Effecting Condition-Based Maintenance for UAVs

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Abstract

All missions, manned or unmanned, are associated with some risk. However, autonomous and semi-autonomous UAVs are exponentially more accident-prone than other kinds of machines. For example, historical data reveals that UAVs have reported failure rates of 20-60%. This rate is even higher when dealing with smaller UAVs and commercial (non-military) systems.

Improving the "reliability" of the subsystems and components comprising the UAVs is important because it underlies their affordability (an acquisition issue), their mission availability (an operations and logistics issue), their acceptance into the civilian sector (a regulatory issue), and their market viability (a business issue). Improved reliability offers potential savings by reducing maintenance and by decreasing procurement of spares and attrition aircraft.

Any UAV failing or crashing and impairing the surveyed environment, equipment, etc. will adversely impact the success of the whole mission.

As UAVs begin to take on more complex and longer-duration assignments, they will need to incorporate knowledge about the current state of their sensing, actuation, and computing capabilities into their mission and task planning as well as their impact on broader operational aspects.

The Impact of Failure

What proportion of the overall UAV operational budget is attributable to "maintenance"?

To calculate this, we need to consider two main factors:

- The direct cost of maintenance (parts, labor, repairs)
- The impact of ineffective maintenance and its frequency
    - Replacement cost of a lost UAV
    - Cost of UAV accidents
    - Reduced productivity due to loss of the actual time that the UAV is airborne
    - Cancellation of contracts due to an on-site crash
    - Liability exposure in the case of a crash causing personal injury, environmental damage or equipment damage

A recent review [1] by the Office of the Inspector General of the UAV program operated by the U.S. Customs and Border Protection (CBP) – covering eight years and >US$600 million in budget expenditures – highlights:

- ~20% of the UAVs crashed and were fully written off – all due to maintenance/reliability issues
- The aircraft were airborne only 22% of the planned time
- While the UAV program intended to survey all the U.S.'s southern border, only 30% of that region was actually covered – maintenance costs caused these reduced operations
- Of the US$62 million yearly operational budget, maintenance (parts, labor, repairs) constituted 54% of costs (excluding personnel) and 39% of the overall cost (including personnel)
- This brings the maintenance cost of the program to ~US$192 million (US$24 million per year) – this does not include the US$54 million cost of each lost UAV

This loss ratio is well-supported by other authorities – a Lockheed Martin report [2] estimates UAV crashes ("Loss Ratio per 100,000 Flight Hours") as:

- Pioneer UAV – 167 – representing ~6 mishaps per UAV per year
- Hunter UAV – 140 – representing ~5 mishaps per UAV per year
- Predator UAV – 27 – ~1 mishap per UAV per year

The 20% loss rate cited by the CBP in fact represents a much more positive ratio than the industry average identified by the Lockheed Martin study.

There are multiple additional reports that support this incident rate [3].

Similarly, U.S.-operated large UAVs have recorded a Class A accident – defined as a crash that destroyed the aircraft or caused at least US$2 million in damage – every 1.5 weeks over the last 10 years. This represents a write-off of over 400 large UAVs and US$5 billion in direct losses – almost exclusively attributed to reliability failures [4].

Additionally, the U.K. lost 447 UAVs in Iraq and Afghanistan to crashes or breakdown. Most of these losses were attributed to ineffective maintenance. The lost aircraft represent over half of the U.K.'s total UAV fleet and an overall direct cost of US$139 million [5].

Furthermore, the UN's US$13 million a year UAV program (MONUSCO), which was launched in late 2013, saw the loss of 2 of its 6 UAVs in less than a year. Both crashes were attributed to mechanical failures. Each UAV cost €10 million, resulting in a cumulative €20 million loss, as well as the acquisition of a replacement UAV for an additional €10 million. Associated higher-than-expected maintenance costs have resulted in 3 of the remaining UAVs being stored rather than operated [6].

Both the empirical data and the Lockheed Martin research highlight that smaller UAVs have a higher loss ratio – and this leads to the 20%-60% yearly loss ratio range for UAVs (with the variance being attributed to the UAV size). The UAVs mentioned in these reports range in cost between US$250,000 and US$15 million per unit.

There is no accurate data available for small commercial UAVs (costing >US$5,000) but empirical data suggests that the reliability rate is much lower for this class of aircraft than the larger, more expensive UAVs.

In Summary

- Maintenance is a recognized priority for UAV operations and is a significant budget item (>%50 of direct operational cost)
- Even where best practices are implemented, reliability is a major issue and UAV crashes are very common across all aircraft types and in all environments

THE NEED FOR A NEW APPROACH

Envisioning an Effective Data-Driven Maintenance Methodology

Big Data and advanced analytics can play a critical role in supporting the maintenance, repair and operation (MRO) of UAVs.

Maintenance is either “scheduled” or “unscheduled”. Scheduled maintenance is preventive – driven by OEM guidelines and triggered by the usage time of the UAV or a component. Following this schedule should, theoretically, ensure the UAV is always ready to fly when needed. However, real-world experience tells us that this is not the case and multiple issues develop undetected, and remain unresolved, by the normal maintenance schedule. In the instance where a pilot or operator identifies a problem, this is usually handled by unscheduled maintenance procedures. In most cases, at that point, the maintenance organization must deal with not just the original failure, but also with the cascading failure.

With UAVs, the high incident rate is due to the ineffectiveness of the scheduled maintenance program.

The solution is to identify a problem when the process of degradation begins – so the appropriate stakeholders can prevent the cascading failure and the adverse impact. This means that we need an additional maintenance process, parallel to the OEM driven one, which focuses on the actual current condition of the UAV.

Condition-Based Maintenance as an Effective Solution

Condition-Based Maintenance (CBM) is a highly-regarded maintenance strategy that monitors the actual condition of the asset, in this case a UAV, to decide what maintenance needs to be done and when to schedule it. CBM dictates that maintenance should be performed when certain indicators show signs of decreasing performance, continuous operation outside the normal operational parameters or upcoming failure. CBM similarly presents an appropriate solution for the UAV sector. The goal is to spot upcoming equipment failure so that maintenance can be proactively scheduled when it is required – and not before or after.

CBM is based on the concept that performance degradation precedes a failure. Most current CBM solutions are applied to a component and can identify when a component is nearing its operational parameter envelope. This effectively identifies some component immanent failure so they could be replaced.

Advantages of the CBM approach:

- Reduces the cost of UAV failures (direct expenditures as well as liability exposure)
- Improves equipment reliability (increased uptime means more fleet productivity)
- Minimizes unscheduled downtime due to catastrophic failure
- Minimizes time spent on maintenance
- Minimizes overtime costs by scheduling the maintenance activities
- Minimizes requirement for emergency spare parts
- Reduces the chances of collateral damage to the system

The AppliedEA approach uniquely performs CBM in a flight regime context, where we establish a baseline for all internal measurements in context of how the UAV is flying.

To achieve this outcome, AppliedEA requires two types of data:

- Kinematics – i.e. flight regime data – attitude (yaw, pitch, roll), speed (horizontal, vertical, lateral), acceleration (multiple dimensions), etc.
- Internal data – either whole system or subsystem specific – RPM, vibration, load, temperature, input to flight control, actual response, power consumption, subsystem code/indicators, etc.

This data is generated by the UAV and is routinely collected – AppliedEA just taps into this information resource to implement the analytics and develop actionable information.

The assumption is that given a set of kinematics, the UAV will have same internal performance characteristics.

While normal CBM will identify a component failure, AppliedEA's approach of generating CBM in a flight regime context will identify an impending failure well ahead of a specific component failure.

A rotorcraft landing at 200 ft/min will endure vibration that is considered normal for this maneuver. The UAV is well designed to withstand this shock so it would not trigger any alerts. However, CBM in flight regime context will differentiate between such vibration in a landing situation, which is normal, versus same vibration incurred during flight – where it may be well above the normal vibration for that flight situation and indicates a problem.

We have seen many cases in which a UAV consumes X power for a specific flight regime. It has gone through the same yaw/pitch/roll/speed over 1000 times and then during 5 times, it consumed 4-8 X power. Obviously, the additional power did not translate to increased RPM or increased speed. A single occurrence may be explained by a head wind, but multiple occurrences, that happen just in a specific flight regime – that's an indication of an internal failure.

Similarly, we have seen cases where, for specific bank angle, the UAV's flight control actuator consumed increasing amount of power. It was within operating parameters, and the aircraft performed appropriately…until the actuator was overwhelmed, it did not have enough power to move the control surface, and then crashed.

These are sample scenarios where escalating degradation in perform can be identified early. This allows the opportunity to fix a problem before it becomes a cascading failure.

MATHEMATICAL CHALLENGES TO SOLVING THE UAV CBM RIDDLE

The Data Analytics Challenge

For any approach to streaming data analysis to be impactful, it must incorporate all three famous Big Data Vs – Volume, Variety and Velocity. Streaming data analysis relates to high volumes of data from different heterogeneous sources, collected to effectively extract useful information about systems characterized by a high working speed and affected by noise and other disturbances (greater volumes of data do not necessarily bring about higher data quality). CBM is one of the most challenging analytics problems to solve, given that the task is to collect and analyze all the data streams that come from the numerous on-board sensors monitoring the UAVs.

Most existing CBM solution use predictive analytics to predict a component failure. This usually requires a complex causality-based model that "understands" the multiple subsystems, their behavior, the interaction between all the thousands of components. Monitoring the behavior of each component, coupled with the model, enables it to predict future behavior.

The main issue is that such models are very complex and none exist for a whole UAV. They are mostly used for specific components i.e. turbine shaft, parts of an engine, etc. Additionally, given that UAVs often operate in harsh environments, a trivial action such as a hard landing might require a new model.

The AppliedEA approach is empiric: Understand the data topology and establish a baseline based on how each aircraft flies and how its internal systems behave. This empiric approach eradicates the need for an in-depth, up-to-date, understanding of each UAV's internal structure.

It does, however, require a new method to deal with a huge amount of data, noisy sensors and continuously changing external conditions.

APPLIEDEA APPROACH AND INNOVATION

AppliedEA's Topological Approach

Using Topological Data Analysis (TDA), it is possible to enable a data-driven solution that implements CBM in a flight regime context.

Utilizing existing sensors, while performing smart analytics, unlocks the road to UAV with much higher reliability and effectiveness.

In summary, AppliedEA can:

- Identify impending failures through escalating degradation per flight regime situation
- Provide context for faster and more accurate troubleshooting – namely: what happened, when it occurred, and what else was happening on the UAV
- Seamlessly integrate with existing personnel and procedures

REFERENCES

1. https://www.documentcloud.org/documents/1390867-oig-15-17-dec14.html

2. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=7&ved=0ahUKEwj-vvSD8L_JAhVGdz4KHWZ2A5QQFghPMAY&url=http%3A%2F%2Fwww.southampton.ac.uk%2F~jps7%2FAircraft%2520Design%2520Resources%2FUAV%2520Resources%2FASE261.12.RMSS.ppt&usg=AFQjCNF7vbYNP9kE-3gDTOk8SF6R8BjBAg&sig2=wg8-vylUnei103YnyE3aww&cad=rja

3. https://fas.org/irp/program/collect/uas-vuln.pdf, pp. 67-69

4. https://www.rt.com/news/military-drones-lost-uk-080

5. http://www.washingtonpost.com/wp-srv/special/national/drone-crashes/database/

6. http://foreignpolicy.com/2015/09/10/how-a-u-n-drone-crashed-in-congo-and-was-promptly-forgotten/