithm was improvised to handle the extra interrupts without nesting. The algorithm was also designed to periodically shut off its receiver to divert processing power for generating signal pulses.

3.3 Information Display

We originally intended our information display to contain information such as battery life, distance from base, attitude, flight speed, and positioning. For one, some of these additional data required the use of extra component such as a GPS module. Being over budget as is with our current design, cost considerations forced us to deviate from our original intent. In addition to budget issues, processing limitation, extending from previous discussions, also inhibited us to go forth with adding more information to our pilot display. Our deviated design included the displaying of throttle power and lateral orientation. These two features were chosen after careful consideration because they were found to be most important during our test flights.

4 Future Plans

4.1 Flight Stability

With our current design, the ability for flight control is realized, however, we did make sacrifices to the flexibility of the controls. From a previous section, one can see that the simplest solution for this problem may be to use more powerful microcontrollers to process the PWM signals. This could be realized in the future with a greater budget. The current prototype also lacks a control feedback system that is typically found in modern UAVs. A future model could include the use of an integrate set of sensors such as gyroscopes, accelerometers, and GPS modules to create a system that can correct erratic flight motions in an effort to improve flight stability. More extensive development will definitely be needed for this system to be realized but making the system more autonomous and easier to control would definitely be a top priority for future improvement to the VPS.

4.2 Signal Processing

As mentioned, the current VPS prototype requires the use of 5 PICs to carry out all signal processing duties. This setup was done out of necessity, however, it would be impractical and uneconomical to assume a similar setup during production. Ideally, a 2-PIC system would be suffice, one on-board PIC and one ground PIC. To make this setup possible, a bigger package and more powerful microcontroller would be needed. The main concern with our current externally oscillated PICs is its inability to generate our needed PWM signal with extremely short periods. A faster clock speed would help to resolve this issue. Modifications would also need to done to our processing algorithms to allow for seamless processing of multiple functions on a single unit. Priorities would have to be established among functions to ensure that more important tasks, such as flight control, would be dealt with more immediately that others.

4.3 Information Display

The most obvious future development of our information display feature would be to increase the amount of data given to the pilot. Thus, including our original intent of having battery life, distance from base, attitude, flight speed, and positioning information would be of priority. Realizing would require additional sensors: GPS for positioning more sophisticated accelerometer for attitude and flight speed, and a voltage/current sensor for battery life. For now, the VPS is setup in a way that would allow for this additional information to be added to the overlay display. A more sophisticated display system would be another endeavor the team could take in the future.

5 Project Details

5.1 Budget

Table A1 and Table A2 of the Appendix summarizes our proposed and actual costs for the VPS project. We originally proposed a budget of $1196.50 USD. Our final project cost ended up being $1685.73 USD resulting in a total overshoot of $489.23.

Various reasons accounted for this overshoot in budget. First, shipping and custom charges, for imported components, accounted for over $300 of the total bill. These charges were far above our estimated shipping cost of $80. Second, as the project development various extra components were needed such as extra PICs, PIC programmers, wireless transceivers, and other hardware components. All these extra components were needed for project completion but were not factored into our proposed budget. Lastly, component failure and damage also accounted for a large portion of the overshoot. In particular, several crashes occurred when during test flights of the helicopter. Each crash caused varying degrees of damage to the bodywork and rotors of the helicopter. We estimate that each crash averaged $15 of damages.

5.2 Timeline

Table A2 and Table 3 of the Appendix illustrates our proposed and actual timeline for the VPS project. The team made a very keen effort to start the project as early as possible. Parts ordering started in December and by the second week of January we had most components acquired. This relatively early start allowed the team to pace ourselves through the development process and gave us more flexibility and leeway later in the project for integration and troubleshooting.

The team was able to complete the overall project within the allotted timeframe. Complication faced in various component designs as well as unforeseen setbacks, however, meant that we had to put on hold some tasks while jumping to other tasks. This situation explains why our actual timeline has a more scattered appearance. The broadness of the project, however, ensured each team members stayed busy regardless of the setbacks we faced. The fact that we never waited around for component to arrive or problems to be fixed, we believe, is the most important reason why we were able finish the project on schedule.

6 Personal Reflections

6.1 Jyh-Yuan Yeh

Before enrolling in this engineering capstone project, I had high expectations for the project and myself. I was glad to find an equally dedicated group of team members who shared the same ambition of raising the bar and making our project one that people will remember. After 15 weeks of tireless research and development, I am proud of what our team has accomplished, and our team is very ecstatic with the final product that spawned from this course.

This capstone project was unlike any other typical courses I have taken throughout my curriculum. This project is a course that requires a tremendous amount of planning, work and self-discipline, as most of the development goes unsupervised by the professors or TA's. What I truly enjoyed about this course is the extra space and flexibility given to everyone to work at their own pace and, quite simply, on their own. Rather than have someone tell you the material you must learn, this course encouraged us to set our own goals, do our own research as a team, and to solve problems that we encountered. This allowed for thoughts to flow freely, and enabled us to concoct some of the brightest of ideas that you will not find with the traditional course.

The increased freedom will come at a terrible price to a team that worked undisciplined. I undertook the role as Chief Executive Officer for our project's company, Rogue Avionics. One of my responsibilities included setting the agenda for the work that needed to be completed each week. I had no doubt in my mind that my team members were talented and knowledgeable enough to shoulder whatever work was required to complete this project. However, for the purpose of this project, I was one with the most vision and perspective on the current state of the project, and what needed to be done. This allowed me to better prioritized the team's agenda, and re-direct the man-hours on sub-systems that were more important at the time. This was absolutely critical given a project of our magnitude, where integration of our multiple sub-systems was a complicated task itself.

Apart from having a general oversight on the project, my main technical responsibilities involved the setup of the RF data link between the two Zigbee modules, and development of the second-generation code for PWM signal generation. I will not dive into the technical details here for how I completed these tasks, as their descriptions can get very involved. Like other sub-systems of the VPS, these two components required a monumental amount of work, and were uncharted territories for everyone one of us to begin with.

Our team has battle through many adversities over the course of the past 15 weeks. There were times throughout our development where our system would not work as planned in theory, and some nights our frustration would get the better of us. However, we all knew what was at stake if we were unsuccessful in finishing the project, and we would come back the next day to start work with a fresh clear conscience. If I had a chance to start work again from the beginning, I would still choice to stick with the same group of team members, as we were each able to bring something to the table for this project. The only thing I would like to do differently is to prepare my team more. I significantly underestimated the amount of work required for the proposed project back in December 2008 when we gained approval for our project. Project budget overshoots could have also mostly been avoided with more careful planning. All in all, I am glad our team was able to cross the finish line at the end, and the experience we all gained, as a team is invaluable, and definitely beneficial to us in the future.

6.2 Xiaofeng Jin

I am very glad for being part of my project team and I really appreciate my group members for giving me such a valuable opportunity to work closely and communicate effectively on such an exciting project. I not only gained many useful academic skills, which include technical and documentation skills, but also learned many beneficial team dynamic skills, which I can apply elsewhere in my future study and career.

From a technical perspective, I am now more knowledgeable on wireless data transmission, microcontroller configuration, and control signal generation. I have never done an actual wireless video data transmission system before. From this project, I learned how every detail of design and setup will affect the whole video transmission system, and what signals and problems to look for during testing. By burning out two video cameras, I know how sensitive such an electronic device can be. I learned that the detail properties of the antenna could directly influence the performance of the whole transmission system. I have gained more practical experiences on noise reducing circuit as well.

All my previous projects are provided with sufficient support documents and help from instructors and TAs. This is the first project that I worked with a microcontroller with no external support. I think this is the most important technical skill I learned from my teammates from this project, which will definitely benefit me for my future engineering projects.

By taking the responsibility of simulating the motor control signals, I learned the importance of taking into account the validity of system integration when producing the control signals. The generation part of the control signals is not difficult. To generate a control signal that will work as part of whole system, however, is a challenging task, since the load may change the properties and the performance of the control signals, or maybe even the entire system.

In addition to the technical skills I have learned from this project, the general learning process and team work dynamics are much more valuable to me for my future career. From each member of my project group, I observed different learning, working and problem solving skills. These observations pulled me out from my own little box to expand my problem interpretation and solving skills to a bigger perspective, which I can refine in the future. The experiences of keeping everyone in the loop, working on the same goal, and helping each other with different tasks are definitely beneficial and memorable for the rest of my life.

6.3 Isaac Chang

The technical knowledge I acquired from ENSC 440 project is probably one of the most practical and useful skills I have learned from my undergraduate studies. I have heard a lot about the importance of microprocessor in designing complex electronic systems and had willingness to learn how it worked. As the design of the project required major signal processing and data manipulation, usage of microprocessor was compulsive. The microprocessor we used was PIC16F88. As the semester goes, I learned in depth about how to program in C and how to use available features in the microprocessor. I believe knowledge from PIC16F88 will be beneficial through out my future career.

Other than microprocessor, two hardware I was responsible for were gyroscope and accelerometer. The most challenging and demanding task was making an integration function using gyroscope signals. It was a function where if one error is fixed, another one comes up again and the cycle repeats for several times. However, when it was working, it gave me more excitement than any other features that I implemented. Working with the sensors to produce interesting effects such as drawing line on the screen according to the tilt angle of helicopter was fascinating experience.

Last valuable skill I learned was how to debug. When the microprocessor behaves in a weird way, there was no way to figure what the problem was from outside and even with oscilloscope. Using logic analyzer, I could speed up the debugging time much faster. From logic analyzer, I realized having more effective method to monitor simultaneous signals will make significant difference in terms of time saving. Therefore, the conclusion I came to is that the better tool one has, the faster the time to realize what the problem is.

As far as team dynamics is concerned, I learned that communication between team members is utmost importance to have the most effective progress. Often times, the group needed to talk to each other to decide upon issues with the individual member's programming. Especially in times of difficulty where there is slow progress on the work because of problems encountered, it is crucial to talk to the members what I am doing in order to avoid confusion and possibly frustration between each other.

From working with my group, I also learned to move on even if something is not perfect and beautiful. By beautiful I mean, as long as the code is working and produces practically acceptable result. Thinking about every single flag and register of the processor may make the code perfect, but it may consume more time than needed and may not be efficient. In the time-pressing project as this, I learned from the advice of other members that it is important to distinguish between perfect function and working function.

If I were to repeat the project, I would definitely apply the things I mentioned above. Communicating with other members more closely and not exceedingly think about aspects and features to implement a particular solution. However, I believe I have learned a lot from my group and from various manuals and in overall picture, everything was well above satisfactory and I am happy to be in such a coordinated group.

6.4 David Guo

I entered into the ENSC 440 project course with a mindset that this course would be the most challenging endeavors in my academic career thus far. This sentiment was definitely true. Our team set off with a very ambitious project of developing an unmanned aerial vehicle in less than 4 months. Considering that a typical UAV system would take years to create, I was quite impressed with what our team was able to accomplish in the allotted timeframe.

One of the smartest decisions the team made, in my opinion, was starting the parts ordering process in December. This decision ultimately allowed us to begin development right from the start of January. This ideal scenario gave us extra flexibility and room for error in the entailing 15 weeks. As the Vice President of Operations for Rogue Avionics, my major responsibly was making sure the project development process ran smoothly. This included keeping the team motivated during all times. One of the toughest experiences for myself was the burden of coming back to the lab to redo a part of the project after a major failure. To resolve this issue, I tried to keep optimistic as much as possible and feed this optimistic emotion to the rest of my teammates.

Apart from my executive duties, my major technical responsibility in the project was on the helicopter control system. This included extensive microcontroller programming for the control algorithm. Before this project, I had no previous experience working with microcontrollers or have done any major programming in C. Learning to work with the microcontroller was therefore one of my biggest challenges. Based on our original scheduling, I had merely 3 weeks to complete the general development of the system because the ensuring wireless data system and control signal generation algorithms were dependent on my completion of the control system. The pressures of such a short deadline and the lack of a “warm-up” phase into the project caused me much stress and agony during the first month of the project.

A unique task I had on the project was being the test pilot. I found quite pleasure from test flying our prototype and found the task to be a great stress reliever. Despite some devastating crashes, the overall experience was positive. The test flights also proved to be a great team dynamic builder because each flight required the collaboration of all team members. Initial tests required three members to hold onto helicopter from three different angles and work in-sync with the pilot. The constant shouting of commands back and forth really helped to team become very familiar with each other and bond in a sense.

Overall, there was no problem with team dynamics among Rogue Avionics team members. The test flight, mentioned previously, and the fact that we knew each other before this project took away much of the communication barriers. Various team organizational tools such as our progress reports, meeting minutes, lab journals, and code history helped us keep everyone on the same page and up-to-date regarding the current phase of our project. We also encouraged members to voice their concerns and make sure that no members were isolated from developmental decisions. I believe the effectiveness of our team was one of the most important factors that enabled us to accomplish our project.

Reflecting back at the past 15 weeks, the team and myself experienced many technical and non-technical difficulties during the development process of our project. Although these complications resulted in numerous setbacks for our project, each will be an invaluable experience that will enrich both our academic and professional careers. I am very proud of Rogue Avionics’ VPS realization and each team member’s dedication and endeavors for Capstone 2009.

7 Conclusion

Rogue Avionics would like to declare its Virtual Piloting System a successful. It took 15 weeks and $1700 to get to this point but the team is satisfied with the resulting product. The first prototype is a fitting proof-of-concept model of Rogue Avionics vision to create a simple, cost effective, and fully functional unmanned aerial vehicle. With added features such as Motion Sensing Goggles and Mimicked Flight Controls, we believe that the VPS is a practical approach in realizing virtual flight. This project required the close collaboration between all team members with each member working tirelessly throughout project development. Stellar team dynamics made this project possible and will continue to be a key player in the future development of the Rogue Avionics’ VPS.

8 Appendix

8.1 Proposed Budget

	Component Name	Make	Model	Quantity	Unit Cost (USD)
Item 1	PIC MCU	Microchip	16F88	4	$5
Item 2	PIC Programmer	N/A	149 USB	1	$65
Item 3	Crystal Resonator	N/A	20 MHz	3	$1.50
Item 4	Tandem Rotor	Walkera	4Ch-38	1	$200
Item 5	Lithium Polymer Battery	N/A	N/A	1	$30
Item 6	USB Logic Analyzer	Saleae Logic	TOL08938	1	$150
Item 7	Voltage Regulators	Fairchild	Various	4	$2
Item 8	Prototyping Board	ProtoBoard	PRT-08810	2	$3
Item 9	Tri-Axis Accelerometer	ST	SEN-08658	1	$30
Item 10	Data Transceiver	Nordic	nRF24AP1	2	$25
Item 11	Joystick	Logitech	Attack 3	2	$30
Item 12	Servo Motors	TowerPro	SG50	2	$9
Item 13	On-Screen Display	Hitt	DEV-08421	1	$130
Item 14	NTSC Video Receiver	Airwave	AWM634RX	1	$60
Item 15	NTSC Video Transmitter	Airwave	AWM630TX	1	$35
Item 16	PCB Camera	Sony	0.25" CCD	1	$45
Item 17	Video Glasses	Myvu	MA-0483	1	$130
Item 18	Dual-Axis Gyroscope	InvenSense	IDG-300	1	$75
Estimated Shipping Charges					$80
				TOTAL	**$1196.50**

Table A1: *VPS Proposed Budget*

8.2 Actual Budget

Core Unit Cost

Item	Quantity	Cost (USD)
Walkera 38# Tandem Helicopter	1	199.00
Myvu Solo Plus - Standard/Universal	1	129.95
High Resolution Video Overlay Module	1	129.95
Logitech Joystick	2	80.00
Gyro Breakout Board - Dual Axis IDG300	1	74.95
Xbee 1mW U.FL Connection	2	49.90
PIC 18 Pin 7-A/D 20MHz	6	29.25
Active Robots 634 RF Video RX / TX Pair	1	76.83
MiniDIN 60Pin Connector	1	0.95
TowerPro SG50 Mini Servo (5.4g)	2	17.80
CMOS Camera Module - 640x480	1	31.95
Triple Axis Accelerometer Breakout	1	19.95
Protective Foam Rubber Pad	1	1.29
Ceramic Resonator 20MHz	3	2.85
Voltage Regulator - 5V	2	2.50
Voltage Regulator - 3.3V	2	3.90
RCA Jack	1	0.95
Break Away Headers - Straight	1	2.50
DIP Sockets Solder Tail - 18-Pin 0.3"	1	1.50
PIC Sockets 18 Pin	6	3.00
Optoisolator - 4 Channel	1	2.25
Capacitors	18	8.00
Hex Invertor	2	1.50
LEDs	10	4.00
Anticrash kit	1	15.00
	Sub-Total:	889.72

Prototyping Cost

Item	Quantity	Cost (USD)
USB Logic Analyzer	1	149.95
PIC 18 Pin 7-A/D 20MHz	2	9.74
40 ZIF USB Interface Microchip PIC Programmer Kit	2	45.82
Hyper-Lithium Polymer Battery	1	26.90
Airwave AWM630TX Transmitter	1	16.50
Optoisolator - 4 Channel	2	4.50
RF Link Pair - 315MHz	1	8.90
RF Link Pair - 455MHz	1	8.90
2.4GHz Ceramic chip Antenna White	1	0.95
ProtoBoard - Round 2"	1	2.95
Transceiver nRF2401A	2	49.90
HM-38-Z-16 Aluminum CNC Small	1	11.50
Electret Microphone	1	0.95
AA batteries	16	8.00
PIC 18 Pin 7-A/D 20MHz 4k	2	9.75
TowerPro SG50 Mini Servo (5.4g)	3	26.70
DPC-161 Color CCD Camera	1	29.95
Sony 1/3 CCD PCB Color Camera	1	27.22
Triple Axis Accelerometer	1	19.95
3X AIRY Harden Blade II	4	35.87
HM-38-Z-08 Main Blade Holder	1	14.90
HM-38-Z-14 Hollow Shaft 2	1	7.80
Voltage Regulator - Adjustable	1	1.95
Custom Fees	NA	59.65
Total Shipping Charges	NA	241.36
	Sub-Total:	820.56

***Table A2**: Actual Budget Breakdown*

8.3 Proposed Timeline

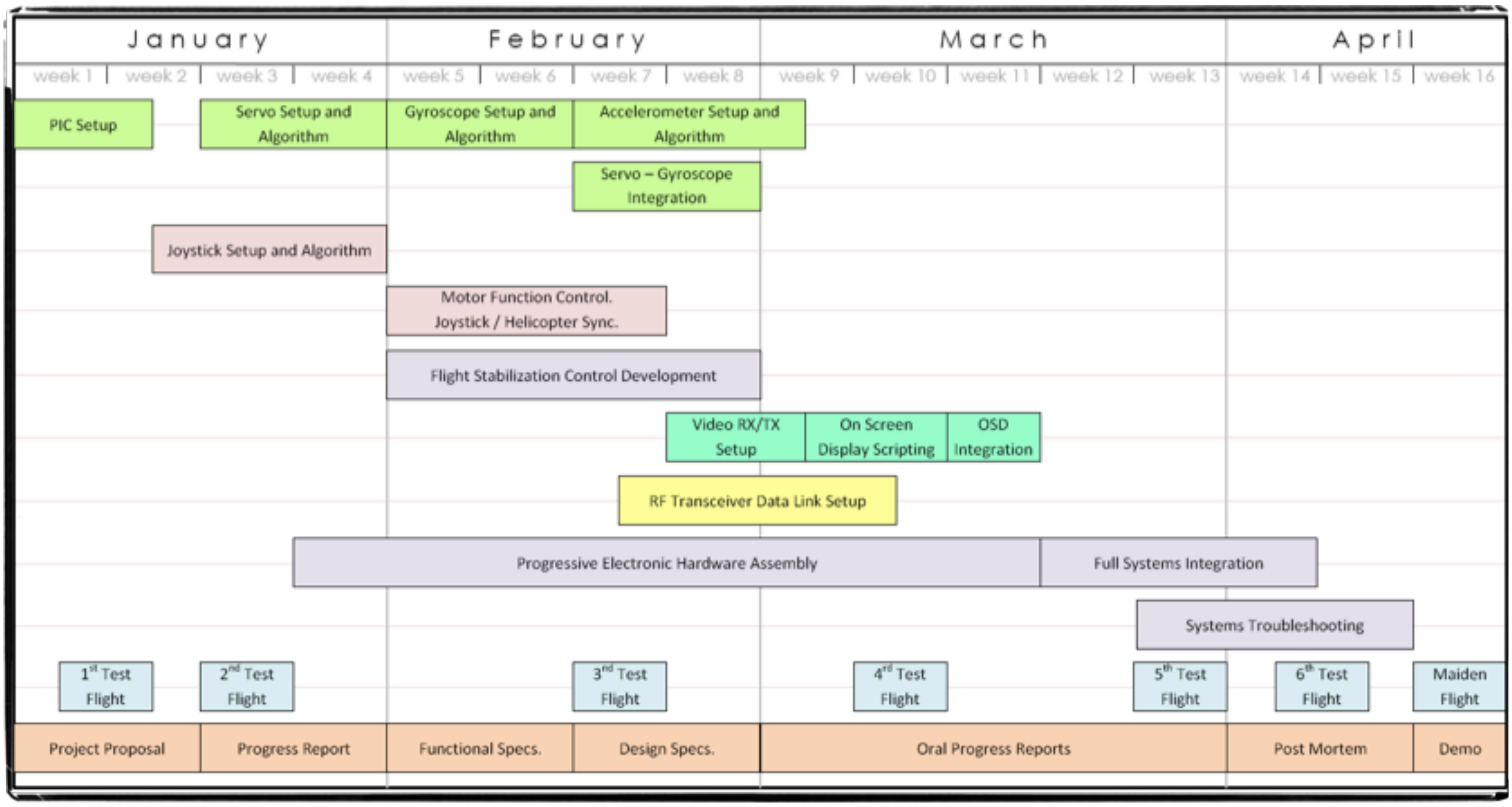

Table A4: *Proposed Timeline*

8.4 Actual Timeline

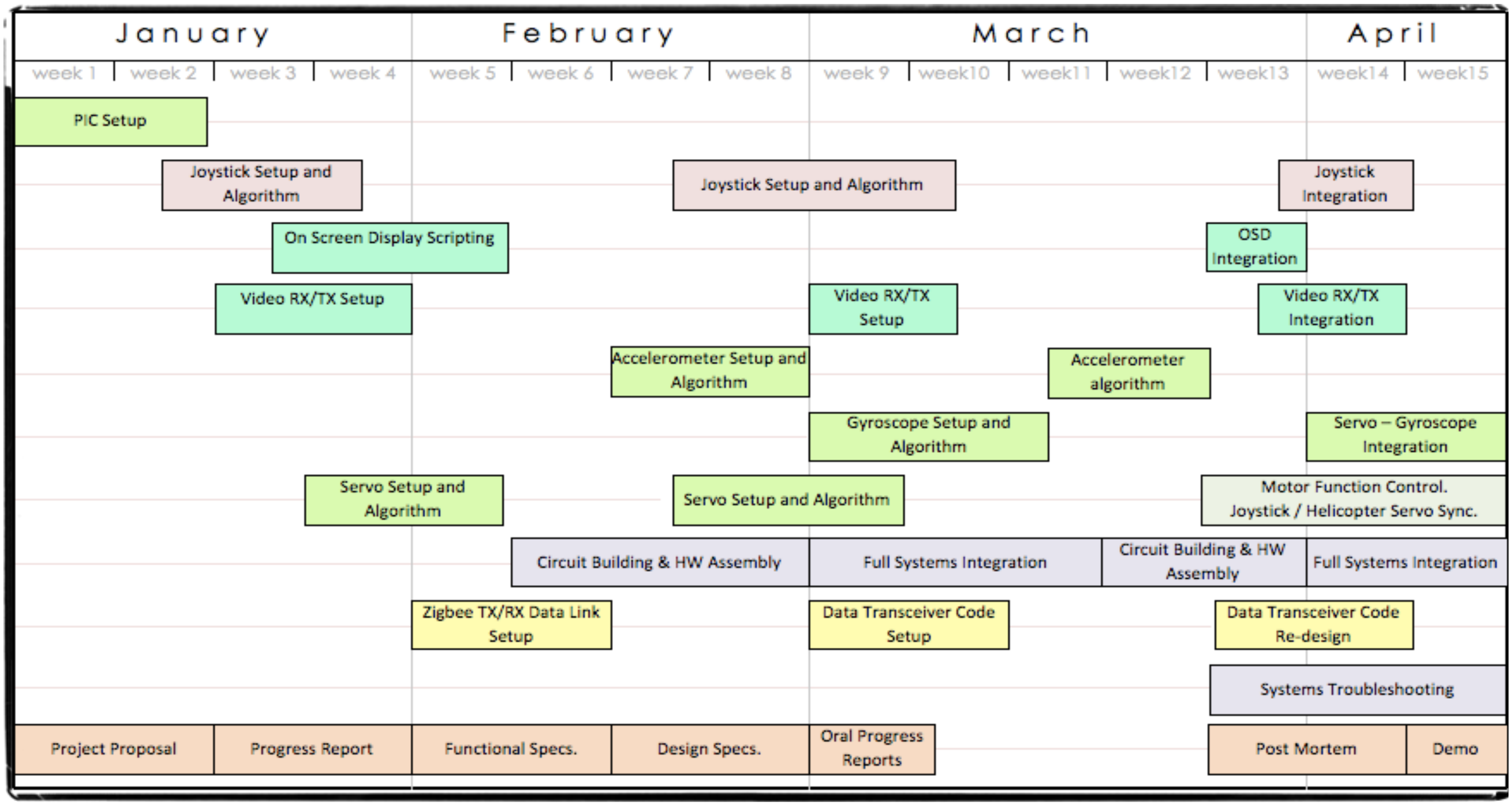

***Table A4**: Actual Timeline*