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Health Monitoring and Failure Detection of Electronic and Structural Components in Small Unmanned Aerial Vehicles

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***Abstract*—**Fully autonomous small Unmanned Aerial Vehicles (UAVs) are increasingly being used in many commercial applications. Although a lot of research has been done to develop safe, reliable and durable UAVs, accidents due to electronic and structural failures are not uncommon and pose a huge safety risk to the UAV operators and the public. Hence there is a strong need for an automated health monitoring system for UAVs with a view to minimizing mission failures thereby increasing safety. This paper describes our approach to monitoring the electronic and structural components in a small UAV without the need for additional sensors to do the monitoring. Our system monitors data from four sources; sensors, navigation algorithms, control inputs from the operator and flight controller outputs. It then does statistical analysis on the data and applies a rule based engine to detect failures. This information can then be fed back into the UAV and a decision to continue or abort the mission can be taken automatically by the UAV and independent of the operator. Our system has been verified using data obtained from real flights over the past year from UAVs of various sizes that have been designed and deployed by us for various applications.

***Keywords*—**Fault detection, health monitoring, unmanned aerial vehicles, vibration analysis.

I. Introduction

Unmanned Aerial Vehicles or UAVs are fully autonomous vehicles that were originally developed by the military for special operations. However, with recent advances in technology and its miniaturization, followed by the reduction in prices, UAVs have now become affordable for wider commercial adoption. Also, the development of open source flight controller electronics and mission control firmware have further eased its adoption. Today, small UAVs (all-up-weight less than 10 kg) are finding applications in surveying, precision agriculture, utilities inspection, real estate, filming and insurance to name a few. The business potential for this technology is huge. This has in-turn fueled tremendous investments in UAVs and ancillary technologies. Although a lot of research is being done to develop safe, reliable and durable UAVs, accidents are not uncommon and pose a huge safety risk to the public. This is compounded by the proliferation of hobby grade hardware with questionable quality and safety standards. Hence there is a strong need to monitor a UAV for potential failures and take appropriate ameliorative measures during a mission. This paper discusses our approach to monitoring the electronic and structural components of a UAV with the goal of minimizing mission failures.

This paper is organized as follows. Section III describes the major components of a UAV. Section IV gives an overview of a UAV's operation along with the role of the various sensors in it. The various failures that can occur in a UAV are discussed in Section V. Section VI, discusses how our system monitors the health of the various electronic and structural components. It also describes the statistical analyses done on the monitored data and a how a rule-based engine is applied to detect failures. Section VII discusses vibrations in small UAVs; one of the major sources of mission failures and the experiments conducted to understand and analyze them.

II. Related Work

Small UAVs have started gaining popularity only recently. A lot of research work has been done in navigation and control algorithms, swarm coordination and applications of UAVs. A lot of work over several decades has also been done in structural health monitoring of aircrafts, helicopters and large UAVs like the ones used in defense applications. Although the basic principles of flight, control and navigation remain the same, the small UAVs have a different set of problems and to a different degree than the larger airborne vehicles. Moreover, the technology used in smaller UAVs is different and costs less than their larger counterparts. All of this necessitates a different approach to health monitoring of small UAVs, which is just beginning to pick up pace. Reference [1] talks of FBG based techniques to monitor the structural health of large UAVs flying at high speeds and altitudes. In [2] the authors model and analyze the vibrations in a UAV helicopter having a vision system, with the goal of improving the image quality. Reference [3] analyzes vibrations from motors and propellers in small UAVs using additional sensors and micro-controllers in each of the motors. In [4] authors talk about monitoring the UAVs for failures in motor mounts and propellers. Reference [5] talks about pattern recognition techniques to monitor the structural health of any structure. In [6], the authors describe techniques to evaluate the health of composite wings in large UAVs. Reference [7] describes a health aware planning framework to route the UAVs to different places in order to maximize the number of completed tasks while taking into consideration the health of the UAV like fuel consumption,

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wind, damage etc. Similar to [7], the authors in [8], describe a framework to improve the reliability in multi-UAV missions through adaptive mission planning based on high level UAV health. In [9] the authors do a qualitative analysis of the failures in a small UAV. Reference [10] describes the design of a health management system for UAVs to monitor the health and uses Bayesian probabilistic fault diagnosis. The Arducopter project [11] talks about analyzing some of the data from the flight controllers with a view to understanding failures.

III. Components of a UAS

An Unmanned Aerial System (UAS) consists of three major systems; viz. the UAV, the payload and the Ground Control System (GCS). The UAV consists of the following components.

- Airframe: This is a mechanical structure that houses all other components in the UAV. In a fixed-wing UAV, it consists of the fuselage, wings and control structures like rudder, elevator and ailerons that provide lift and control during flight. In a multi-rotor UAV it consists of arms or booms that support electric motors, a central bay housing the battery, flight controller, sensors and electronic components. An additional structure for mounting payloads is also usually present.
- Propulsion system: In UAVs with electric propulsion, it consists of motors, propellers, Electronic Speed Controllers (ESCs) and batteries.
- Flight controller: This is a specialized electronic component with sensors to control and navigate the UAV autonomously. It takes data from sensors, other electronic components and control signals from the user and runs navigation algorithms to autonomously control and navigate the UAV.
- Navigation system: This is a logical unit, consisting of sensors like Inertial Measurement Units (IMUs), magnetometers, barometers and GPS. IMUs have accelerometers and gyroscopes inside them. These provide the flight controller with the necessary data to control and navigate the UAV. The sensors may be physically placed inside the flight controller or outside.
- Communication system: It consists of radio receivers on the UAV to receive control inputs from the Ground Control System (GCS) and telemetry radios to send data from the UAV back to the GCS. It may also include video transmitters to send real-time video feeds from the UAV to the GCS.
- Sense and avoid: These are sensors to sense and avoid obstacles during flight.
- Payload: This may consist of one or more cameras (visual, multi-spectral, hyper-spectral) or sensors for aerial data collection. It may also be packages meant for delivery.

The GCS consists of the following components.

- A flight display: This is used for system status monitoring via telemetry data received from the UAV.
- Communication system: This is usually a radio transmitter used by the pilot to communicate with and control the UAV.
- Data processing: A light weight, on-the-field system for displaying and processing data from the payload.

IV. Working of a UAV

In this section we give an overview of how a multi-rotor UAV flies autonomously. A multi-rotor UAV consists of multiple rotors; 3, 4, 6, or 8 rotors are common. Each rotor or propeller is driven by an electric motor. All motors are powered by the main battery. The speed of each motor is controlled individually using an Electronic Speed Controller (ESC). By changing the speed of each motor, the lift produced can be adjusted in order to achieve the desired flight characteristics of speed, altitude, direction and stability. Based on the data obtained from the various sensors and electronic components mentioned below, the flight controller sends commands to the ESCs to change the motor speeds to achieve the desired flight characteristics. A modern UAV has the following major sensors and electronic components.

- IMUs: UAVs can have one or more IMUs (Inertial Measurement Units). These have accelerometers and gyroscopes inside them. Accelerometers give the acceleration values in each axis whereas the gyroscopes give the angular rates in each axis. Reference [12] gives an overview of the navigation algorithms in a UAV. The angular rates from the gyros are integrated to calculate the angular position. Acceleration values are converted from body coordinates (x,y,z) to world coordinates (North, East, Down) using the angular position calculated above. Accelerations are then integrated to calculate velocities and velocities are integrated to calculate position. The above technique is called ‘State Prediction’. During state prediction, integration errors, rounding errors and sensor biases cause uncertainties in the predicted states. If not corrected, these errors will become very large in just a few seconds and the state predictions will become unusable. Hence the navigation algorithms use data from other sensors like GPS, barometer and compass to reduce the uncertainties in the predicted states.
- Compass: Also called a magnetometer, it gives the direction or heading of the vehicle based on measurements of the Earth’s magnetic field.
- Barometer: This is used to determine the height or altitude of the vehicle by measuring the air pressure.
- GPS receiver: This receives signals from various GPS satellites in order to triangulate the UAVs latitude, longitude and altitude. This information is also used to determine the speed and heading of the UAV.
- Power module: Some UAVs have power modules that monitor the current and voltage of each motor and the main battery.
- Radio receiver: This receives control signals from the radio transmitter in the GCS.
- Telemetry modem: This sends data from the UAV back to the GCS. The data provides the operator with a complete

status of the UAV including but not limited to its speed, location, altitude, heading, distance from home, distance to the next waypoint, flight mode, GPS status, voltage and current of motors and battery, radio signal strength and radio noise.

V. Types of Failures

A modern UAV is a very high tech device consisting of electronic and structural components. There are a number of potential sources of failures other than manufacturing defects, which we describe below. They can be categorized into electronic glitches, electronic failures and structural failures.

A. Electronic Glitches

Glitches are temporary or transient failures usually due to signal losses resulting from interference either from within the UAV or from the environment.

- Magnetic interference: Improper UAV design can cause strong magnetic fields to be generated by high currents flowing through the battery, ESCs and motors. Strong magnetic fields are also present around high voltage power lines and transformers. These strong magnetic fields can interfere with the compass resulting in loss of heading.
- Electrical interference: This happens when flying near high voltage power lines and transformers. This type of interference can crash the vehicle.
- Radio interference: Interference from other radios and communication devices either on-board the UAV or in close proximity can result in increased noise and loss of signal. Electrical noise from ESCs also increase radio noise. Obstacles like trees and buildings also cause signal losses.
- GPS signal loss: This is usually due to thick cloud cover, tall buildings or trees.
- Barometric pressure drop: This can happen if the barometer is improperly exposed to wind. Increased wind velocity will decrease wind pressure resulting in inaccurate altitude estimates.

B. Electronic Failures

1) Sensors
   a) IMU: IMUs have accelerometers and gyroscopes in them that can fail if operated beyond their voltage, temperature or shock rating. This usually happens due to voltage fluctuations in UAVs or flying in extremely cold climatic conditions.
   b) GPS receivers: GPS receiver failures are usually due to bad wiring or physically damaged components.
   c) Compass: Exposure to strong magnetic fields like those produced by high voltage transformers and power lines can cause permanent damage to compass.
2) Radios: Radio transmitters and receivers used for control and communication can fail if not operated within their rated voltage. Antennas can fail due to physical damage.
3) Controllers
   a) Speed Controllers: These can fail if used above their rated current or have improper airflow over their surface resulting in insufficient cooling.
   b) Flight controller: This can fail if the power supply is not within the specified range. It usually happens in UAVs when high current components like servos and radios are connected to the same power supply as the flight controller thereby resulting in voltage spikes.
4) Battery: Poor quality batteries, poor maintenance (over charge/discharge), overuse (too many charge/discharge cycles), abuse (operating beyond the rated temperature range) can result in poor performance and failure.

C. Structural Failures

1) Motor
   a) Mount failure: Motor mounts can dislodge significantly or break away completely from the airframe.
   b) Mount vibration: Improperly secured motor mounts can cause severe vibrations.
   c) Bearing failure: This is usually a slow process and results in increased vibrations overtime.
   d) Motor vibrations: Motors that are big or have many magnetic poles (> 10 poles) like those used in heavy lift multi-rotors tend to vibrate more.
2) Propeller
   a) Propeller failure: Propellers can slip, fracture or break off completely.
   b) Propeller vibrations: Loosely mounted propellers can cause vibrations. Big propellers vibrate a lot more than small ones. High quality propellers made of composite materials like carbon fiber or fiberglass reinforced plastic vibrate less than plastic propellers.
3) Airframe: Poor quality materials, poor design and construction techniques and damaged parts can cause significant flexing and vibrations.

VI. UAV Health Monitoring

This section describes our techniques to monitor the various components in the UAV with the goal of detecting failures. We have used data from our UAVs for all of the analyses below. We have designed, built and deployed multi-rotor UAVs of different sizes for a number of applications. These UAVs have flown in varied weather conditions, terrain, geographies, payloads and applications. The relevant specifications of our UAVs of different sizes are listed below.

- Type: Fully autonomous multi-rotor UAV with 4 rotors.
- Propulsion: Battery powered electric motors.
- Propeller diameter: Ranging from 9 inches to 18 inches.
- Weight without payload: Ranging from 1.5 kg to 4.5 kg.
- Payload capacity: Ranging from 200 g to 4 kg.
- Max speed: Ranging from 40 km/h to 85 km/h.

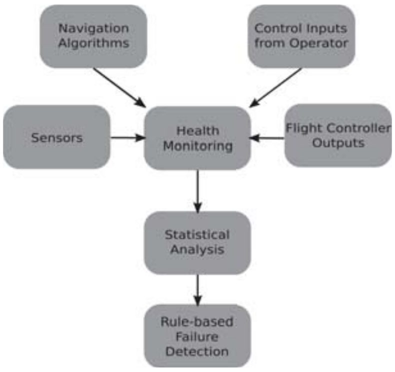

Fig. 1 A rule-based system for detecting failures in small UAVs

- Safety features: Geo-fence, radio failsafe, battery failsafe and emergency return to home.
- Navigation: Inertial navigation and GPS.

The basic architecture of our system for monitoring the electronic and structural components for failures is shown in Fig. 1. It consists of three main modules viz. 'Health Monitoring', 'Statistical Analysis' and 'Rule-based Failure Detection'.

A. Monitoring Module

This monitors data from four sources viz; sensors, navigation algorithms, control inputs from the operator and flight controller outputs.

1) Sensors
   a) 3-axis accelerometers: Acceleration in the x, y and z axis.
   b) 3-axis gyroscopes: Angular rates in the x, y and x axis.
   c) Compass: Magnetic field and interference in the x, y and z axis.
   d) GPS: Latitude, longitude, altitude, Horizontal Dilution of Precision (HDOP) and number of satellites. The HDOP is a measure of the geometric quality of the satellite configuration in the sky. A good geometric configuration reduces the triangulation errors. For example, if the satellites that are visible at a particular point of time are clustered in one area in the sky, the HDOP will be high, which is not good. If the satellites are uniformly distributed across the sky, then the HDOP will be low, which is good.
   e) Barometer: Altitude based on air pressure.
   f) Power module: Voltage and current drawn from the main battery and current drawn by individual motors.
   g) Flight controller power module: Input voltage to flight controller.
   h) Radio signal: Radio signal strength of the radio transmitter in the GCS and the radio receiver in the UAV.
   i) Radio noise: Radio noise in the radio transmitter in the GCS and the radio receiver in the UAV.
2) Navigation algorithm: Most flight controllers run non-linear state estimation algorithms like Extended Kalman Filtering (EKF) to control and navigate the UAV. An overview of the working of the EKF algorithm was given in Section IV. The monitoring module captures the uncertainty in estimating the position and velocity in all the 3 axis by the EKF. The uncertainty, also known as 'innovation' is the difference between the values estimated by the EKF and the actual values observed using sensors like GPS, barometer and compass.
3) Control inputs from operator: During an autonomous flight, the control inputs from the operator are ignored. However, during a semi-autonomous or manual flight, the operator's control inputs of throttle, yaw, pitch and roll are monitored.
4) Flight controller output: In an autonomous flight, the flight controller outputs of desired yaw, desired pitch, desired roll, desired altitude and throttle values to motors are monitored. In a semi-autonomous or manual flight, only the throttle values to the motors are monitored. The desired yaw, pitch, roll and altitude are calculated by the flight controller based on the desired flight characteristics and the sensor data.

B. Statistical Analysis and Rule-Based Failure Detection

Statistical analysis is done on the data captured by the 'Monitoring Module'. The statistical analyses include min, max, mean, standard deviation, coefficient of variation and correlation of the data. Then a rule based engine is used to detect failures. While the rules are based on the assumption that the UAV is flying in a fully autonomous mode, most of these rules also apply to other flight modes supported by UAVs. Some of the important rules for detecting electronic failures are listed below.

1) $R_{sample} \approx 50Hz$: Most algorithms that use the accelerometer data for inertial navigation require a high sampling rate of about 50 samples per second. However, vehicle movements can be captured even at 5 Hz. The higher sampling rate allows us to detect vibrations, which we discuss in Section VII.
2) $I \leq I_{max}$: Current through motors, ESCs and battery must be less than the max allowed values. Higher currents even in short bursts can cause significant heating or failure of the components. This is especially true if there is insufficient airflow for cooling.
3) $Vmin > 3.3V$: During discharge, minimum voltage of each cell of the battery must not go below the minimum cell voltage ($3.3v/cell$ for lithium polymer), otherwise permanent damage can occur to the cell.
4) $CV(V_c) < 0.03$: Coefficient of variation in the input voltage to the flight controller should be $< 3\%$. Many flight controllers are sensitive to variations in the input voltage. If the flight controller is connected to the same power supply as servos and other devices, significant voltage spikes can occur especially during hard maneuvers thus causing a brownout and total loss of the vehicle.

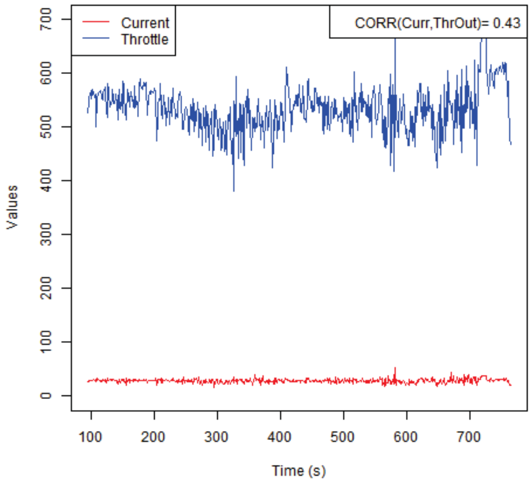

Fig. 2 Correlation between battery current and throttle out signal

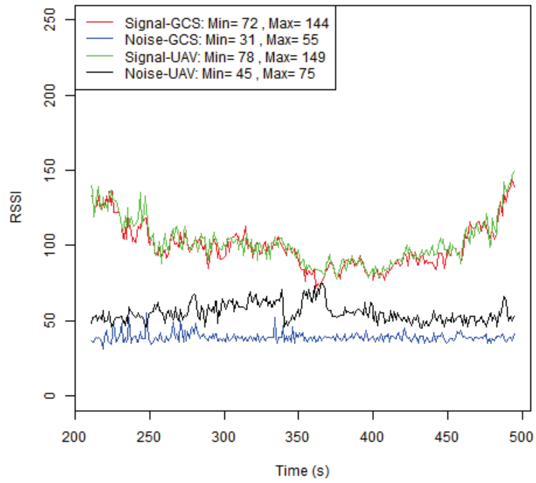

Fig. 3 Radio signal and noise at GCS and UAV

5) Main battery must not be discharged below the specified levels. For lithium polymer batteries, it is 20% of the rated capacity. Failure to ensure this will result in permanent damage to the lithium polymer batteries.
6) $corr(I_{batt}, thr_{out}) > 0.8$: The correlation between the current drawn from the main battery and the throttle out signal from the flight controller must be high. We found that a correlation of > 0.8 is indicative of a good battery. A lower correlation means that the battery is not able to supply the required current as per the requirements of the motor as shown in Fig. 2. The battery current is in amperes and the throttle out signal is the width of the PWM signal in μs. The correlation there is 0.43 indicating an overloaded battery. This could be due to reasons discussed in Section V-B.

Some of the important rules for detecting electronic glitches are given below.

1) $gps_{hdop} < 2.0, gps_{sats} >= 9$: Under normal conditions, the GPS HDOP value should be less than 2.0. A higher value indicates that the satellites that are visible are clustered in the sky and not spread out. This will result in more triangulation errors. Also, the number of visible satellites should be $>= 9$ for accurate triangulation. Tall buildings, rain-bearing clouds and trees can result in higher HDOP values and a lower satellite count.
2) $0.3G < \sqrt{mag_x^2 + mag_y^2 + mag_z^2} < 0.6G$: In most places on Earth, the magnetic field length, should be between 0.3 to 0.6 Gauss. A value beyond this range indicates strong influences of other magnetic fields. This is usually because of poor design where the heavy currents flowing through the battery, ESCs and motors produce strong magnetic fields that interfere with the on-board compass. It could also be due to high voltage power lines in the vicinity.
3) $corr(yaw_{des}, yaw_{act}) > 0.9$: Correlation between desired yaw and actual yaw must be > 0.9. A low correlation is indicative of a heading loss due to compass interference. A heading loss can also be due to a GPS glitch. However, by looking at the above two rules, one can determine the cause of heading loss.
4) $CV(mag_{x,y,z}) < 0.3$: Coefficient of variation in the magnetic field as measured by the compass must be $< 30\%$ under full throttle condition. As the throttle is increased, the current through the battery, ESCs and motors increases thus increasing the magnetic fields generated by the current (especially if there are loops in the wires). Under full throttle, there is maximum magnetic interference and this should be $< 30\%$ in order to prevent loss of heading.
5) $S_{gcs} - N_{gcs} > 25, S_{uav} - N_{uav} > 25$: The Radio Signal Strength Indicator (RSSI) values for the separation of radio signal from radio noise (in both GCS and UAV) must be at least 25. A lower value is indicative of severe signal loss. This usually happens if the UAV flies beyond the radio range, there are obstacles like trees or buildings in the line of sight to the UAV, there is high noise floor due to other UAVs, high voltage power lines, communication towers or electronic devices operating in the vicinity.

Fig. 3 shows the radio signal and noise both at the GCS and the UAV. The radio signal strength in dBm is $(RSSI/1.9) - 127$. As can be seen in Fig. 3, the minimum separation between the signal and noise on the UAV was 3; in other words, the signal was barely distinguishable from the noise and resulted in loss of communication.

Some of the important rules for detecting structural failures are given below.

Many structural failures can be detected by the vibrations caused by them. However, classifying the failures based on the vibrations can be difficult. Our system uses two different techniques for detecting vibrations and quantifying their levels based on accelerometer data. Most flight controllers today carry two IMUs inside them for redundancy. In this case we find the correlation between the acceleration values from the two accelerometers in the two IMUs. The idea behind this approach is that if vibrations are absent, then the vehicle movements will induce the same accelerations in the two accelerometers. So their values will show a high correlation. However, if vibrations are present, they will induce different accelerations in the two accelerometers. So their values will show poor correlation.

The second technique makes use of the fact that accelerations induced by UAV movements have a frequency of less than $5Hz$, while those induced by vibrations usually have a much higher frequency. This makes it easy to separate the vehicle movements from the vibrations. A high pass filter at $5Hz$ can remove the vehicle movement and the standard deviation of the vibrations can then be calculated.

Low vibrations do not affect the stability of the UAV in any way but high levels of vibrations result in flight instability leading to a crash. This is because the higher noise in the acclerometer readings due to vibrations will result in higher uncertainties in position and velocity estimates by the navigation algorithms.

1) $(-3m/s^2 < acc_{x,y} < 3m/s^2), (-15m/s^2 < a_z < -5m/s^2)$: Acceleration values are usually between -3 to +3 m/s^2 in x and y axis and -5 to -15 m/s^2 in the z axis. Although this is configurable and can change from one UAV to another, the idea is that smooth vehicle movements especially in the autonomous mode will induce accelerations in the above range. Physical impact or damaged structural components will induce much higher values. A higher acceleration value does not always indicate a failure but is usually an anomaly that needs to be investigated.
2) $-3deg/s < gyr_{x,y,z} < 3deg/s$: Angular rates in all three axis should be in the range of -3 to +3 deg/s. Again, smooth vehicle movements especially in the autonomous mode are usually within the above range. As in the case of accelerations, a higher angular rate does not always indicate a failure.
3) $corr(acc1, acc2) > 0.8$: Correlation between the acceleration values from the two IMUs should be > 0.8 in x, y and z axis. As described above, a high correlation indicates low vibrations. We discuss this in greater detail in Section VII, but just as an example, Fig. 4 shows a $corr(acc1_z, acc2_z) = 0.35$ during airframe vibrations due to loose payload mount. Note that the z-axis accelerations are beyond the usual range of -5 to -15 m/s^2.
4) $corr(gyr1, gyr2) > 0.9$: Correlation between the angular rates in all three axis should be > 0.9. This is again based on the same idea discussed above for accelerometer readings.
5) $corr(alt_{iner}, alt_{baro}) > 0.8$: Correlation between inertial navigation altitude and barometric altitude should be high. A lower correlation value indicates heavy winds.
6) $corr(alt_{iner}, alt_{des}) > 0.8$: Correlation between inertial navigation altitude and desired altitude should be high. A lower correlation value indicates inability of the UAV to maintain the desired altitude due to vibrations along the z axis. Fig. 5 plots the three altitude readings; barometric altitude (BarAlt), desired altitude (DAlt) and inertial navigation altitude (InerAlt) during airframe vibrations along the z axis. Note the high correlation between barometric altitude and inertial navigation altitude thus indicating the absence of heavy winds.

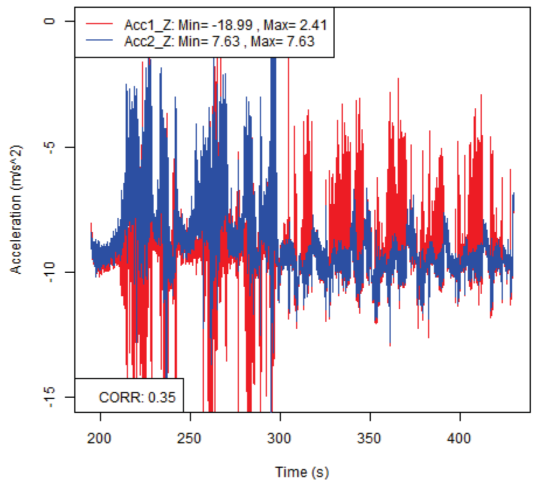

Fig. 4 Z-axis accelerations from two IMUs due to airframe vibrations

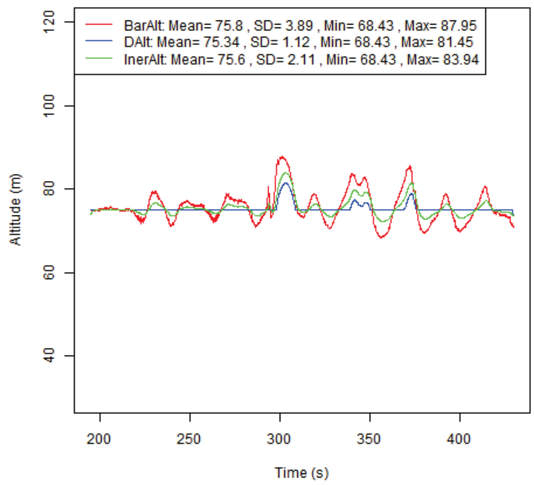

Fig. 5 Altitude readings from barometer and inertial navigation during airframe vibrations

7) $corr(roll_{des}, roll_{act}) > 0.7$: Correlation between desired roll and actual roll should be > 0.7. A very low correlation indicates a catastrophic structural failure like a propeller or motor mount breaking off.
8) $corr(pitch_{des}, pitch_{act}) > 0.7$: Correlation between desired pitch and actual pitch should be > 0.7. The idea behind this is the same as above.
9) $IP_n, IP_e, IP_d < 0.25m$: Uncertainty in position estimates in the x, y and z axis (North, East, and Down) as predicted by EKF should be $< 0.25m$. As discussed before, vibrations will induce noise in the IMUs, thus causing higher uncertainties in the position and velocity estimates by the navigation algorithms making the UAV unstable. This is a common problem because vibration damping is difficult and not very effective in small UAVs.
10) $IV_n, IV_e, IV_d < 0.25m/s$: Uncertainty in velocity

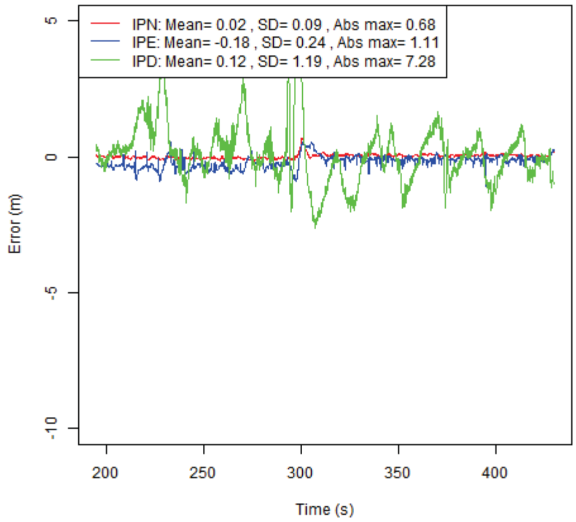

Fig. 6 3-axis position estimation uncertainty due to airframe vibrations

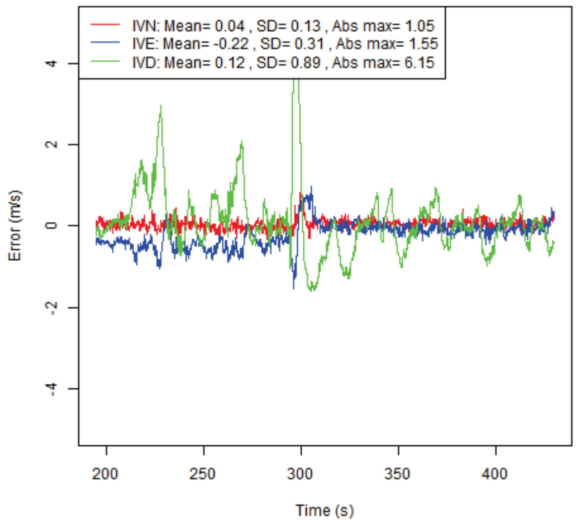

Fig. 7 3-axis velocity estimation uncertainty due to airframe vibrations

estimates in the x, y and z axis as predicted by EKF should be $< 0.25m/s$.

Figs. 6 and 7 show the uncertainties in estimating the position and velocity along the x, y and z axis due to the airframe vibrations.

VII. Vibration Analysis

Several experiments were conducted by us to understand the following.

1) The common causes of vibrations in multi-rotors.
2) How to detect and quantify the vibrations.
3) The effect of vibrations on the flight stability of a multi-rotor.

While the vibration experiments were done on a quad-copter, the experiments and findings are applicable to other most commonly used multi-rotor systems like hexa-copters and octo-copters. Vibrations are detected by analyzing the data from the accelerometers inside the two IMUs inside the flight controller. This was one of the techniques discussed before in Section VI-B. Based on data from hundreds of flights, the mapping between the correlation values to the vibration levels and the flight stability was done and is shown in Table I.

TABLE I
Vibration Levels, Flight Stability and Correlation of IMU Data

Vibrations	High	Moderate	Low
Flight Stability	Unstable	Moderate	High
Accel Corr	< 0.5	0.5 to 0.8	> 0.8
Gyro Corr	< 0.6	0.6 to 0.9	> 0.9

TABLE II
Quantitative Definition of Stability

	Unstable Flight	Moderately Stable Flight	Highly Stable Flight
$\sigma_{ipn}(m)$	> 0.5	0.25 to 0.5	< 0.25
$\sigma_{ipe}(m)$	> 0.5	0.25 to 0.5	< 0.25
$\sigma_{ipd}(m)$	> 1	0.25 to 1	< 0.25
$\sigma_{ivn}(m/s)$	> 0.5	0.25 to 0.5	< 0.25
$\sigma_{ive}(m/s)$	> 0.5	0.25 to 0.5	< 0.25
$\sigma_{ivd}(m/s)$	> 0.5	0.25 to 0.5	< 0.25

The following is our qualitative definition of stability.

- Highly stable flight: The UAV is able to follow the desired flight path. Generally speaking, there are only small deviations in the position and velocity in all 3 axis. Occasional moderate deviations are considered normal.
- Moderately stable flight: The UAV is able to follow the desired flight path. Generally speaking, there are frequent and moderate deviations in the position and velocity in all 3 axis but not enough to cause it to crash.
- Unstable flight: The UAV is not able to follow the desired flight path. It has frequent large deviations in position and velocity in all 3 axis. It is very likely to crash or crashes during flight.

Table II gives our quantitative definition of stability in terms of the standard deviation of the uncertainties in estimated positions and velocities. Note that the allowed uncertainty in the z axis position IP_d is higher than that in the other two axis. This is because UAVs use barometers to estimate altitude and the barometric pressure depends not only on the altitude but also the wind velocity and ambient temperature. So higher variations in the z axis position estimates are normal.

In our experiments, three major causes of vibrations in multi-rotors were analyzed.

A. *Vibrations Due to Damaged Propellers*

Propellers are a major source of vibrations in multi-rotors. Vibrations are caused by uneven flexing of the propellers especially if they are long and not stiff. Vibrations can also occur if the propellers are worn out or damaged or not balanced. High quality propellers from reputed brands come pre-balanced from the factory and do not need further balancing. So only the vibrations caused by partially damaged propellers were studied. One of the damaged propellers blades

Fig. 8 A propeller with a damaged tip that was used in our experiments

TABLE III
CORRELATION OF IMU DATA FOR DAMAGED PROPELLERS

Correlations: Damaged propellers						
Flight	AccX	AccY	AccZ	GyrX	GyrY	GyrZ
1	0.96	0.72	0.65	0.76	0.97	0.83
2	0.92	0.63	0.57	0.74	0.96	0.76
3	0.88	0.55	0.53	0.70	0.91	0.60
4	0.74	0.85	0.65	0.77	0.96	1.0
5	0.89	0.54	0.69	0.84	0.97	0.77

used in our experiments is shown in Fig. 8 along with an undamaged propeller blade.

Table III shows 5 of the flights conducted with damaged propellers. It can be seen that the correlation between the accelerometer readings (from the two different IMUs inside the flight controller) is only moderate; in the range of 0.5 to 0.8 in at least one of the 3-axis (highlighted in red color). This indicates moderate levels of vibrations. Also, the correlation between the gyroscope readings is also only moderate in the x and z axis. This indicates high frequency rolling and yawing of the UAV. Also, during these experiments, the UAV was found to be only moderately stable. This was verified by looking at σ_{ip} and σ_{iv}; the uncertainties in the estimated position and velocity in the x, y and z axis. The uncertainties were more than what we would find in a stable flight but definitely not high enough to cause a crash. However, propellers with more damage would have resulted in more vibrations and potentially a crash. Also, the vibration characteristics may change if the degree, type and place of propeller damage changes. Our experiments did not cover all such cases.

Table IV shows the correlation values with good propellers under the same test conditions. Note the highly stable nature of all the flights with correlations > 0.8 in the x, y and z axis for the accelerometers and the gyroscopes.

Based on these experiments we were able to conclude the following.

1) Even partially damaged propellers cause significant vibrations.
2) The vibrations can be detected by finding the correlation between the acceleration values from the two IMUs.
3) The vibrations affect the flight stability. The extent of instability depends on the degree, type and place of damage.

B. Vibrations Due to Loose Payload Mount

Experiments were conducted where the payload mount was loosened to study its effect on the vibrations of the UAV.

TABLE IV
CORRELATION OF IMU DATA FOR GOOD PROPELLERS

Correlations: Good propellers						
Flight	AccX	AccY	AccZ	GyrX	GyrY	GyrZ
1	0.98	0.94	0.89	0.98	0.99	0.99
2	0.94	0.83	0.90	0.96	0.99	1.0
3	0.97	0.89	0.95	0.97	1.0	1.0
4	0.95	0.82	0.91	0.96	1.0	1.0
5	0.91	0.83	0.90	0.94	1.0	1.0

TABLE V
CORRELATION OF IMU DATA FOR LOOSE PAYLOAD MOUNT

Correlations: Loose payload mount						
Flight	AccX	AccY	AccZ	GyrX	GyrY	GyrZ
1	0.99	0.91	0.69	0.99	0.99	0.99
2	0.99	0.73	0.62	0.97	0.99	1.0
3	0.99	0.95	0.46	0.98	0.99	1.0
4	0.99	0.87	0.35	0.98	1.0	1.0
5	0.98	0.95	0.49	0.99	1.0	1.0
6	0.95	0.97	0.59	0.99	1.0	1.0

Severe vibrations were seen with a loose payload mount. As before, the correlation values of the accelerometer readings from the two IMUs were analyzed. The correlation values for some of those flights are shown in Table V. It is clear from the data that the vibrations were quite high and happened to be mostly in the Z-axis (although they could occur in any axis). These z-axis vibrations are shown in Fig. 4. Note the poor correlation of 0.35 between the accelerometer readings.

Also, the correlations between the gyroscope values in the x, y and z axis are high unlike in Table III with damaged propellers. This is because the vibrations due to the loose payload mount were centralized; i.e. near the geometric center and CG of the quad-copter and hence did not result in rapid pitching, rolling or yawing of the UAV. In the case of damaged propellers, the vibrations were at the tip of the arms/booms of the quad-copter where the propellers were mounted, thus increasing the moment and thereby causing the rolling and pitching. The uncertainties in the position and velocity estimates are plotted in Figs. 6 and 7 respectively. These values indicate an unstable flight as described in Table II.

C. Vibrations Due to Loose Motor Mount

Loose motors are another common cause of vibrations in multi-copters. In our experiments, the motor mounts were loosened a little. Since we did not have a torque wrench to quantify the tightness of the screws, they were loosened a little based on our experience. It was found that even if the motor mount was a little loose, it caused vibrations that could be detected from the IMU data just like in the other vibration studies. Most of the times, the characteristics of the vibrations were very similar to those from damaged propellers. Also, it was found that in some cases, the loose motor mount caused vibrations only in the Z axis resulting in significant yaw errors as shown in Fig. 9.

VIII. CONCLUSION

The paper describes our system to detect some of the electronic and structural failures in a small UAV without using

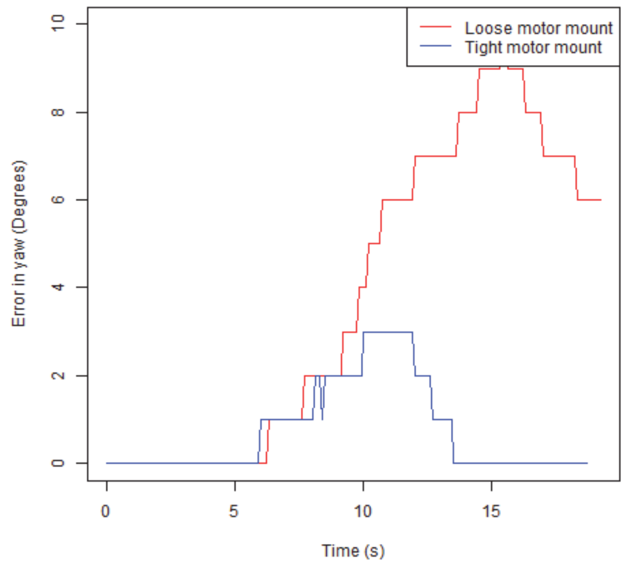

Fig. 9 Error in yaw due to loose motor mount vibrations

any additional sensors or devices. This makes the system easier to implement. The system monitors data from four different sources; sensors, navigation algorithm, control inputs from the operator and flight controller outputs. It then does statistical analysis and uses a rule based engine to detect failures. Our system has been verified using real flight data from our UAVs that have been operating under real conditions for various applications over the past year. However, some experiments were also conducted to detect and analyze vibrations due to propellers, motor mounts and payload mount. Our work on vibration analysis has demonstrated that it is possible to detect the most common causes of vibrations using the data from the two IMUs inside the flight controller. Classification of vibrations and identifying their causes based on the vibration data is part of our future work. Although the current system is capable of real-time health monitoring and failure detection, it does not yet give feedback to the flight controller to abort the mission or take appropriate ameliorative measures in case of anomalies or failures. Integrating this in real-time mission control of UAVs is part of our future work.

References

[1] Iddo Kressel, J. Balter, Naama Mashiach, Ido Sovran, and O. Shapira et al. High speed, in-flight structural health monitoring system for medium altitude long endurance unmanned air vehicle. In *EWSHM - 7th European Workshop on Structural Health Monitoring*, July 2014.

[2] Marichal N., Tomas-Rodriguez M., Castillo Rivera S., and Hernandez A. Modelling and analysis of vibrations in a uav helicopter with a vision system. In *International Journal of Advanced Robotic Systems*, volume 9, 2012.

[3] Yong Keong Yap. Structural health monitoring for unmanned aerial systems. Technical Report UCB/EECS-2014-70, Electrical Engineering and Computer Sciences University of California at Berkeley, May 2014.

[4] Joseph M. Brown, Jesse A. Coffey, Dustin Harvey, and Jordan M. Thayer. Characterization and prognosis of multi-rotor failures. In *Structural Health Monitoring and Damage Detection: Proceedings of the 33rd IMAC, A Conference and Exposition on Structural Dynamics, 2015*, volume 7, pages 157–173. Springer International Publishing, 2015.

[5] C. R. Farrar and H. Sohn. Structural health monitoring using statistical pattern recognition techniques. In *Journal of Dynamic Systems, Measurement, and Control*, volume 123, 2001.

[6] Chan Yik Park, Jong Heon Kim, and Seung-Moon Jun. A structural health monitoring project for a composite unmanned aerial vehicle wing: overview and evaluation test. In *Special Issue on a Structural Health Monitoring Project for a Composite Unmanned Aerial Vehicle Wing*, volume 19, pages 567–579, 2012.

[7] N. Kemal Ure, Girish Chowdhary, Jonathan P. How, Matthew A. Vavrina, and John Vian. Health aware planning under uncertainty for uav missions with heterogeneous teams. In *European Control Conference*, July 2013.

[8] Mario Valenti, Brett Bethke, Jonathan P. How, Daniela Pucci de Farias, and John Vian. Embedding health management into mission tasking for uav teams. In *American Control Conference*, 2007.

[9] Issac Olson and Ella M. Atkins. Qualitative failure analysis for a small quadrotor unmanned aircraft system. In *AIAA Guidance, Navigation and Control (GNC) Conference*, Aug 2013.

[10] Johann Schumann, Kristin Y. Rozier, Thomas Reinbacher, Ole J. Mengshoel, Timmy Mbaya, and Corey Ippolito. Towards real-time, on-board, hardware-supported sensor and software health management for unmanned aerial systems. In *Annual Conference of the Prognostics and Health Management Society*, 2013.

[11] Apm copter, http://ardupilot.org/copter, 10 oct 2016.

[12] Extended kalman filter navigation overview and tuning, http://ardupilot.org/dev/docs/extended-kalman-filter.html, 10 oct 2016.

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