Montgomery County
Community College

The making of vertical takeoff unmanned air vehicle (VTUAV) quadrotors –R1 Final

Research Document - G02

EGR299 Students and Engineering Faculty

2012

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Introduction

Now that the DARPA's UAVForge project has officially ended, we will present our results for delivering a Vertical Takeoff Unmanned Air Vehicle (VTUAV[1]).

During 2012, we actively monitored and exchanged ideas on multiple forums, blogs and other technical websites to anticipate what would be the best VTUAV that could fulfill a wide variety of missions for UAVForge. We prototyped, tested and destroyed many VTUAVs and even lost one during the painful learning curve. These experiences gave us a deeper understanding and respect for the complexities of the platform.

We did not try to emulate what was done at nearby universities because their objectives, completing UAV R&D for a Master or a PhD, and their missions, flying solely in a laboratory environment, differed from ours. We spent most of our time outside and learned the hard way that temperature, wind and other elements could end an experiment in minutes, if not seconds of flying time.

Cost factors are not discussed within this report for the simple reason that DARPA's goal was to have a VTUAV under $10,000, we are at less than $2,000 per quadrotor with the open source version and less than $6,000 with a comparative quadrotor with proprietary hardware and software.

Our findings are essentially divided into 6 chapters:

- ***Form factor –*** a frame small enough to fit a rucksack with a substantial mission payload and flight time
- ***Frame materials –*** a frame capable of surviving multiple crashes with a minimal time-to-repair
- ***Current results -*** open source flight control for taking advantage of a worldwide user community
- ***Mission computer –*** open source development platform with microprocessor and WiFi module
- ***Ongoing research –*** proprietary flight control for open-source comparison
- ***Undeliverable items –*** what was not achieved in this research program

[1] The acronym VTUAV is used by the Department of the Navy to differentiate fixed-wing UAVs requiring normal takeoff and landing runways or platforms.

Credits

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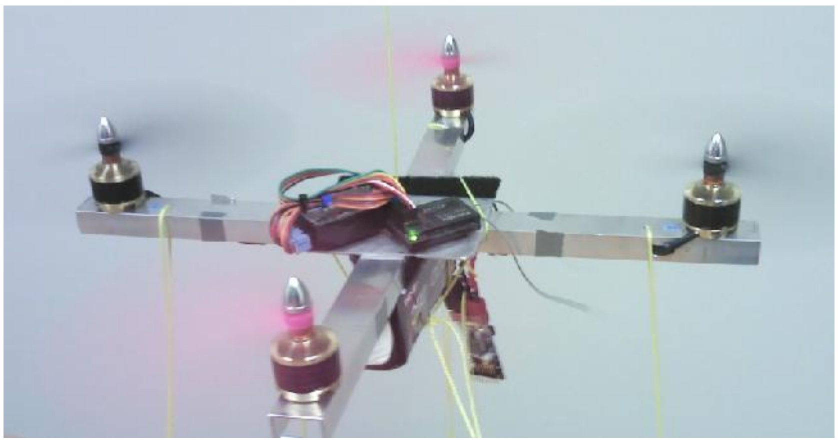
Chapter 1 – Form factor

We first constructed a small X-frame made of a C-channel cut from a strip of aluminum in order to test payload and flight endurance. This test bench allowed us to test the quadrotor's parameters (voltage, RPM, and power) without outside interference, including, but not limited to, temperature, wind, and/or rain. It also allowed us to run these tests in a safer environment than free flight. We collected data from the Lithium-Polymer (LiPo) battery to calculate how many watts of power were needed for each gram of payload. The preliminary results were not acceptable for the DARPA mission because we were getting about 20 minutes of flight time with a 5300mAh LiPo battery whose weight was about half of the total payload.



The next step was to select an X-frame quadrotor which would give us a maximum operational payload and hopefully a longer flight time. The GAUI 330XS was the best in its range, with frame, motors and propellers weighting only 400g (LiPo battery not included), and a theoretical mission payload of about 700g (total payload is 1.1kg) which is outstanding for a small frame quadrotor. We increased the flying time in the labs to 28 minutes with a 5300mAh battery, without outside interference, including, but not limited to, temperature, wind, or rain. The battery's weight was still well over half of the mission payload.

To increase the total payload we selected the GAUI 500X quadrotor which doubled the total payload of an X-frame quadrotor while having a foldable form factor capable of fitting in a rucksack. Once more the GAUI 500X was the best in its range, with frame, motors and propellers weighting only 600g (LiPo battery not included), and a theoretical mission payload of about 1,6kg (total payload is 2.2kg). The idea was to increase the flying time by using two LiPo batteries in parallel (2 x 5300mAh, total 10600mAh). We then opted for lighter 5000mAh LiPo batteries in a soft case in order to save weight and tested two LiPo batteries in parallel (2 x 5000mhA, total 10000mAh). Unfortunately we were unable to break the 28 minutes barrier with 2 LiPo batteries in parallel. Doubling the total payload required more energy than we originally thought.

Finally, we opted for a totally different X-frame for the reasons covered in Part 2 of this report. The final choice was a DJI FlameWheel 450 (F450) that outperformed some of the UAVForge requirements (rucksack size, ease of deployment, etc.).

Chapter 2 – Frame materials

Our first small X-frame made from a cut piece of aluminum C-channel was never a candidate in our delivery of a VTUAV because it required heavy-duty welding of all the aluminum parts. We only intended to use it as a test bench.

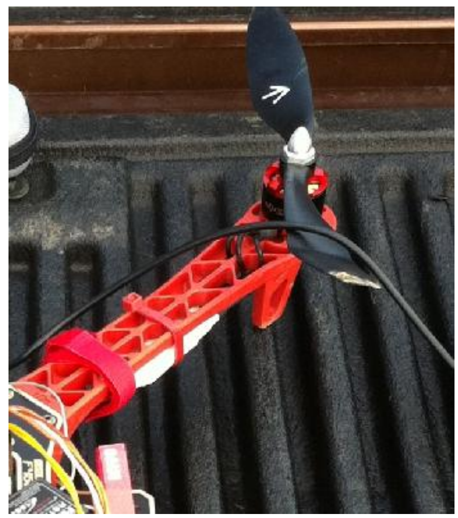
Our second X-frame, the GAUI 330XS, was essentially made of carbon fiber parts with the ability to reduce weight and increase structural stiffness. This seemed ideal, but in reality after numerous crashes, the carbon fiber parts developed cracks and fractures. To repair them was an uphill battle, we even sandwiched thin aluminum strips and epoxied them, cracks and fractures would continue to develop. Motors and propellers were another source of disappointment as we had to replace a sizable number of them even after low speed crashes.

Our third X-frame, the GAUI 500X, was comprised of aluminum, carbon fiber and plastics parts. We were quite impressed with the stability of this quadrotor even in rough windy conditions. The arms of the 500X were made of thin, lightweight tubular aluminum rods ending in the plastic housing of the motors. The aluminum rod would bend and split open when crashing, making repairs impossible. As the quadrotor was flying (or crashing), the sharp end of the aluminum rods would slowly grind the lock pins located inside the plastic motor housing, and once these delicate plastic pins were gone, the motors were free to rotate. Propellers were still a source of irritation as we had to replace an astonishing numbers of them. For all these reasons, we abandoned the GAUI 500X.

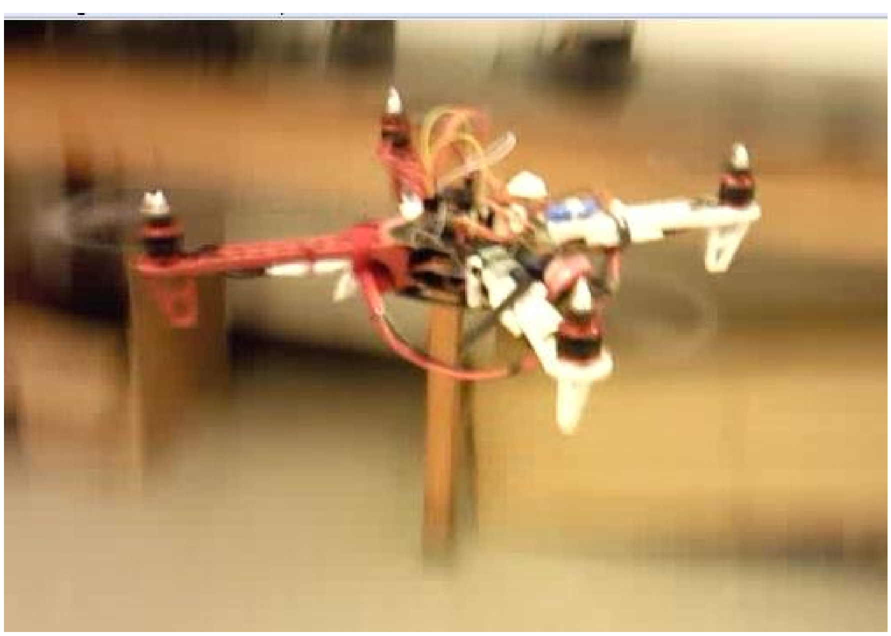
Our selected X-frame, the DJI FlameWheel 450 (F450), has frame arms made of flame retardant, reinforced polyamide nylon resin with 30% glass fiber (PA66+30GF) resulting in outstanding mechanical properties and high impact resistance designed to provide better crashworthiness. The F450 is truly a ruggedized quadrotor capable of withstanding rough treatment. Vertical pressure directly applied on the F450's arms would not rupture or fracture them.

It does not, by any means, mean that it is unbreakable. We had many bad crashes, from low to high altitude, where we broke numerous arms and bent a few propellers. See next section "New frame materials under research" for the next frame design. Lateral impacts, at any speed, directly applied on the F450's arms could rupture or fracture them.

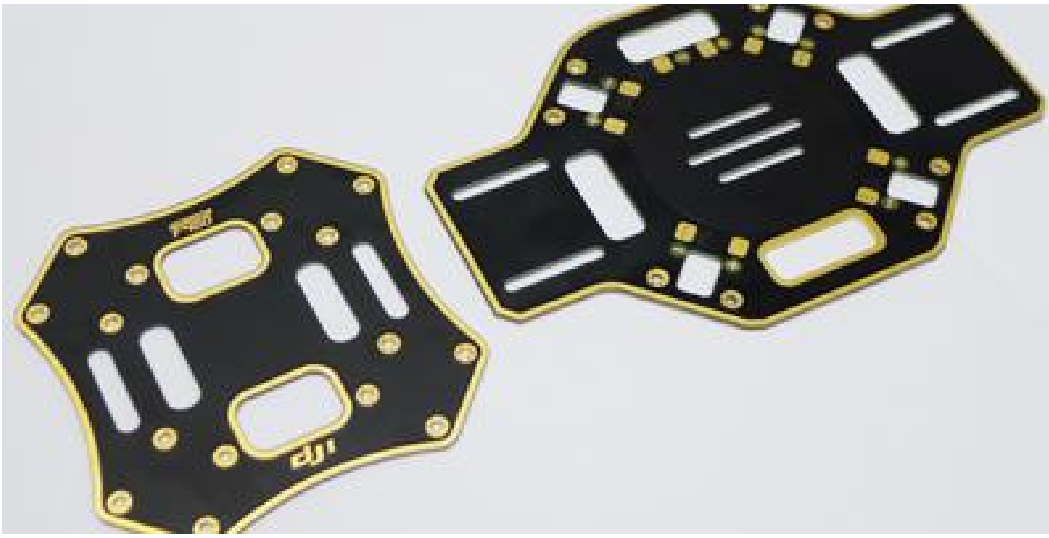
Crashing at a speed of 74km/h, on a hot day (over 40C in the sun) on a soccer field only caused light damage. One red arm broke on impact but the motor and the Electronic Speed Controller (ESC) were given a clean bill of health after testing. The other red arm had only a bent propeller and no other damage was recorded. The cause of the crash was due to a firmware update that malfunctioned.



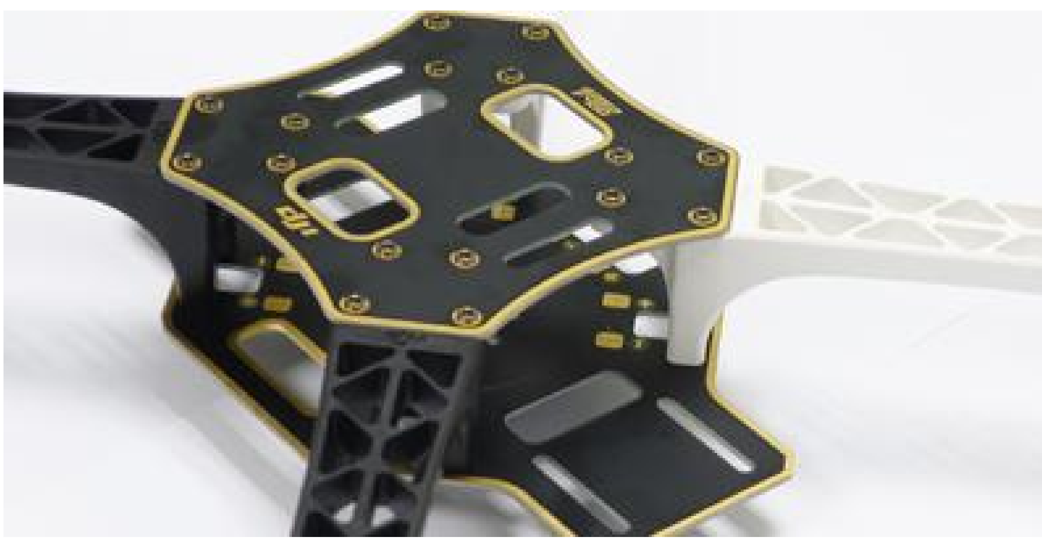
Back in the lab, the F450 was flying in no time.



One reason that the F450 is stronger than anything we tested to date is the high strength compound glass epoxy laminate[2] PCB frame boards that make up the two base plates. These plates also make the wiring of ESCs and battery safer and easier.



The optimized frame design provides ample assembling space for the autopilot system and the mission computer.

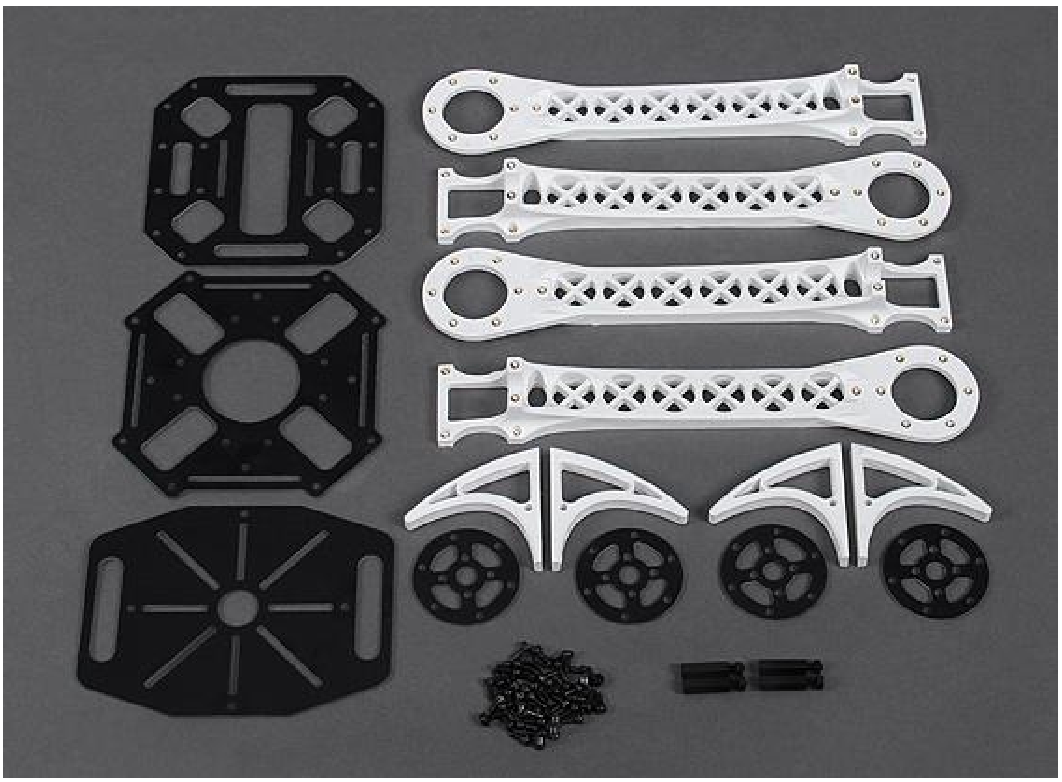


[2] It is likely to be FR-4 glass epoxy, a popular and versatile high-pressure thermoset plastic laminate grade with good strength to weight ratios. With near zero water absorption, FR-4 is most commonly used as an electrical insulator possessing considerable mechanical strength. The material is known to retain its high mechanical values and electrical insulating qualities in both dry and humid conditions. These attributes, along with good fabrication characteristics, lend utility to this grade for a wide variety of electrical and mechanical applications. G-10, the predecessor to FR-4, lacks FR-4's self-extinguishing flammability characteristics.

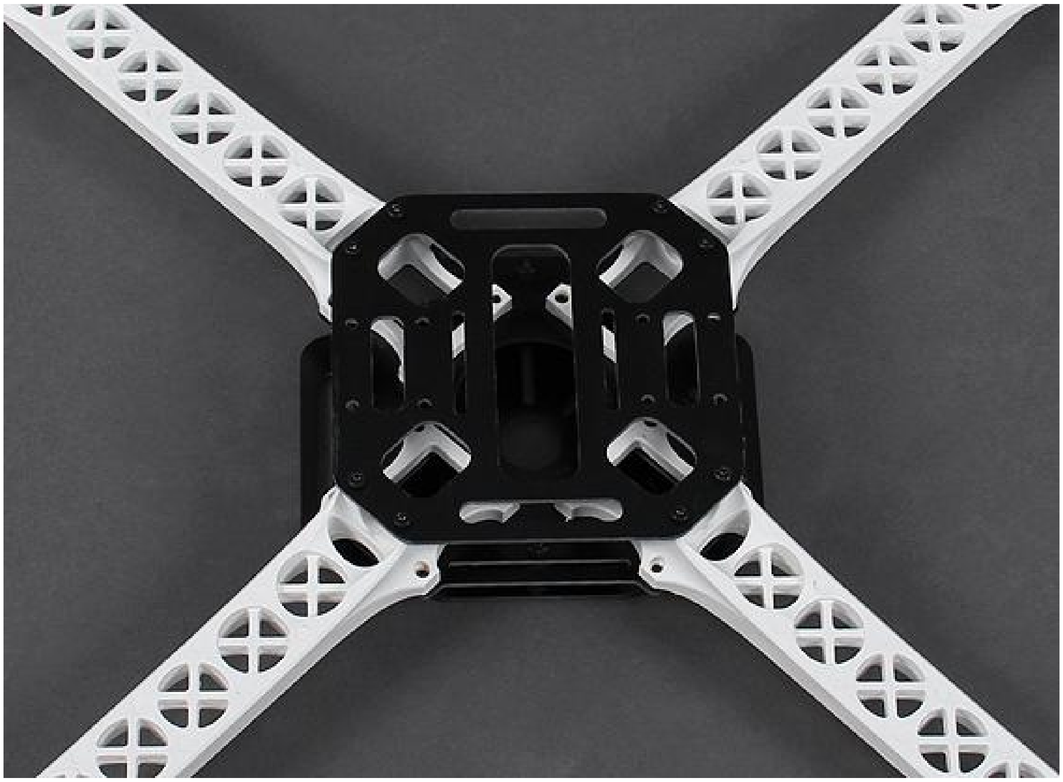
New frame materials under research

The new frame materials have arms constructed from ultra durable polyamide nylon which is less stiff than the arm material for the F450. Nylons, including the F450, are strong and tough but notch-sensitive, they are rather resilient polymers with good barrier properties and high fatigue and abrasion resistance. The sensitivity of nylons to fracture is increased by a notch, a sudden change in section, a crack, or a scratch. Low notch sensitivity is usually associated with flexible materials, and high notch sensitivity with stiff materials.

Like the F450, assembly is a breeze with pre-threaded brass sleeves for all of the frame bolts, so no lock-nuts are required. It utilizes one size of bolt for the entire build, making the hardware very easy to keep in order and only requiring one size[3] of hex wrench to assemble.



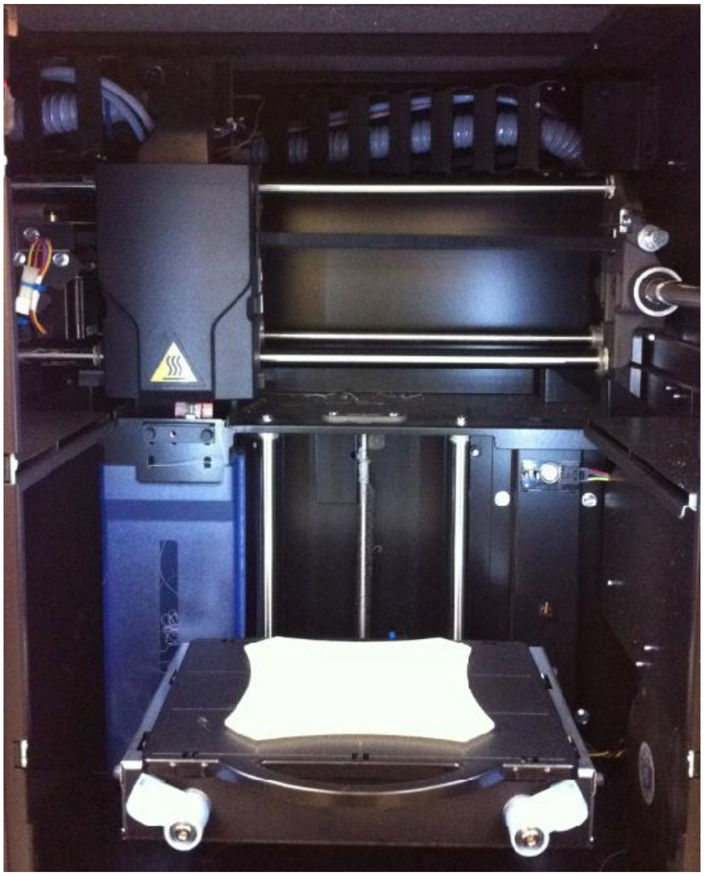
[3] The F450 requires 2 different bolt sizes and hex wrenches.

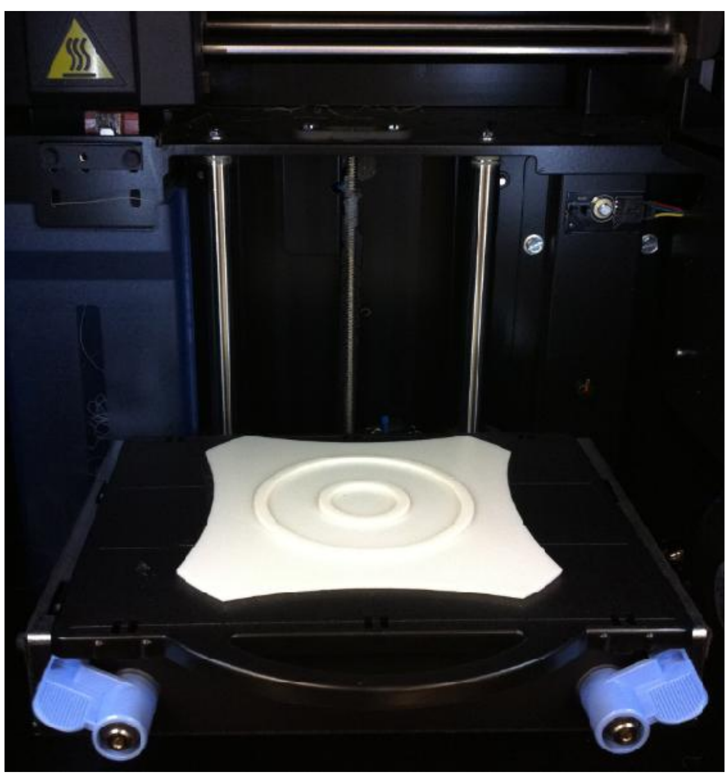


3D Printing

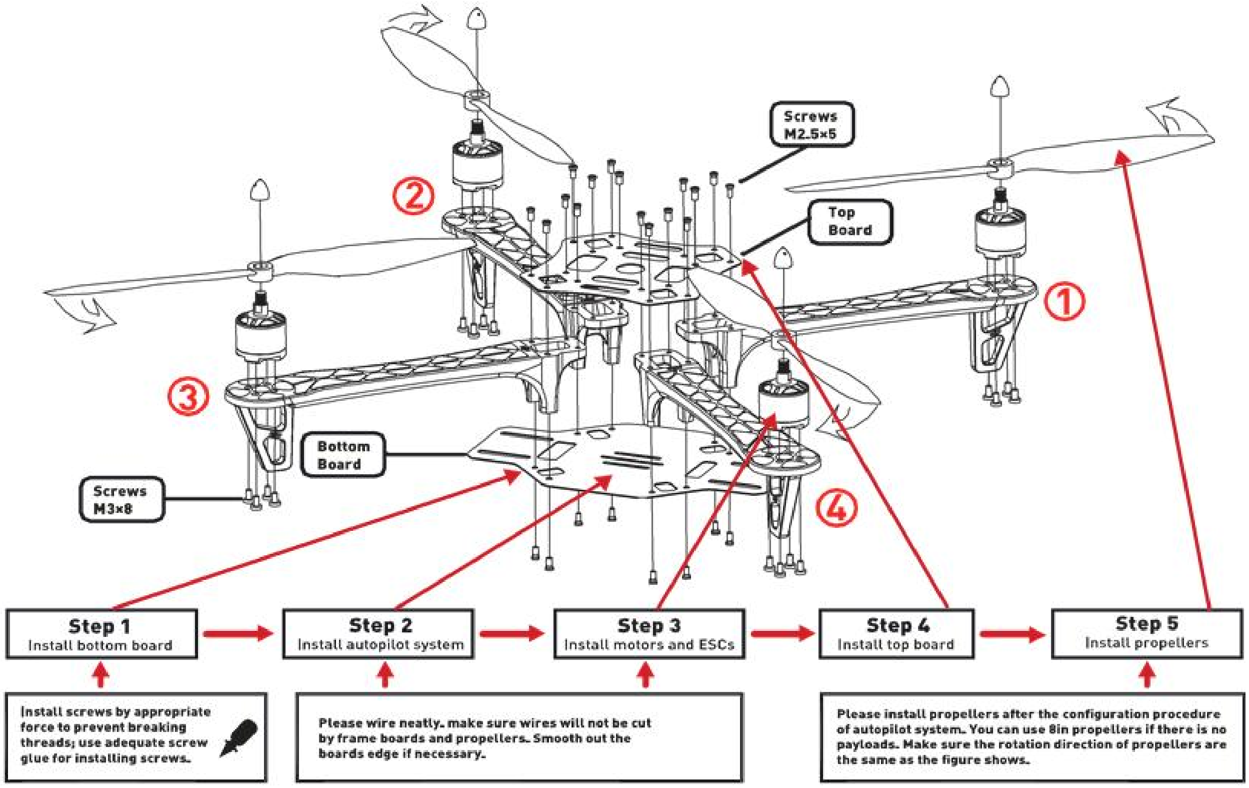
We built a durable ABS*plus*[4] plastic canopy to be mounted to the top frame board to protect avionics, electronics and the mission computer against crashes and weather. Our 3D printer uses a patented Stratasys FDM® (Fused Deposition Modeling) technology that allows us to build layer by layer, from the bottom up, this key part. We also intend to build a new weatherproof base and canopy for testing the quads in inclement weather.

[4] ABS*plus* is up to 40 percent stronger than standard ABS material and is an ideal material for conceptual prototyping through direct digital manufacturing (3D printing).

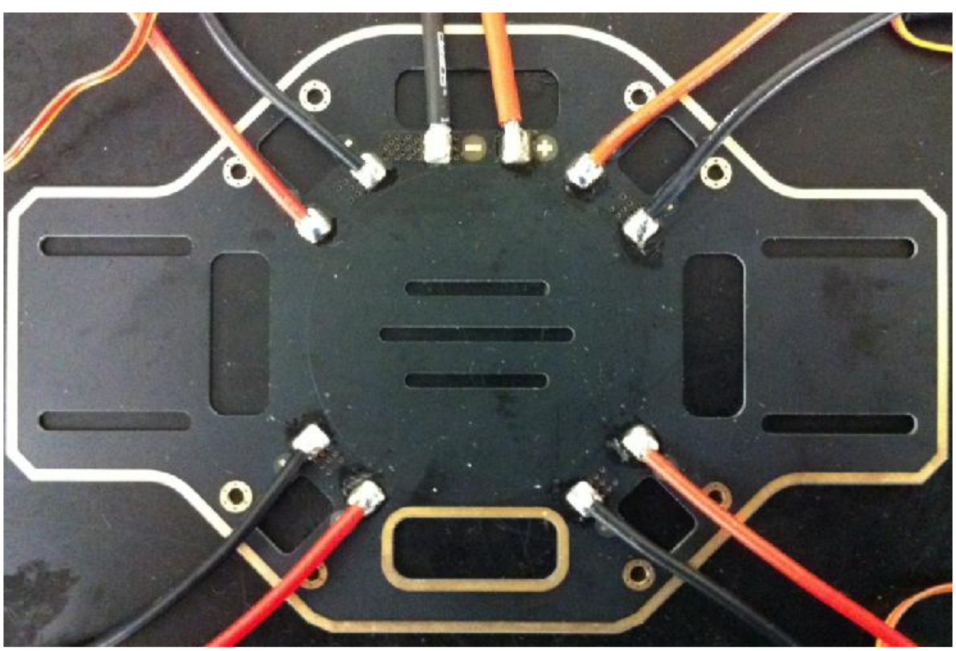


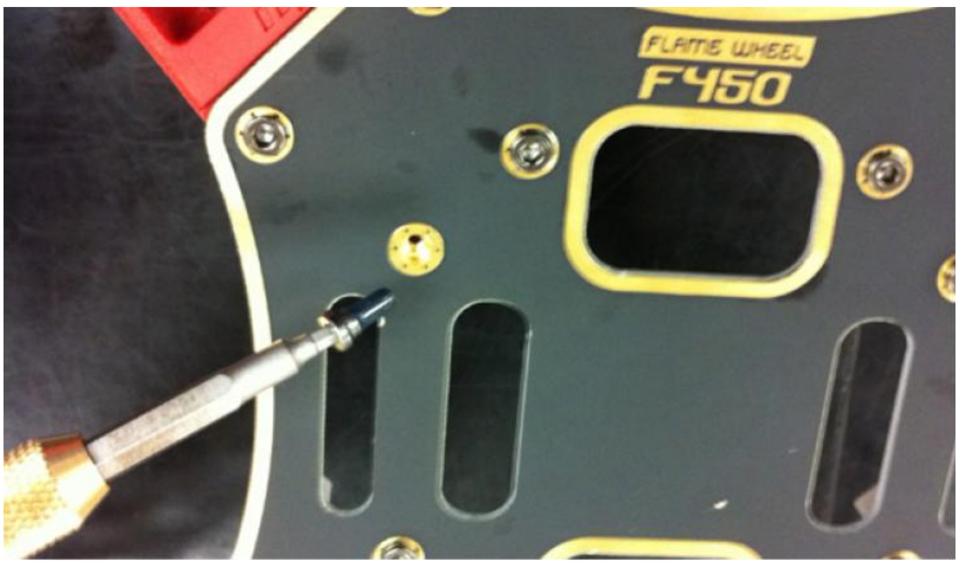


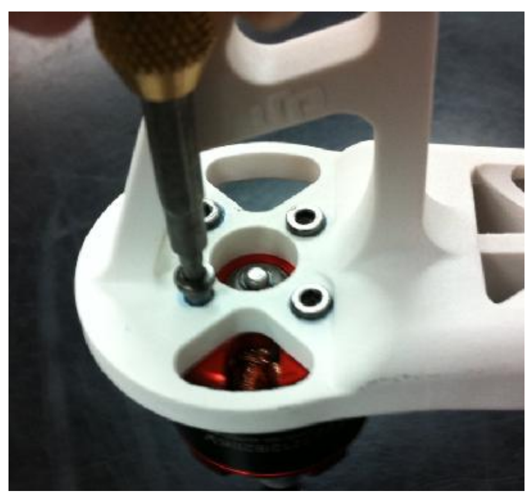
DJI F450 assembly

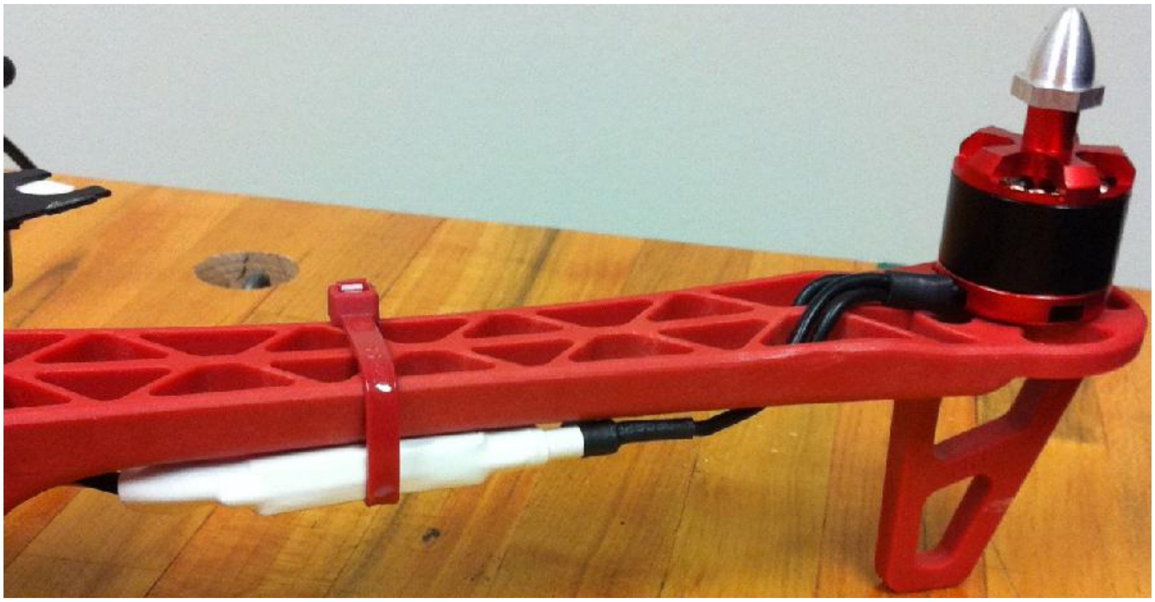


Each step of the construction is done with the highest standards that second-year students have acquired at the college.




FLAME WHEEL
F450





DJI F450 technical specifications

Model	FlameWheel 450 (F450)
Frame weight	282g
Diagonal wheelbase	45cm
Takeoff weight	0.8 to 1,6kg
Propellers	20 x 11cm and 25 x 11cm (8 x 4.5in and 10 x 4.5in)
Proposed battery	3S 35-70C LiPo 5000mAh
Motors	920KV, maximum 12A, 144W 22 x 12mm and 22 x 15mm
ESC	Current: 30A Opto, signal: 30 to 450Hz

Two types of propellers are available, 8 and 10” length. We are using the 10” blades to maximize performance.

We tested several makers of high performance Lithium Polymer (LiPo) batteries ranging from 5000 to 5300mAh. Our choice is the Turnigy NanoTech 5000mAh based on weight, endurance and a form factor capable of fitting between the 2 base plates.

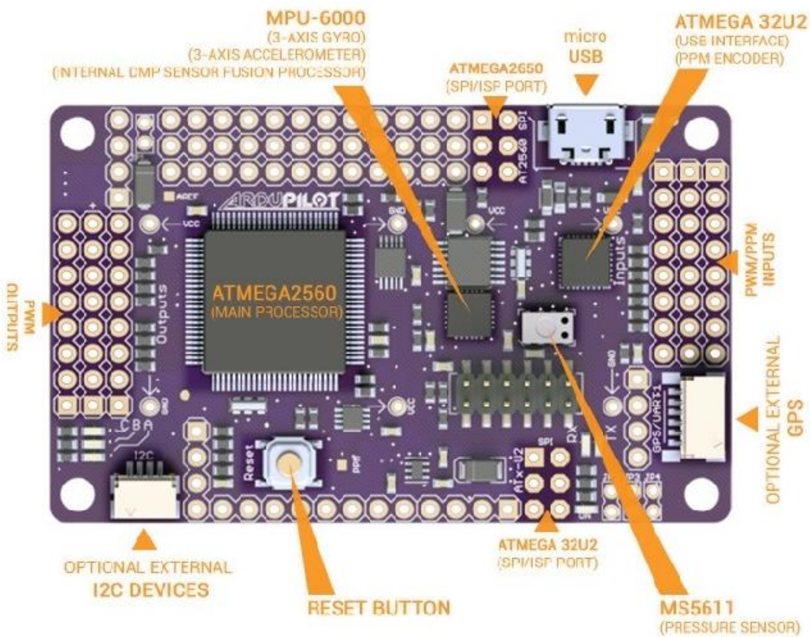
Each 920KV-rated brushless outrunner motor offers great performance and small size. This external rotor design eliminates the need for a gearbox, saving valuable weight for maximum performance.

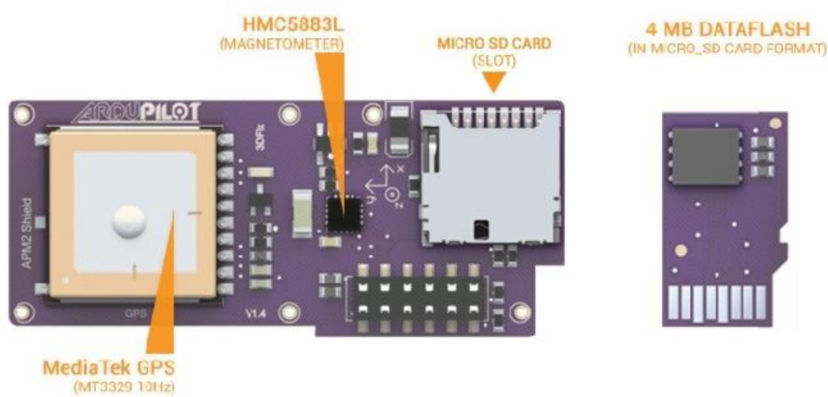
Each electronic speed controller (ESC) is rated at 30A (current) with a signal frequency from 30Hz to 450Hz, an optimal range for a UAV.

Chapter 3 – Current results

Autopilot

The ArduPilot Mega version 2 (APM2) is a complete open source autopilot system. It allows the quadrotor to be a fully autonomous vehicle capable of performing programmed GPS missions with waypoints.





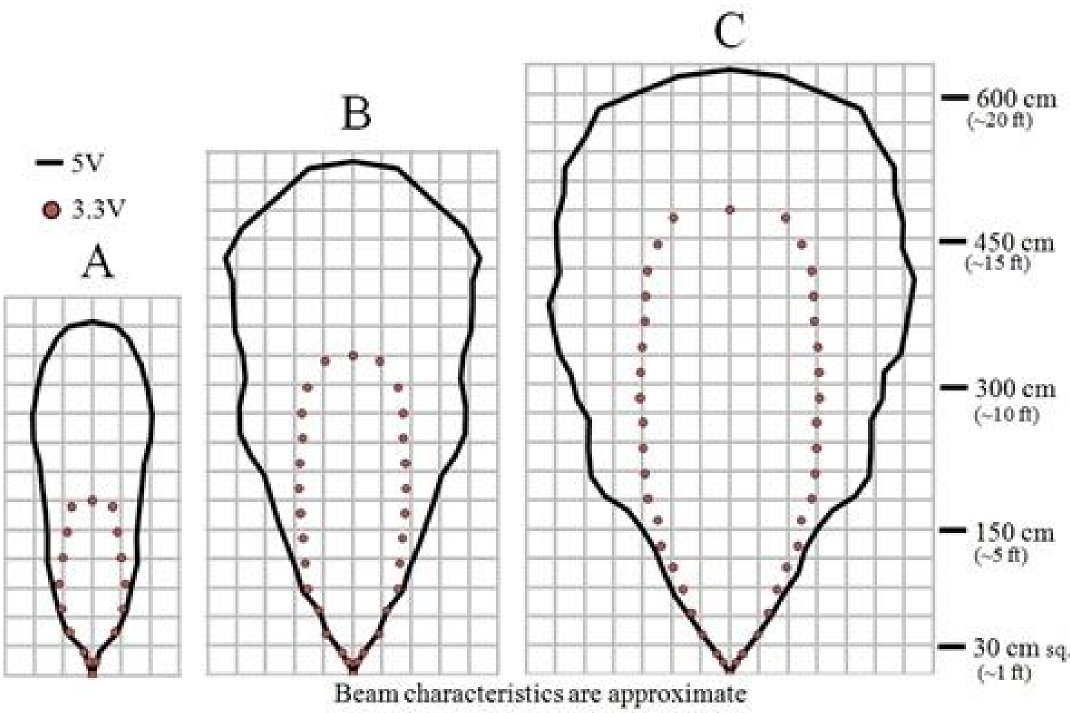
Features

- ✓ Arduino compatible
- ✓ 1 x Dataflash
- ✓ Digital compass powered by Honeywell's HMC5883L-TR chip
- ✓ On-board GPS, Mediatek MT3329 module
- ✓ One of the first open source autopilot systems to use Invensense's 6 DoF Accelerometer/Gyro MPU-6000
- ✓ Barometric pressure sensor upgraded to MS5611-01BA03 from Measurement Specialties
- ✓ Atmel's ATMEGA2560 and ATMEGA32U-2 chips for processing and USB functions respectively

High Performance Ultrasonic Range Finder

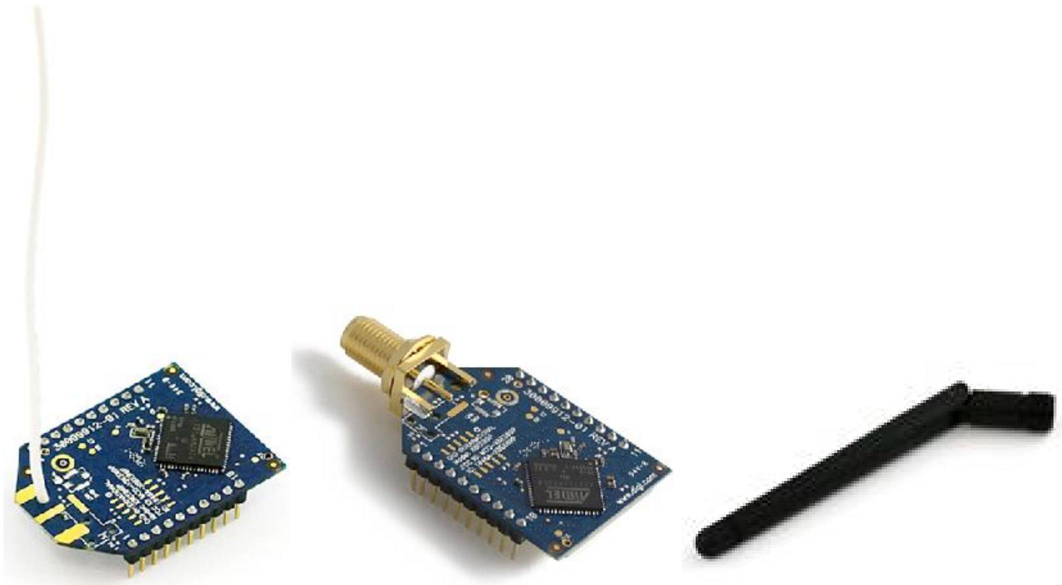
The MB1200 XL-MaxSonar-EZ0 was less than 1-cubic-inch in size, yet the sensor puts 1/2 watts of peak power into the efficient transformer driving the transducer, yielding high output acoustic power. This acoustic power combined with continuously variable gain, real-time background automatic calibration, real-time waveform signature analysis, and real-time noise rejection algorithms resulted in virtually noise free distance readings for most users. This was holding true even in the presence of many of the various acoustic or electrical noise sources.

After numerous field tests the range finder did not slow down, during the last 6 meters, the landing speed of the quadrotor; we decided to remove the sonar from the final delivery version.



Telemetry

We started with the Xbee-Pro RF 915MHz, 50mW radio set equipped with a wire antenna for the quadrotor and a rubber antenna for the laptop.



Understanding that the 900MHz is reserved for GSM telephony in many parts of the world, we switched to the 3DR Radio telemetry system. The 3DR Radio telemetry system is designed as an open source Xbee replacement radio set, offering a lower price, longer range and superior performance to Xbee radios. It's available in 433MHz and in the following configurations: serial board (for the air) and USB (for the ground). We are currently using the serial board for both air and ground.

Features

- ✓ Very small size
- ✓ Light weight (under 4 grams without antenna)
- ✓ Available in 433MHz variant
- ✓ Receiver sensitivity to -121 dBm
- ✓ Transmit power up to 20dBm (100mW)
- ✓ Transparent serial link
- ✓ Air data rates up to 250kbps
- ✓ MAVLink protocol framing and status reporting
- ✓ Frequency hopping spread spectrum (FHSS)
- ✓ Adaptive time division multiplexing (TDM)
- ✓ Support for LBT and AFA
- ✓ Configurable duty cycle
- ✓ Built in error correcting code (can correct up to 25% data bit errors)
- ✓ Demonstrated range of several kilometers with a small omni antenna
- ✓ Can be used with a bi-directional amplifier for even more range
- ✓ Open source firmware

3DR Radio telemetry system (433MHz)

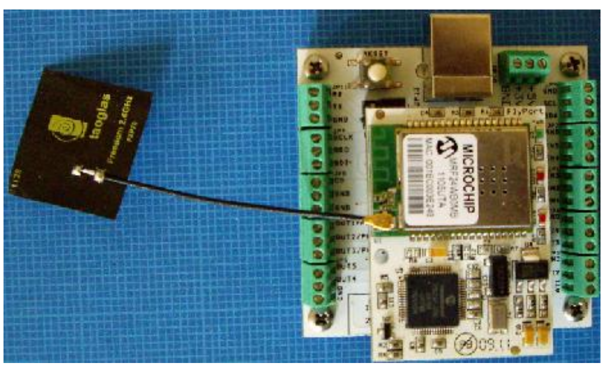
Chapter 4 – Mission computer

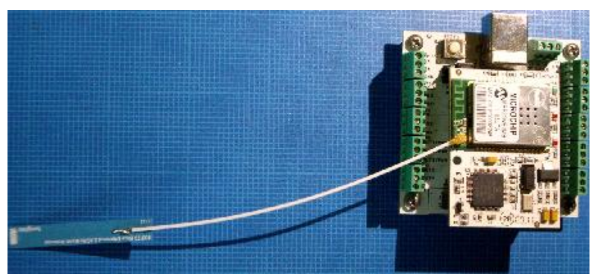
The Flyport[5] mission computer, with uFL antenna connector, performs device control and connects to an 802.11 b/g/n WiFi network. The network can use WEP and WPA security variants, or no security.

Features

- ✓ Support infrastructure and ad-hoc networks
- ✓ DHCP server, DHCP client, TCPIP socket
- ✓ Can send emails
- ✓ Can go into low power sleep mode
- ✓ 3V at 154 mA XMIT, 85 mA RX, 250 uA sleep, <0.1 uA hibernate
- ✓ One UART port
- ✓ One SPI port
- ✓ One I2C port
- ✓ Five digital outputs
- ✓ Five digital inputs
- ✓ Four 10-bit analog inputs
- ✓ Four PWM outputs

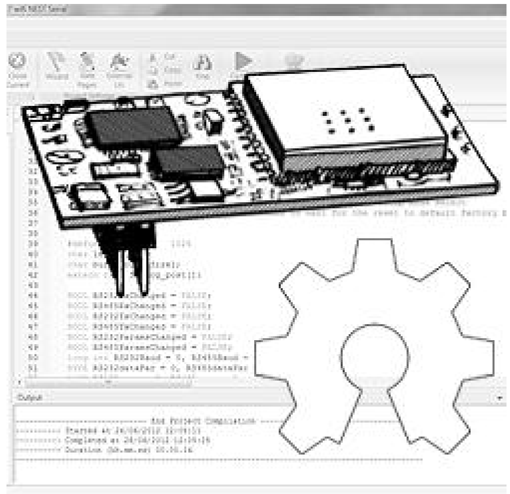
The Flyport mission computer supports DHCP, SNTP, HTTP, TCP, DNS and more. The maximum data rate is 2 Mbps and the radio regulation is certified for USA, Canada, Japan, and Europe. The pictures below illustrate the Flyport mission computer with its development board (nest) and two types of external antennas. Only the 3.5 x 4.8cm Flyport board is onboard the quad.





The IDE (Interactive Development Environment) from openPicus has an integrated C compiler, linker, firmware downloader, website importer, external libraries importer and a robust TCP/IP configuration wizard.

[5] http://www.openpicus.com/site/openPicusTechnology



The 3.5 x 4.8cm Flyport board onboard the quad

Flyport technical specifications

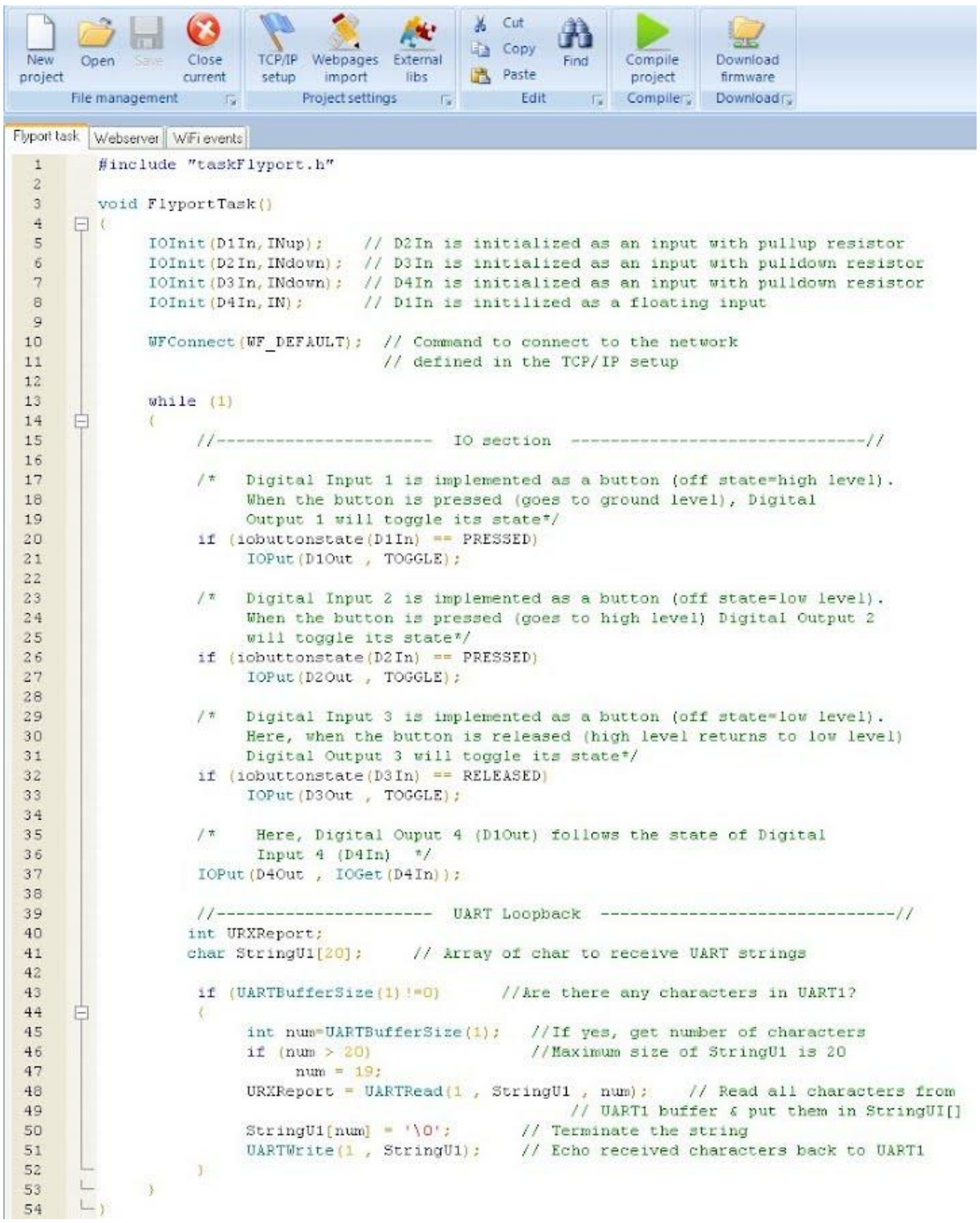
WiFi module	Microchip MRF24WB0MA (Wi-Fi certified) with choice of on-board antenna or uFL antenna connector
Microprocessor	Microchip 24FJ256GA106 with 256K Bytes program (flash) memory, 16K Bytes RAM
I/O default configuration	5 Digital Inputs (5V tolerant, with programmable pullup / pulldown / none) 5 Digital Outputs (4 can be used as PWM, 3.3V level, each individually configured) 4 Analog Inputs (10-bit ADC, VRef=2.048V, 1bit=2mV, 2 configurable to PGC/PGD) 1 UART port, 1 SPI port, 1 I2C port, Reset (active low) NOTE: The above is the default I/O configuration and the I/O pins may be flexibly re-configured to use other I/O peripherals
Real-time clock	On-board Micropower real-time clock continues to run in hibernate mode
On-board battery	Yes
Transmit power	Settable or variable up to 10 dBm with automatic power minimizing option (PS Poll)
Receiver sensitivity	-91dBm typical
Range with external antenna	At least 400m
Supply voltage	3 and 5V, when used with optional development card, the board is powered by USB port to PC
Supply current	At 3V RX 85 mA, Sleep 250 uA, Hibernate 0.1 uA, TX at maximum power 154 mA

WiFi specifications

Networking	Supports and joins infrastructure and ad-hoc 802.11 b/g/n compatible networks
Email capability	Can send emails via WiFi network, but SSL encryption is not supported
Internet protocol capabilities	HTTP, TCP, socket, UDP, DHCP client, DHCP server, DNS client, DNS server, dynamic DNS, SNTP client, ICMP client, ICMP server, announce service, NetBIOS name service, debug option on UART, remote reboot service, active or passive scan
Security options	WEP, WPA-PSK Personal, WPA2-PSK Personal, WPA or WPA2 auto select
Website capabilities	HTML, XML, CSS, JavaScript, JQuery, CGI, AJAX - single click imports user website into project
Operating temperature range	0 - 70C
Supported socket types	Generic TCP client, generic TCP server, Telnet, UART 2 TCP bridge, HTTP server, default, FTP commands and FTP data
Download method	Contains protected boot loader for download via serial port or USB port (external programmer not required), remote firmware update supported, can also be programmed via the Microchip programmer using PGC and PGD inputs
On-board LEDs	one green (power) and two user-programmable red LEDs
Certifications	USA (FCC), Canada (IC), Japan (ARIB), Europe (ETSI). WiFi-certified (WFAID: WFA7150)

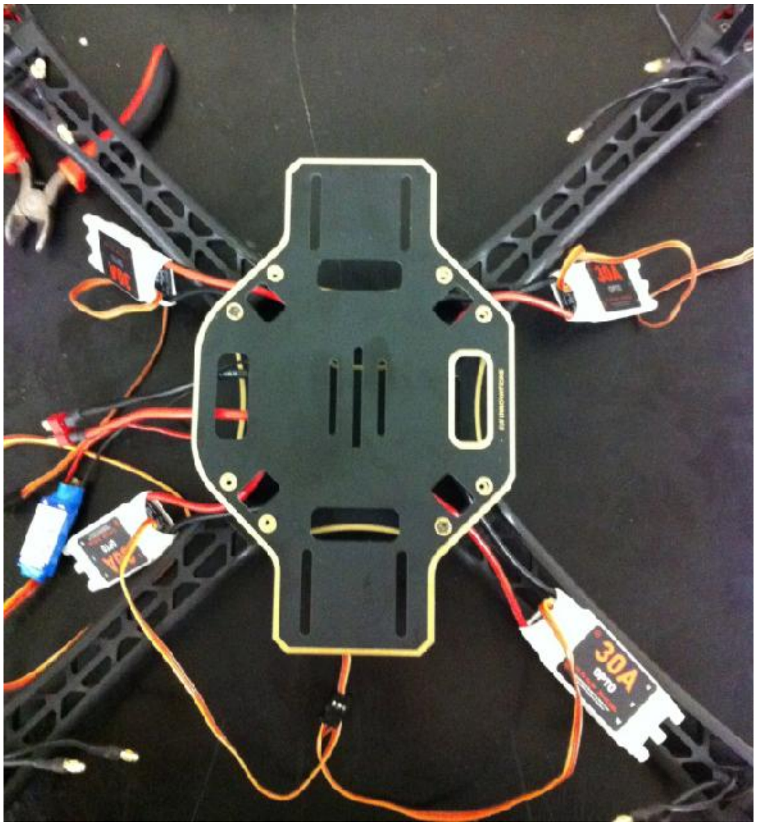
Specifications of the IDE (Interactive Development Environment) from openPicus

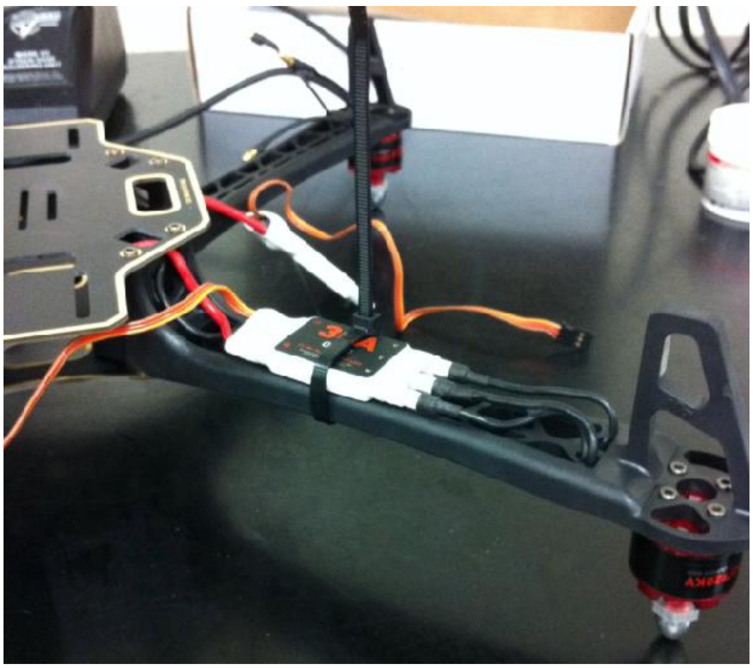
Operating System	PC with Windows XP or Windows 7
User tabs	Three tabs expose templates into which the user can write C code: (1) Flyport Task - the commands to set and read hardware I/O; (2) Web server - the commands to manage real-time communication with the internal website; (3) Wi-Fi events - events such as CONNECTION ESTABLISHED, CONNECTION TEMPORARILY LOST, etc. are exposed to allow optional user action

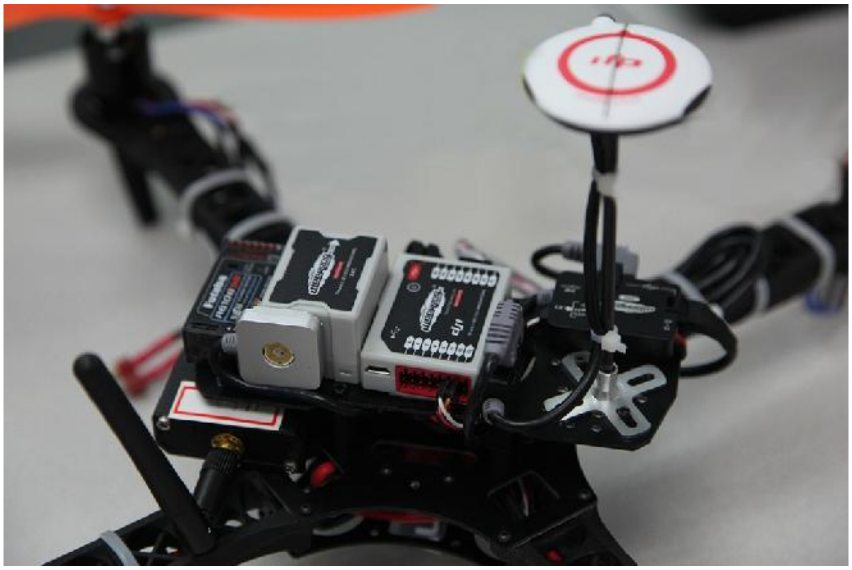


Chapter 5 – Ongoing research

We are building an experimental black quadrotor to compare the open source ArduPilot Mega version 2 (APM2) against the semi-professional DJI WOOKONG M (multi-rotor) flight system, a system for commercial and industrial applications used almost exclusively with hex and octorotors.







DJI FlameWheel F450 with DJI WOOKONG M flight system

Technical specifications of the DJI WOOKONG-M

Built-in functions	Autopilot Auto Hover Fail Safe Camera mount stabilization control	
Multi rotor types	Quadrotor Hexrotor Octorotor	
Supported ESC output	200Hz refresh frequency	
Recommended transmitter	PCM or 2.4GHz with minimum 5 channels and Failsafe function available on all channels	
Recommended power supply	DC 4.8 ~ 12V	
Power consumption	MAX 5W (0.9A@5V, 0.7A@5.8V, 0.5A@7.4V, 0.4A@8V)	
Operating temperature	-5°C to +60°C The IMU must be kept warm if you want to use it under low temperature, could be -5°C or lower.	
Flight Performance (can be affected by mechanical performance)		
Hovering accuracy	Vertical: Horizontal:	± 0.5m ± 2m
Suitable wind conditions	8m/s (28.48Km/h)	
Maximum rotate angle	30°	
Vertical speed	3m/s	
Packaging &Shapes		
Total weight	<= 150g	
Dimensions	Main Controller IMU GPS & Compass	61mm x 39.6mm x 15.8mm 40mm x 31mm x 26mm 50mm (diameter) x 9mm

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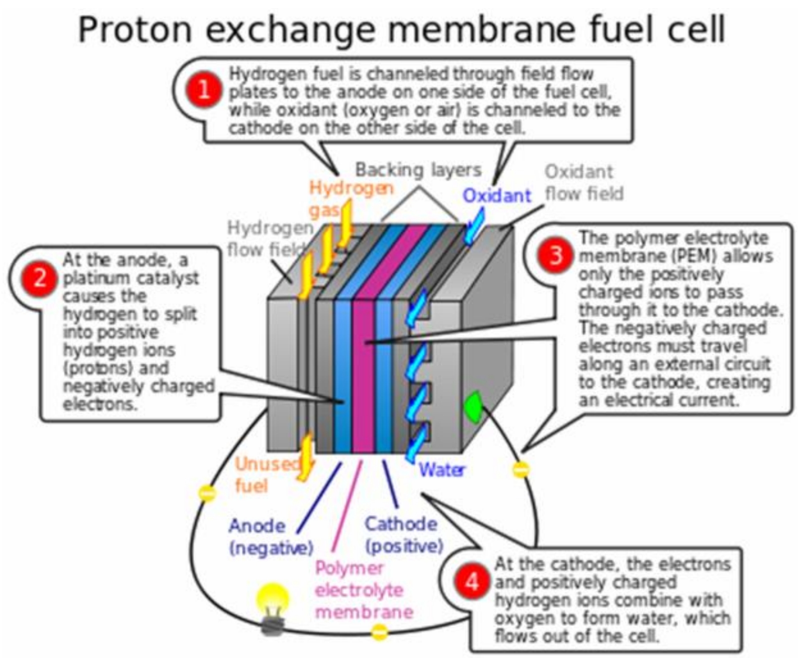
Chapter 6 – Undeliverables

Two essential components were not available during the first EGR299 curriculum, primarily a fuel cell battery to attempt increasing the mission time to up 3.5 hours and the video transmission module for the APM Mission Planner (Ground Control).

Fuel cell

In late 2011, the Montgomery County Community College (MC3) made an official request to the Air Force Research Laboratory at Wright-Patterson Air Force Base in Dayton, Ohio to gain an Educational Technology Transfer in order to validate their fuel cell[6] for the UAVForge project. The request was denied but MC3 will re-apply later this year, and as we have demonstrated our willingness to continue our research in the second EGR299 curriculum starting in October 2012, we hope our request will be granted.

A fuel cell resembles a small generator. But unlike an ordinary LiPo battery, which can keep a VTUAV in the air for 30 minutes or less, fuel cells have the potential to power it for more than twice that amount of time.



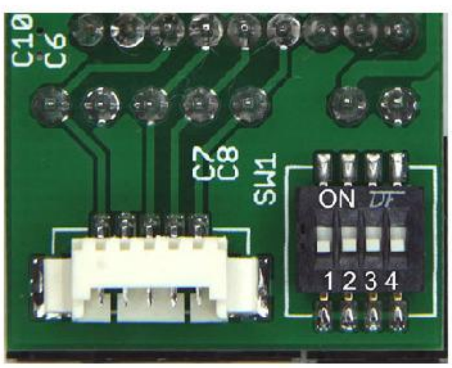
6 http://www.ndep.us/Flying-Fuel-Cells

Video transmitter

The ImmersionRC's 600mW 5.8GHz audio/video transmitter has been unavailable for the first half of the year and therefore we could not purchase and test one.

A 5V camera can be connected directly as an audio/video transmitter to provide real-time streaming video, with clean, noise free 5V power output, to the APM Mission Planner to enable On Screen Display (OSD) for the APM Mission Planner. The OSD is a very important part of First Person View (FPV) flying also called "Video Pilotage".

The ImmersionRC600mW 5.8GHz audio/video transmitter features robust and durable locking connectors that won't work themselves lose during a flight. Its design includes a super quiet, high efficiency regulator that has zero interference with the video image, or any other sensitive Radio Control (RC) equipment. Its small form factor consumes a mere 3W and is ideal for airborne missions.



1	2	3	4	
off	off	off	x	5860MHz
on	off	off	x	5860MHz
on	on	off	x	5820MHz
on	on	on	x	5740MHz
off	off	on	x	5800MHz
off	on	on	x	5760MHz
on	off	on	x	5780MHz
off	on	off	x	5840MHz

ImmersionRC transmitter specifications

- ✓ 600mW (+28dBm) typical output power
- ✓ 6-25V input voltage, 2S-6S LiPo compatible
- ✓ Typical power consumption of just 3W at any input voltage
- ✓ Super-quiet, high efficiency switching regulator
- ✓ Small, lightweight, all-in-one A/V transmitter solution
- ✓ 5V power output, ideal for powering cameras
- ✓ No interference with sensitive RC equipment by design
- ✓ High bandwidth video
- ✓ High bandwidth stereo-audio
- ✓ Composite video input at 1Vpp/75ohm
- ✓ Two sets of A/V connectors, for easy patch-in of an audio source
- ✓ 7 channels (5740MHz, 5760MHz, 5780MHz, 5800MHz, 5820MHz, 5840MHz, 5860MHz), PL synthesized
- ✓ FM Audio/Video modulation
- ✓ 50 ohm antenna impedance
- ✓ Weight: 18grams
- ✓ Size: 50 x 23 x 15mm
- ✓ Requires airflow for cooling, do not mount in an enclosed area
- ✓ Must be used with an antenna at all times
- ✓ May require a license to operate

Video Receiver

Unfortunately the ground video receivers are still bulky and require between 6 to 13V DC power. Since the Ground Station software is running on a tablet, we have not found a compact receiver that would only require 5V from any USB port.

ImmersionRC Uno receiver specifications

Typical sensitivity	-90dBm
Frequencies	5740MHz, 5760MHz, 5780MHz, 5800MHz, 5820MHz, 5840MHz, 5860MHz
Dual buffered A/V outputs	2x 3,5mm Jack
Single Cable Grounds Station connection	Power, Audio, Video, Control
DC Supply	6-13v
High Bandwidth Stereo Audio	Yes
Size	85x75x25mm
Weight	130g

Digital joysticks

We could not find semi-professional digital joysticks that met our needs. Most of the joysticks we evaluated were analog joysticks, some had poor screen resolution, some were perfectly adequate for video gaming but not precise enough for the Ground Control program running on the Acer tablet. We had to exclude all professional joysticks for piloting UAVs as they cost hundreds of dollars and are very bulky.

Montgomery County
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