

# Systems Health Monitoring: Integrating FMEA into Bayesian Networks

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**Abstract**— The foreseeable high traffic density suggests that a large number of electric propulsion systems will enter the airspace, and that they will also operate at high frequency, e.g., large number of take offs and landings per unit time. The reliability of such critical systems is therefore key to ensure high safety standards in the low-altitude airspace. Diagnostic systems, which aim at identifying incipient faults, can mitigate unexpected failures or lower-than-expected reliability by performing early fault detection by monitoring the systems. A key element of fault diagnosis is fault detection and isolation (FDI), which complexity increases with the complexity of the system itself, namely the number of subsystems and components, interactions among sub-systems, and the number of sensors available. The proposed approach leverages combination of failure mode and effect analysis (FMEA) integrated with Bayesian networks, thus introducing dependability structures into a diagnostic framework to aid FDI. Faults and failure events from the FMEA are mapped within a Bayesian network, where network edges replicate the links embedded within FMEAs.

The integrated framework enables the fault isolation process by identifying the probability of occurrence of specific faults or root causes given evidence observed through sensor signals. In this work, sub-systems of Urban Air Mobility (UAM) type vehicle like avionics, structures, power-train etc are taken into account to show the approach at the system level. This work integrates early design phase in the development of UAM type vehicles with diagnostic tools, which are often developed later in the product life-cycle, or retrofitted at a later time on systems. Failure mode and effect analysis (FMEA) derived for the system in the design phase is embedded within a Bayesian network (BN).

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## 1. INTRODUCTION

Recent developments in the area of Urban Air Mobility (UAM) vehicles are at the forefront of the aeronautics transformation. [1], [2], [3], [4].

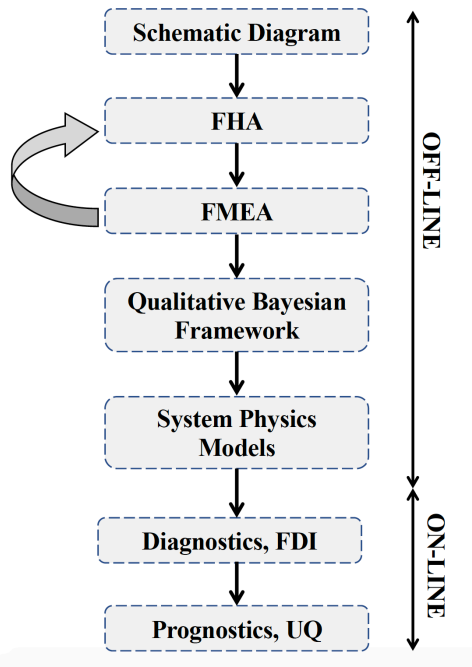
Current forecasts of high-density, low-altitude airspace op-

erations suggests that a large number of UAM vehicles will enter the airspace, operating at high frequency, e.g., large number of take offs and landings per unit time. The reliability of such low flying critical systems is hence key to ensure high safety standards in the low-altitude airspace. Diagnostic systems, which aim at identifying incipient faults, can mitigate within or with other systems unexpected failures or lower-than-expected reliability by performing early fault detection using sensor data. System diagnosis is a fundamental step to initiate prognostics step for estimating the remaining useful life of a subsystem, trigger mitigating actions during flight or request maintenance actions in-between flights. A key element of fault diagnosis is fault detection and isolation (FDI), the complexity of which increases with increase in the complexity of the system itself, interactions among sub-systems, and the number of different sensors monitoring the systems.

This work discuss integrating information from different systems of a UAM vehicle during the design phase with diagnostic tools, which are often developed later in the product life-cycle, or retrofitted to existing specimens. Information from the failure mode and effect analysis (FMEA) from the system design phase is embedded within a Bayesian network (BN) [5]. Each node in the network can represent either a fault, failure mode, root cause or effect, and the causal relationships between different elements are described through the connecting edges.

The approach developed in this work demonstrates that FMEAs can aid and enable the effective implementation of diagnostics, prognostics and health management frameworks by feeding causal relationships identified during the design phase into the FDI stage. Earlier works in this area can be found in [6], where the idea of mapping FMEA into BNs was developed, and [7], where a failure tree was embedded in BN.

Earlier research work in the area of autonomous system diagnosis was presented in [8], [9], which focused on individual systems and components to implement prognostics methodologies. In the later approaches, effects of component-level degradation on the system as a whole were studied to implement the prognostics framework [10], [11]. The development of new models and integration with previous models enables us to study and identify cascaded effects of fault interactions within the systems and cascaded between systems. In [12], the implementation of a prognostic framework to batteries in fixed-wing e-UAS was studied. The process flow in Figure 1 shows the implementation of the integrated FMEA and Qualitative Bayesian approach, and where the FDI method-



**Figure 1.** Process Flow Chart of the developed approach to UAV Health Management

ology discussed in this work stands in the health monitoring framework proposed in those previous works<sup>2</sup>.

This work differs from earlier attempts where BNs aided the design of the FMEA structure [6], and from [7], where dependability between system components were defined by failure trees. Here, the BN supports FDI, possibly in real time as new sensor data are collected during or post-flight capturing system aging and degradation to update failure probabilities. Systems and sub-systems interact heavily especially in complex systems. These tend to affect each other and the faults may cascade into other systems e.g a structural fault in an UAM leading to damage in avionics or battery systems. The paper discusses issues related to the embedding of probability of fault detection, false alarms, and other indicators of system diagnosis performance into the framework.

The paper’s goal are two-fold. First, present how the developed approach can help FDI, discussing issues like probability of mis-detection, false alarms, and sensor sensitivity in compiling the conditional probability tables. Second, embedding of FMEA information into a BN for a specific case study, namely the powertrain system. The result is a framework capable of isolating the cause of sub-system level fault and degradation.

Our broader research effort is to identify failure modes, develop a failure modes and effects criticality analysis (FMECA) for the system and combine it within a fault detection and prognostics framework. This research is aimed towards accomplishing the following objectives:

- Identify and quantify the effects of the identified hazards, the severity and probability of their effects, their root cause

<sup>2</sup>The acronyms in Figure 1 not yet defined will be defined later in the section.

and the likelihood of each cause.

- Develop a Bayesian framework for fault detection and isolation
- Based on the FDI results estimate current health of the faulty component and predict the remaining useful life (RUL),
- Performing uncertainty quantification (UQ) for all the steps of the process.
- To identify potential hazards and perform a functional hazard analysis (FHA) for Urban Air Mobility (UAM) vehicles.

## 2. BACKGROUND

The need for safety assurance and health management capabilities is particularly relevant for aircraft electric propulsion systems, which are relatively new and with limited (or none) historical data to learn from. They are critical systems requiring high power density along with reliability, resilience, efficient management of weight, and operational costs. It is clear how a fault diagnosis and prognosis tool can aid such safety and reliability requirements, as well as system state-awareness, thus enabling autonomous decision making capabilities for safe and efficient operation. The approach proposed in this paper allows to compute in quantitative ways the failure probabilities of the components (or sub-systems) of such complex systems, while integrating modeling and measurement uncertainty.

### *Failure Mode and Effect Analysis*

Failure Mode and Effect Analysis (FMEA) methodology has evolved over the years, introducing variations like process FMEA, design FMEA, FMEA embedding criticality analysis (failure modes, effects, and criticality analysis, FMECA), etc. In this work a general FMEA methodology is being implemented. In reference to the general definition SAE J1739 [13], the scope is narrowed here, with the key objective of FMEAs to recognize and evaluate potential failures and their effects, identify the weak links within the system (i.e., powertrain) that leads to failures, and develop resources to reduce the chance of potential failure occurring at those links. The FMEA will aid the diagnostic process by providing the causal links among failure events potentially occurring within the system.

The list below shows an FMEA header example. Such a list is not always exhaustive, and subject to changes based on particular component, system, application etc.

- Failure / degradation mode
- Failure effect
- Severity
- Cause
- Frequency
- Detectability
- Risk Priority Number

The FMEA table developed is based on this header example but curated for a powertrain of a quadrotor electric vehicle discussed later in the Section 3. Functions were defined at the equipment level to facilitate the development of meaningful functional failures. Each function was reviewed and potential failure modes were postulated for each function and assigned failure mode.

Failure rates depend and vary based on design, application, and operation of the system. Reliability is designed into equipment based on operational requirements, which is de-

veloped by the manufacturer based on resulting consequences observed in terms of severity or criticality due to failure. In this study, some of the failure rates were obtained through the manufacturer of the subsystems, while some others were defined based on similarities to other systems. In the future, once the actual failure rates are obtained, the tool will be able to generate an updated output.

Currently, state-of-the-art components designed for specific distributed electric/hybrid-electric propulsion vehicles may not have accurate reliability data based on operations [14]. This gap is currently being filled thanks to some parallel work [15], where a hardware-in-loop testbed in being developed to test and age the components. Some of our earlier work included Virtual lab [15] where powertrain components were loaded using realtime data from the UAV vehicle to age the subsystems. Once the system is fielded in the testbed, aging tests are performed using accelerated aging methods, and the system is tracked to keep records of any degradation due to operational loads. The data from which is then used to update the degradation/failure rates of respective sub-system.

FMEAs may not cover all possible fault modes when systems become very complex. Hence, for such systems, approaches to combine FMEA and FTA are being implemented [16]. FTA is a top-down analysis approach which captures interrelationships between respective subsystems of the powertrain. The FTA documents any catastrophic or severe outcome at the top level, while the less severity hazards become evident based on the FTA structure that describes the subsystems interrelationship with each other. The UAV propulsion system consists in the electronics that control the motors, the motors, and batteries, all captured in the FTA. The top level hazards defined from the propulsion system FHA were used to inform the top level of the fault tree. The FMEA combined with details from FTA is evolved further using a Bayesian framework which will be discussed in the later section.

### Bayesian Networks

Bayesian Networks (BNs) are directed acyclic graphs where nodes represent propositions or variables, the arcs represent the existence of direct causal influences between the linked propositions, and the strength of the causal relationships is represented through conditional probabilities [5]. The example below, reproduced from [5], is used as illustrative explanation of how BN works.

Figure 2 shows a representative BN, where the complete joint probability distribution  $p(x_1, x_2, x_3, x_4, x_5, x_6)$  is the product of the conditional probabilities of each proposition given its ancestors, Eq. (1).

$$p(x_1, \dots, x_6) = p(x_6|x_5) p(x_5|x_2, x_3) p(x_4|x_1, x_2, x_3) p(x_3|x_1) p(x_2|x_1) p(x_1) \quad (1)$$

The joint probability distribution could also be expressed with the short notation:

$$p(\mathbf{x}) = \prod_{j=1}^n p(x_j|\mathbf{a}_j), \quad (2)$$

where  $\mathbf{a}_j$  represents the set of ancestors of variable  $x_j$ , and  $\mathbf{x}$  is the random vector containing all variables  $x_1, \dots, x_n$  [17], [7]. For example, the term  $p(x_4|x_1, x_2, x_3)$  becomes  $p(x_4|\mathbf{a}_4)$ .

Dependencies among propositions are described through the definition of sets of ancestors (or parents) and descendants (or children). For example, the set  $\{x_1, x_2, x_3\}$  contains the ancestors of  $x_4$ , while  $\{x_2, x_3\}$  contains the children of  $x_1$ . This structural model allows analysis over interventions, i.e., enable the computation of the joint probability density function (pdf) conditioned on some specific assumptions over a specific variable in the network [17]. Starting from the example in Figure 2, it is possible to evaluate the joint pdf given, e.g.,  $x_2$  has been defined *True*:

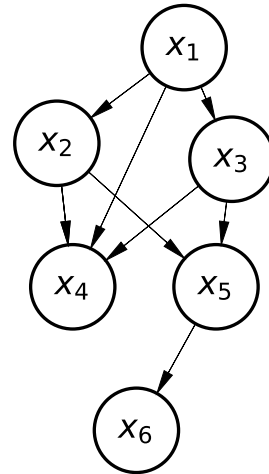
$$p_{X_2=1}(x_1, x_3, \dots, x_6) = p(x_6|x_5) p(x_5|X_2 = 1, x_3) p(x_4|x_1, X_2 = 1, x_3) p(x_3|x_1) p(x_1). \quad (3)$$

The dependency of  $x_2$  from  $x_1$  has been removed in Eq. (3), since forcing  $X_2 = 1$  does not depend on the value of  $x_1$ . Therefore, the edge connecting  $x_1$  to  $x_2$  should be removed to represent the proposed intervention. The challenge presented by BN is the assessment of all conditional probabilities of the system. Each node of the network requires a conditional probability table that defines the probability of the node being 1 (or 0) given all possible values of its ancestors. The dimension of the table increases in a combinatorial fashion with the number of ancestors. Some of these issues are addressed in Section 3 where a BN is applied to a electric propulsion system diagnosis.

### FMEA to BN

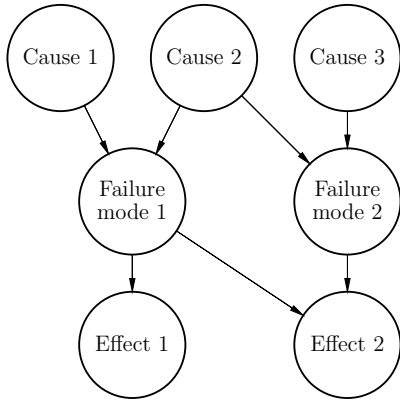
In order to develop an efficient system level diagnosis procedure that takes uncertainty into account, both information from the FMEA and from the BN are combined. To this end, two main steps are involved: (i) build the BN structure and (ii) establish the conditional probability tables (CPT) of each node.

In order to construct the BN structure, the qualitative information about failure modes, causes and effects contained in the FMEA worksheet are transformed into nodes. As a starting point, observable nodes (simulating sensors), may represent simply events triggered by sensor signals, like, for example, a boolean variable for “temperature of the electronic speed controller too high”. Such information can help disambiguate



**Figure 2.** Example of directed acyclic graph used to create a Bayesian network.

among potential causes of the observed event. Then, the relationships between each node is defined by pointing arcs from causes to failure modes, and from failure modes to effects, resulting in the construction of the BN structure. A simple example of a BN structure build from FMEA is shown in Fig.3 for illustration.



**Figure 3.** Example of a simple BN structure build from FMEA.

Once the BN structure is built, the next step consists in assigning prior marginal probabilities to the root nodes (with no ancestors) and conditional probabilities to each of the other nodes, based on the qualitative information provided by the FMEA.

Probability values can be defined for example from historical failure data, expert knowledge about the probability of failure of each component, or by using maximum entropy theory as in [18].

Once the BN is completely defined, it can be used to detect and localize a fault within a complex system by turning observable nodes to *True* or *False*. The diagnosis procedure updates the probabilities using Bayesian inference in order to determine the root cause with the highest failure probability when an evidence (observable) node is triggered. The evidence nodes, also known as fault symptoms, are associated to observed variables such as sensor measurements, and can be for example triggered when the observed value exceeds a certain threshold.

Possible external sources that can affect the diagnosis procedure, such as environmental conditions or false alarm, are discussed in the next section.

#### Modeling approach and issues

The dependency among elements in FMEAs do not have to be restricted to deterministic relationships in BNs [7], and this property intrinsically enhances the modeling of the diagnostic system. Let us consider, for simplicity, a fault event  $f$  with two root causes, its ancestors,  $x_1$  and  $x_2$ . Table 1 is the conditional probability table of the model, where probabilities are defined through three binary subscripts  $i, j, k \in \{0, 1\}$ . The term  $p_{k|i_j}$  defines the probability of the outcome  $k$  given values  $i, j$ , with  $k$  referring to the fault event  $f$  and  $i, j$  referring to its ancestors  $x_1$  and  $x_2$ . For example,  $p_{1|00}$  is the probability that  $f = 1$  given both ancestors  $x_1, x_2$  are 0 (or *False*).

**Table 1.** Example of conditional probability table for a fault event with two known root causes.

$x_1$	$x_2$	$f$	
		0	1
0	0	$p_{0 00}$	$p_{1 00}$
0	1	$p_{0 01}$	$p_{1 01}$
1	0	$p_{0 10}$	$p_{1 10}$
1	1	$p_{0 11}$	$p_{1 11}$

The fault event may happen, with low probability, because of external causes or unknown events not described by its ancestors. Such external forcing was called *Common Cause Failures* in [7], and following that idea,  $p_{1|00} \geq 0$ , and so  $p_{0|00} = 1 - p_{1|00}$ . On the opposite side of the spectrum, the fault event may not happen even if both ancestors are activated (true). This option describes the ability of a system to work partially or reconfigure, [7], or describes a statistical relationship between the three elements, suggesting that root causes do not deterministically trigger the failure, so  $p_{1|11} < 1$ . As a result, the two ancestors may occur without triggering the fault event, so  $p_{0|11} \geq 0$  and  $p_{1|11} = 1 - p_{0|11}$ . Different ancestors may influence the fault event in different ways, e.g. according to the severity of the root cause. This properties can be easily embedded in the network by assigning different values to the probabilities conditioned over  $\{X_1 = 1, X_2 = 0\}$  and  $\{X_1 = 0, X_2 = 1\}$ .

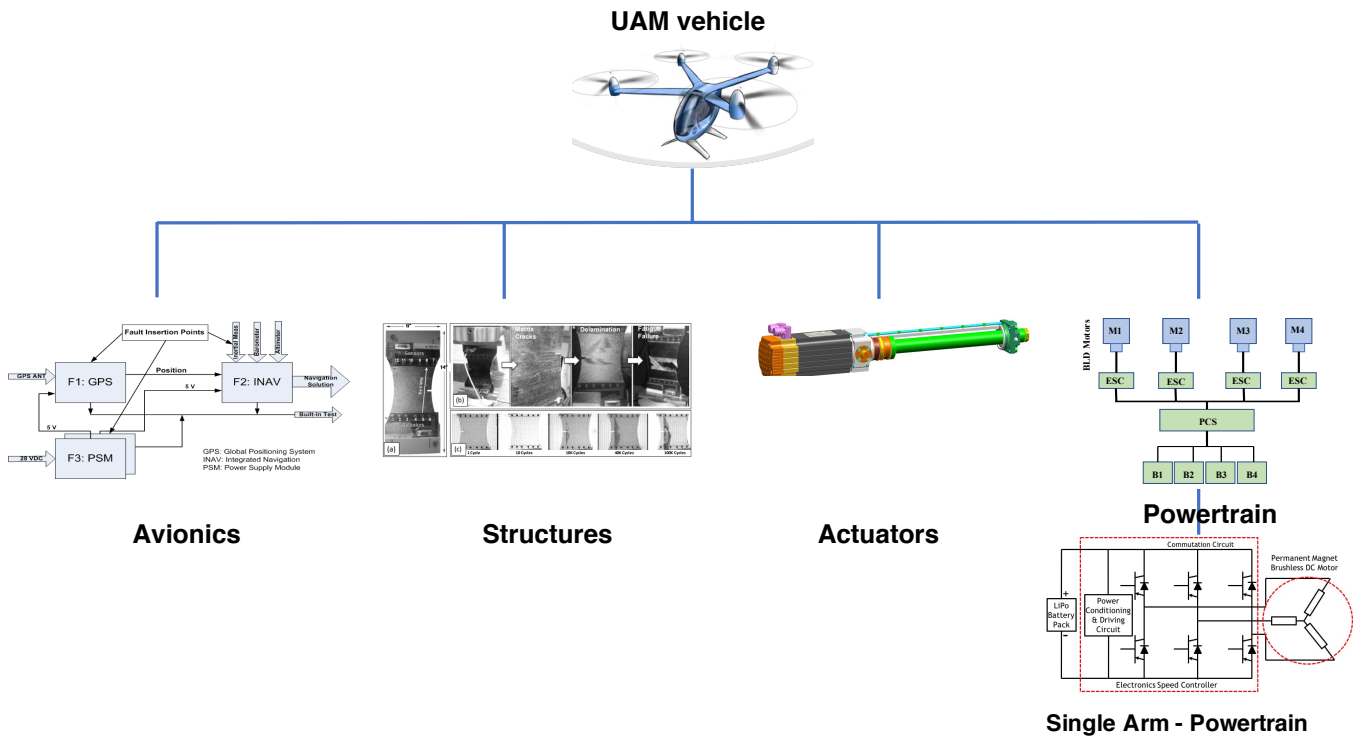
In addition to the cases of failures induced by external variables or prevented system reconfiguration, the BN should also account for the performance of the measuring and/or detection system. In the proposed architecture, the evidence used to perform inference over the network is collected through sensors that measure variables connected (directly or indirectly) to the fault event we aim to detect. The sensor performance or, similarly, the ability of the detection system to identify anomalous sensor data, should be embedded in the estimation of the CPT values. Reconnecting to the previous example, therefore, the element  $p_{0|00}$  in Table 1 should account for false alarm rates, and  $p_{1|11}$  should include, on top of any statistical relationship between the elements, the probability of mis-detection.

### 3. UAM SYSTEMS - CASE STUDY

An UAM system is a combination of several critical systems and sub-systems interacting with each other in tandem. To maintain vehicle safety and ability to take quick decisions in case of malfunctions it is key to monitor the health of critical systems. Some of the key systems include avionics, structure, actuator and power-train as shown in schematics of Figure 4.

From a practical standpoint, the first step is to build a FHA to assess any associated risk of failures in the respective systems of the vehicle as shown in Figure 4. The output from the hazard analysis is an assessment of the different type of hazards along with their probability of failures. The next step is to move to FMEA/FMECA methodology to include reliability and performance information, as well as the effect of faults and non-catastrophic failures based on system understanding and operational constraints.

The knowledge of prior probabilities typically comes from operational data, OEM data-sheets, and SME's to develop the framework. However, depending upon the availability



**Figure 4.** Schematic diagram of UAM electric powertrain system

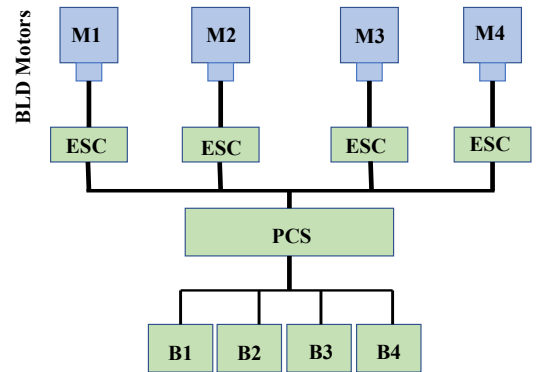
of prior information the probability of occurrence of failures from the FHA and FMEA can be qualitative or quantitative. In this work an qualitative is utilized to exemplify the methodology.

Bayesian theorem, at the foundation of BNs, can be implemented using quantitative as well as qualitative methods [19], [20], and so it is particularly suitable for the approach utilized here. To demonstrate the proposed framework a quad-rotor e-UAS vehicle is being used. A case study of the UAV powertrain on of the subsystems is presented with a fault detection and isolation example using the developed framework.

#### Electric Power-train System

This section shows how the BN - FMEA can aid the fault isolation process for a sub-system of the power-train of a small autonomous quad-rotor vehicle by showing a simple, yet representative, working example. The power-train design consists of a Li-ion battery composed of Li battery packs, power condition unit, electronic speed controller (ESC) with pulse-width modulation (PWM), and brushless DC motor. A scheme of the power-train is shown in Figure 5.

A simplified FMEA for a UAV vehicle currently used for our experiments is shown in Table. 2. This is a dynamic working table and is being updated as additional information becomes available from either the operation tests or SME's. The examples of BN application shown in the later subsections are based on the information from such table. The table is used to compute the qualitative conditional probability of occurrence of each element of the power-train in the case study.



**Figure 5.** Schematic diagram of basic quad-rotor power-train elements.

**Table 2.** FMEA for quad-rotor e-UAS power-train system

Component	Faults	Root Cause	Effect on UAV	Effect on Airspace	Severity	Probability of Occurrence	Safety Critical
Battery Pack	SOC	Operational Conditions	Directly affects operation of the power train system	In case the SOC goes below set low threshold and UAV is not able to do a safe landing may violate safety with crash landing/ may interfere in path of other UAV	High	High	High
Battery Pack	SOH	Operational conditions, loading profiles	Aging in the batteries may not directly affect other systems	The UAV may not able to do certain maneuvers within required time period	High	High	High
Motor (Single)	Low insulation resistance	Operational conditions, loading profiles	Aging in the batteries may not directly affect other systems	The UAV may not able to do certain maneuvers within required time period	High	High	High
Motor (Single)	Bearing Faults, mass unbalance	Operational conditions, loading profiles	Aging in the batteries may not directly affect other systems	The UAV may not able to do certain maneuvers within required time period	High	High	High
Motor (Single)	Power Consumption	Change in winding resistance, bearing faults	High draw currents decrease the battery RUL shortening flight time considerably	In case the SOC goes below set low threshold and UAV is not able to do a safe landing may violate safety with crash landing/ may interfere in path of other UAV	Medium	Medium	Low
Motor (Multiple)	Power Consumption, Low insulation resistance, bearings	Change in winding resistance, bearing faults	High draw currents decrease the battery RUL shortening flight time considerably	In case the SOC goes below set low threshold and UAV is not able to do a safe landing may violate safety with crash landing/ may interfere in path of other UAV	High	Low	High
ESC (Single)	Power Consumption	Operational stress, High electrical, thermal stress on the components	Change in switching frequency, MOSFET degradation, stuck faults	The UAV may not able to do certain maneuvers within required time period and flight profile	Medium	Low	Low
ESC (Multiple)	Power Consumption	Operational stress, High electrical, thermal stress on the components	Change in switching frequency, MOSFET degradation, stuck faults	The UAV may not able to do certain maneuvers within required time period and flight profile	High	Low	High
CES	Filtering Capacitor/MOSFET failures	Operational stress, High electrical, thermal stress on the components	Directly affects operation of the power train system	The UAV may not able to do certain maneuvers within required time period and flight profile	High	Low	High

If the qualitative probability is in one of the intermediate categories, then further analysis is required and identified by the fault diagnosis framework. Further, once the fault is detected and isolated using the BN-based tool, the prognostics tool can be triggered to estimate and predict the RUL for the faulty sub-system. In this case the remaining useful time is defined as the time till the state of charge (SOC) of a battery pack reaches a lower bound threshold. In the next section an example is discussed which includes a few components from Table 2 for demonstration of the framework.

### Case Study Scenarios

In this Subsection, different scenarios of faults observed in each of the sub-systems is discussed. These are based on the operational load conditions for the vehicle and may occur in flight. In the later section each fault case considered is then further used in the Bayesian formulation.

*Energy Source - Li-ion Batteries*—Under nominal conditions the battery voltage is above a certain threshold during which time the vehicle is able to perform all required objectives which are updated prior as part of the flight plan.

Lithium corrosion, plating, electrolyte layer formation, and contact losses are examples of faults that batteries are susceptible to [21]. These faults lead to an increase in internal resistance and impedance, as well as a decrease in charge capacity. These are related to the state-of-health (SOH) of the battery. Based on vehicle and safety requirements, the SOC threshold is set such that the vehicle must be capable to make a safe landing. Nonetheless, certain faults may lead to the battery discharging at a faster rate. This could be due to some internal battery pack fault or due to other connected subsystems down the stream. One of the scenarios considered is a large resistive fault in the wiring which may discharge one of the battery packs faster and loose SOC considerably. The faults described here will be at the foundation of the BN utilized to perform FDI.

*Electronics Speed Controller*—Electronics speed controllers (ESCs) are half bridge rectifiers and most of the faults observed in them are due to switching circuits. Faults in the conditioning circuit are not considered here. Such switching-circuit faults are observed when the MOSFETs are not synchronized while operating, or when the switching circuit is malfunctioning [10]. The first one results in a variable PWM control waveform, and the second one results in a non-operational voltage phase switching pair. Generally, a degraded ESC or an ESC operating under a faulty condition will draw more/less current than a healthy ESC when operating under similar environmental conditions and load.

*BLDC Motor*—DC motors are susceptible to mechanical faults in the form of general motor or bearing wear, and electrical faults in the form of poor contacts and insulation deterioration [22], [23]. Typically, changes in the vibration characteristics are caused by mechanical faults, and changes in the current draw characteristics are caused by electrical faults, but can also be caused by mechanical degradation. For example, bearing wear can result in increased friction, which would result in higher current draw to maintain the same output due to the increase in mechanical resistance.

In addition, winding degradation over time, due to high load usage, cause changes in insulation resistance. Winding faults can lead a short or open circuit condition.

### Computing conditional probabilities given sensor-based fault detection

In this section, the fault diagnosis procedure presented earlier in Section 2 is applied to a simplified example based on the fault scenario from Section 3.

First, based on the FMEA in Table 2, the BN architecture of the case study is developed. As can be seen in Figure 6, different colors distinguish the main components; battery nodes are in blue, motor nodes in red and ESC nodes in pear green. The root cause nodes in black represent chemical reaction in the battery (*chem*), *flight profile*, operational conditions (*op. cond*), and electrical/thermal stresses (*el. therm stress*). As described in the previous subsection, the failure mode nodes are composed of: (i) three battery faults, SOC, SOH and thermal runaway (*therm. runaway*), (ii) two ESC faults, MOSFET and PWM, and (iii) two motor faults, bearing and winding resistance (*winding res.*). Finally, the observation nodes for each of the three components are related to their voltage, current and temperature measurement sensors; battery voltage  $V_b$ , current  $I_b$ , and temperature  $T_b$ , ESC voltage  $V_e$ , current  $I_e$ , and temperature  $T_e$ , and motor voltage  $V_m$ , current  $I_m$ , and temperature,  $T_m$ .

The architecture shows the causal relationships between the nodes, but it is necessary to quantify such relationships by assigning all node prior probabilities conditioned on the state of their ancestors. Despite the limited size of the problem considered, the solution requires the definition of several CPTs. The prior conditional probabilities utilized to produce the results are reported in the Appendix. They are based on qualitative assumptions by subject matter experts, are for illustration only and should not be considered accurate. Indeed, as more information about the system failure probabilities are available over operational usage, these values can be updated for more accuracy. The prior probability of root causes like operational conditions or flight profile (black nodes) are all set to default values of  $1e-6$ , since those are dependent on the true operations of the vehicle. Also, assessing such causes, for example whether the ambient temperature is high with respect to the operational range of the battery, is straightforward, and the corresponding nodes could be set to *True* to assess how much such external factors influence the isolation process.

Once the prior probability values are assigned to each of the nodes, the constructed BN can be used for fault isolation. Indeed, when abnormal sensor measurements are detected, the BN will update the failure probability values of the fault nodes. This will allow the isolation of the most probable faulty component, which is the one with the highest failure probability given the abnormal sensor measurements. The proposed diagnosis methodology in this paper is based only on the multiple sensor measurements, and enables the disambiguation of the causes. For simplicity, performance of sensors or anomaly detection systems is not discussed, and implicitly embedded in the conditional probability tables in the Appendix. However, the reader is referred to Subsection 2 and references therein for additional details on the subject.

The MATLAB open source toolbox (<https://github.com/bayes-net/bnt>) was used to compile the network and compute the posterior probabilities. The latter were calculated by resolving the network using a junction tree algorithm, which perform exact inference [24]. Given the limited size of the example proposed here, exact inference was achieved in a few seconds of computation. More complex or larger BN may need approximate inference methods to resolve the entire

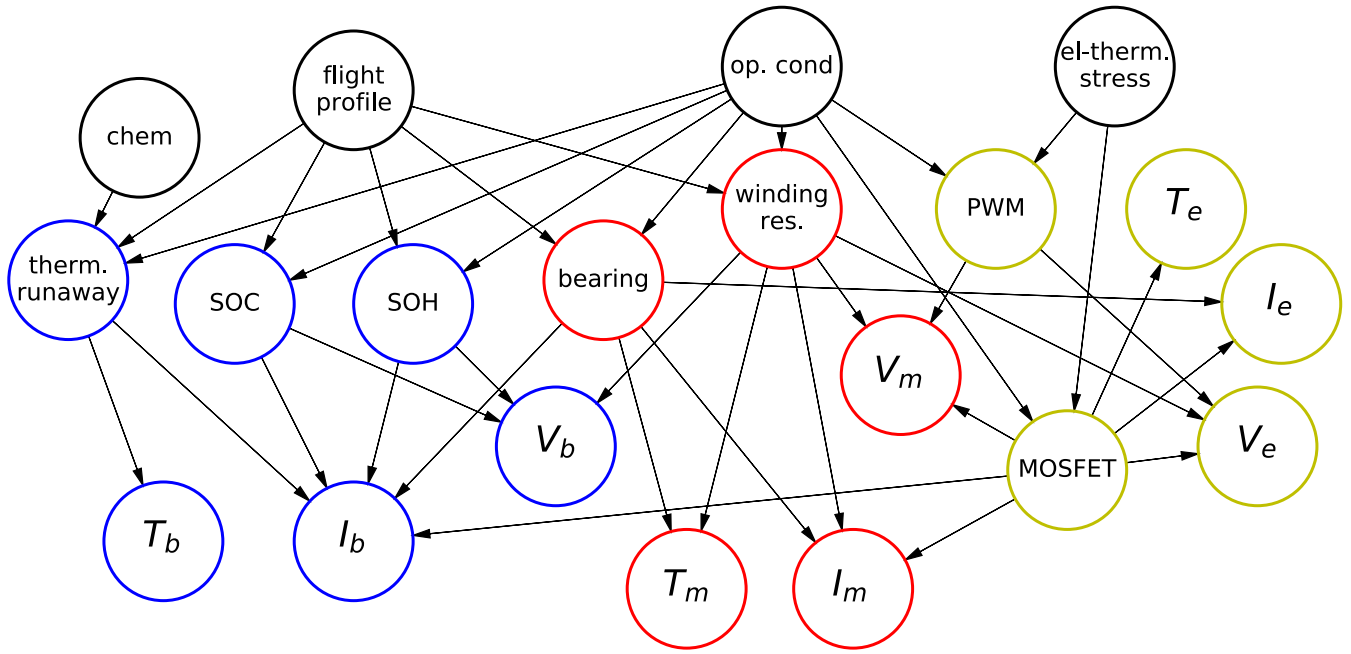


Figure 6. Bayesian network of the power-train case study

network.

In the synthetic failure scenario illustrated here, all three voltage sensors  $V_b$ ,  $V_e$  and  $V_m$  indicate anomalous values. The relationship between those voltage sensors and potential faults are visible in Figure 6. Changes in voltage readings at the battery level  $V_b$  can be caused by SOC, SOH or changes in the winding resistance of the motor. Similarly, changes in voltage readings at the ESC and motor level  $V_e$ ,  $V_m$  can be caused by MOSFET or PWM faults, or again by the winding resistance of the motor.

If all 3 sensors suggests anomalous voltage values, however, the BN suggests that the most probable cause is the battery SOC, given the direct link to the voltage measurements at the battery level:

$$\begin{aligned}
 \Pr\{\text{SOC} = 1 | V_b, V_e, V_m\} &= 0.82021, \\
 \Pr\{\text{SOH} = 1 | V_b, V_e, V_m\} &= 0.5943, \\
 \Pr\{\text{TR} = 1 | V_b, V_e, V_m\} &= 0.00056469, \\
 \Pr\{\text{MOSFET} = 1 | V_b, V_e, V_m\} &= 0.044391, \\
 \Pr\{\text{PWM} = 1 | V_b, V_e, V_m\} &= 0.45402, \\
 \Pr\{\text{bearing} = 1 | V_b, V_e, V_m\} &= 0.00049766, \\
 \Pr\{\text{M.Wind.} = 1 | V_b, V_e, V_m\} &= 0.50274.
 \end{aligned}$$

The second most probable cause is the battery SOH, also strictly connected to the voltage. The third most likely cause is a change in winding resistance of the motor, since it affects the voltage at all levels (battery, ESC, motor). Therefore, after investigating the charge and the health of the battery, the network aid identification by pointing to the component that most likely affect the voltage of the power-train system, which is the motor winding's.

The BN-based tool appears to be able to detect and isolate faults based on the their failure probabilities. Though this is

not the final version of the proposed tool, and still a work-in-progress. As discussed earlier in the Section, with additional information from experiments, SME's, etc, it is possible to further fine tuning the CPTs and introduce quantitative values for the probability of mis-detection and probability of false alarms, thus enhancing the accuracy of the BN posterior probabilities when a fault is detected.

#### 4. CONCLUSIONS

This work presented the integration of failure mode and effect analysis (FMEA) with Bayesian networks (BN) to enhance fault detection and isolation approaches to complex interacting systems like UAM vehicles. The methodology does not introduce novel instruments, but works on the advantage of the synergistic effect of design tools (FMEA) and computer science methods (BNs) to enhance system level diagnosis at different levels. This is demonstrated through and e-UAS quad-rotor power-train system example.

The framework based on a BN consists of nodes representing faults, failure modes, sensors (or anomaly detectors), and root causes through the FMEA design of the system. The challenge, already well known in the field of reliability analysis, is represented by the assessment of the failure probabilities and the effort to fill conditional probability tables, which grow exponentially with the number of ancestors. The analysis presented in this work with respect to the e-UAS case study suggests that even qualitative assessment of such probabilities can help disambiguate between faults that would be otherwise defined equally probable without information from the FMEA and their likelihood of occurrence.

However, the broader goal of the research is to provide a comprehensive tool to perform anomaly detection, diagnosis and prognosis methodologies to multiple interacting systems in a UAM/UAV-type vehicles in the future. This objective is supported by experimental activities aimed at refining and testing such diagnostic and prognostic tools.

Next steps of the research proposes to build-up on the current work to implement the BN model with multiple rotor type systems as well as to other interactive systems in the vehicle. The primary goal would be to develop a complete tool for fault quantification and assess severity of the observed fault to estimate failure prediction for risk and safety.

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## APPENDIX

We report the prior conditional probabilities utilized to produce the results in the paper. They are based on qualitative assumptions by subject matter experts, are for illustration only and should not be considered accurate.

The prior conditional probabilities of root causes: operational conditions, flight profile, internal chemical reactions, and electro-thermal stress, were all set to a default value of 1e-6. Some of the root causes are easily observables (like external temperature, or longer-than-expected flight profile), and therefore their nodes can be set to *True* when observed. Internal effects like chemical reactions and electro-thermal stresses can only be inferred by the output of the network. To illustrate the approach, we did not discuss likelihood of these internal root causes that cannot be directly measured, so their prior probability was set to the default value. Their likelihood of occurrence of such unobservable root causes, as well as intermediate faults and failures, depends on several

Op. Cond	Flight Prof.	Pr{SOC=1}
0	0	1e-12
1	0	0.6
0	1	0.45
1	1	0.99

**Table 3.** Battery SOC. influenced by operational conditions and flight profile.

Op. Cond	Flight Prof.	Pr{SOH=1}
0	0	1e-6
1	0	0.7
0	1	0.3
1	1	0.9

**Table 4.** Battery SOH. Influenced by operational conditions and flight profile.

factors including design choices, manufacturing processes, initial product defects, and precision of assembly. The prior conditional probabilities of observable variables like voltage, current and temperature depend on sensor properties like sensitivity, accuracy, failure rates, among others.

All tables shows only the probability of observing the node to be *True* (1), since the probability of the node to be *False* (0) is the complement to 1,  $\Pr\{X = 0\} + \Pr\{X = 1\} = 1$ .

Op. Cond	Flight Prof.	Chem.	Pr{TR=1}
0	0	0	1e-15
1	0	0	1e-3
0	1	0	1e-6
0	0	1	0.8
1	1	0	1e-3
1	0	1	0.9
0	1	1	0.85
1	1	1	0.95

**Table 5.** Battery thermal runaway. Influenced by operational conditions, flight profile, and internal chemical reaction.

Op. Cond	el. them. stress	Pr{PWM=1}
0	0	1e-15
1	0	1e-3
0	1	0.05
1	1	0.1

**Table 6.** ESC PWM fault. Influenced by operational conditions and electrical and thermal stresses.

Op. Cond	ETS	Pr{MOSFET=1}
0	0	1e-15
1	0	1e-2
0	1	0.1
1	1	0.2

**Table 7.** ESC MOSFET fault. Influenced by operational conditions and electrical and thermal stresses (ETS).

Op. Cond	Flight prof.	Pr{B=1}
0	0	1e-6
1	0	1e-3
0	1	1e-5
1	1	0.01

**Table 8.** Motor bearing fault (B). Influenced by operational conditions and flight profile.

Op. Cond	Flight prof.	Pr{W=1}
0	0	1e-15
1	0	1e-3
0	1	1e-2
1	1	0.1

**Table 9.** Motor winding resistance fault (W). Influenced by operational conditions and flight profile.

SOC	SOH	M. Win.	Pr{V <sub>b</sub> =1}
0	0	0	1e-15
1	0	0	0.9
0	1	0	0.3
0	0	1	0.95
1	1	0	0.1
1	0	1	0.95
0	1	1	0.55
1	1	1	0.99

**Table 10.** Voltage readings at battery level. Influenced by SOC, SOH, and motor winding fault.

SOC, SOH, Bearing, TR, MOSFET	Pr{I <sub>b</sub> =1}
all ancestors <i>False</i>	1e-15
1 ancestor <i>True</i>	0.3
2 ancestors <i>True</i>	0.55
3 ancestors <i>True</i>	0.7
4 ancestors <i>True</i>	0.85
5 ancestors <i>True</i>	0.95

**Table 11.** Current readings at battery level. Influenced by 5 ancestors: SOC, SOH, motor bearing fault, thermal runaway (TR) and MOSFET fault. The table would have  $2^5 = 32$  rows. We have made the simplifying assumption that the probability of observing a current anomalous value depends only on the number of active ancestors, rather than which individual ancestors is activated. By so doing, the prior conditional probabilities to be defined falls from  $2^n$  to  $n + 1$ , 6 in this case).

TR	$\Pr\{T_b=1\}$
0	1e-15
1	0.999

**Table 12.** Temperature readings at battery level. Caused by thermal runaway (TR).

PWM	MOSFET	M. Wind.	$\Pr\{V_e=1\}$
0	0	0	1e-15
1	0	0	0.6
0	1	0	0.6
0	0	1	0.6
1	1	0	0.65
1	0	1	0.65
0	1	1	0.65
1	1	1	0.9

**Table 13.** Voltage readings at ESC level. Influenced by PWM fault, MOSFET fault, and motor winding resistance.

MOSFET	Bearing	$\Pr\{I_e=1\}$
0	0	1e-15
1	0	0.6
0	1	0.2
1	1	0.85

**Table 14.** Current readings at ESC level. Influenced by MOSFET fault and motor bearing fault.

MOSFET	$\Pr\{T_e=1\}$
0	1e-15
1	0.9

**Table 15.** Temperature readings at ESC level. Caused by ESC MOSFET fault.

PWM	MOSFET	M. Wind.	$\Pr\{V_m=1\}$
0	0	0	1e-3
1	0	0	0.85
0	1	0	0.87
0	0	1	0.89
1	1	0	0.9
1	0	1	0.93
0	1	1	0.95
1	1	1	0.999

**Table 16.** Voltage readings at motor level. Influenced by ESC PWM and MOSFET faults, as well as motor winding resistance.

MOSFET	Bearing	M. Wind.	$\Pr\{I_m=1\}$
0	0	0	1e-12
1	0	0	0.8
0	1	0	0.85
0	0	1	0.85
1	1	0	0.9
1	0	1	0.92
0	1	1	0.92
1	1	1	0.99

**Table 17.** Current readings at motor level. Influenced by ESC MOSFET fault, motor bearing fault and winding resistance.

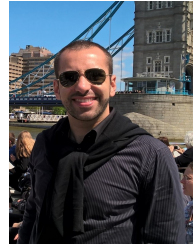
Bearing	M. wind.	$\Pr\{T_m=1\}$
0	0	1e-12
1	0	0.85
0	1	0.9
1	1	0.99

**Table 18.** Temperature readings at motor level. Influenced by motor bearing fault and winding resistance.

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