Failure Analysis and Finite Element Simulation for structural systems in an Unmanned Aerial Vehicle

B. Wang, P. H. Ng, B. M. N. A. K. Elhadidi, H. S. Ang and S. K. Moon*

Abstract— **In this paper, failure analysis of an unmanned aerial vehicle (UAV) has been conducted through failure mode and effects analysis (FMEA) and finite element (FE) simulation. For FMEA, a system is broken down into subsystems, and possible failures are considered for each subsystem. Each failure is then ranked in 3 categories: severity, occurrence, and difficulty of detection. Each category has 1 of 5 ranks: very low, low, moderate, high, and very high. Since these ranks are linguistic variables that cannot be properly assigned a definitely value, fuzzy logic is applied. Using a membership function and a defuzzification formula, the variables are defuzzified. Grey relational analysis is applied to factor in the relationship between the variables. With these methods applied, the battery failure and rotor arm failure (including motors, ESC & arm structure) were found to be the most critical failures followed by avionics failure and structural failure. For the FE simulation, a 3D model is created. The stress distribution and fatigue life of fuselage are simulated by using the commercial software Comsol. The fuselage was made of Al 7076 T6 with an ultimate tensile strength of 572 MPa. The stress distribution at different loads (5 kg, 50 kg & 75 kg) are simulated. According to the simulation results, the maximum stress occurs at the corner of the fuselage. The fatigue life under different loads were also simulated. The potential failure mode and risk level analysis enables the identification of critical component and prediction of system failures. With FE simulation, the limit of the structure is simulated. Maximum load the structure can support is determined, the simulation of fatigue life cycles enables the prediction of structure failures.**

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have been initially developed for military usage. With the advancement of technology and reduction in costs, UAVs are now also applied commercially in wider areas such as the agriculture, entertainment and other industries, [1] especially small UAVs. Most of researches has been done on the health monitoring of large UAVs for defense applications including the structural failure analysis, motor failure analysis and human-caused failures [2-5]. Currently, more research works are focused on small UAVs such as the control algorithms, application of UAVs as well as the failure analysis [6]. The reliability and durability of small UAVs are critical and there is a strong need for the investigation.

Failure Mode Effects Analysis (FMEA) was firstly developed in 1950s for aerospace usage. It is a generally used systematic method for failure analysis and often used as the first step for reliability analysis [7]. During the analysis, the whole system is divided into several subsystems. For each subsystem, the possible failure mode, failure effects and severity is evaluated. The causes and effects of each component failure are analyzed as well as any methods of detecting those failures [8, 9]. In this research work, FMEA is conducted to identify critical components and failure modes. Since these ranks are linguistic variables that cannot be properly assigned a definitely value, fuzzy logic method is applied. Using a membership function and a defuzzification formula, the variables are defuzzified. Grey relational analysis is also applied to determine the relation between the risk factors.

Measuring and monitoring the health condition of an UAV structure is not always possible, since the loading and the structure geometry are complicated. This makes it difficult to monitor the health condition of every component. Simulation is a simple and efficient method to model the complicated scenario and is suitable for the prediction of structural failures. Finite element method (FEM) is a generally used numerical method for solving engineering and mathematical problems. It has an advantage in dealing with problems with complicated loadings, geometries and material properties [10-12]. The fuselage is the main support and most important structure of the airplane. Thus in this research work, the stress distribution of the fuselage at different loads has been simulated. Fatigue is an important factor of the fuselage need to be considered especially for predictive maintenance. Thus, the fatigue life cycle of fuselage under different loads has also been simulated.

The remaining of the paper consists of four sections. The research FMEA method is explained in Section Ⅱ following by FE simulation method in Section Ⅲ. Case study is discussed in section Ⅳ. The closing remarks and future work are presented in section Ⅴ.

II. FMEA ANALYSIS

A. FMEA method

FMEA has been conducted as part of the reliability analysis. There are four steps for the analysis: (1) identification of the failure modes, (2) determination of the parameters for FMEA analysis, (3) defuzzification of the linguistic variables and (4) application of grey theory. For the failure mode analysis. the

---

*This research was conducted in the ST Engineering-NTU Corporate Laboratory with funding support from the Nation Research Foundation (NRF), ST Aerospace and Nanyang Technological University; under the Corp Lab@University Scheme.

B. Wang is with the Nanyang Technological University, ST Engineering-NTU Corporate Laboratory, School of EEE, 637335 Singapore (e-mail: wangbing@ntu.edu.sg).

P. H. Ng, is with Nanyang Technological University, ST Engineering-NTU Corporate Laboratory, School of EEE, 637335 Singapore (e-mail: nicholasnph@ntu.edu.sg).

B. M. N. A. K. Elhadidi is with the School of Mechanical & Aerospace Engineering, Nanyang Technological University, 639798 Singapore (e-mail: mbasman@ntu.edu.sg).

H. S. Ang is with the ST Engineering Aerospace, 539938 Singapore (e-mail: anghuishan@stengg.com).

S. K. Moon is with the School of Mechanical & Aerospace Engineering, Nanyang Technological University, 639798 Singapore (corresponding author to provide phone: +65-6790-5599; e-mail: skmoon@ntu.edu.sg).

sub-systems and parts that require health monitoring are identified. Each failure is then ranked in 3 categories: severity, occurrence, and difficulty of detection. Severity is how the component failure affects the system. For example, a battery or motor failure could result in crashing and catastrophic failure of the UAV. Occurrence refers to the frequency of the failure occurrences. Difficulty of detection refers to how hard it is to detect the failure using methods or sensors currently in use. Each category would have 1 of 5 ranks: very low, low, moderate, high, and very high as described in Table Ⅰ.

TABLE I. RANK CRITERIAS

Description	Severity	Probability	Detectability
very low	No impact on the UAV system	Virtually impossible or no known occurrences on similar products or processes, with many running hours	Validated automatic detection system that is direct measure of failure
low	A failure not serious enough to cause system damage, but will result in a unscheduled maintenance or repair.	Few failures	High chance the failure can be detected
moderate	A failure which may cause minor system damage which will result in a delay or loss of availability or mission degradation.	Occasional failure	Moderate change the failure can be detected
high	A failure which may cause major system damage which will result in the mission loss.	Repeated failures	very low chance the failure can be detected
very high	A failure which may cause system or UAV platform loss	Frequent, failure is almost inevitable	No ability to detect the failure

Since these ranks are linguistic variables that cannot be properly assigned a definite value, fuzzy logic can be applied to the linguistic variables [13]. Using a membership function and a defuzzification formula, the variables are defuzzified as shown in Fig. 1.

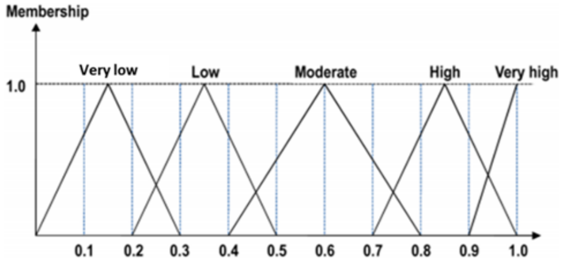


Figure 1. Membership function for linguistic terms

For the FMEA analysis, generally the risk priority number (*RPN*) is calculated to rank risk levels. The RPN can be calculated as:

$$RPN = S \times O \times D \tag{1}$$

Where *S* is the severity, *O* is the occurrence of failures and *D* is the detectability of the failure. These three parameters can be presented either as linguistic terms or numbers. In this case, linguistic terms are used to descript the risk levels. The traditional FMEA method implies the same importance of the three factors which may actually not true. Another disadvantage of this method is different set of variables may give same *RPN* values however the risk implications may be quite different [14]. To solve this problem, the linguistic terms are transferred to numbers by deffuzzification. Grey theory are applied to determine the relation of parameters. The crisp number of fuzzy set and can be calculated by equation 2[13].

$$K = \frac{\sum_{i=0}^{n}(b_i - c)}{\sum_{i=0}^{n}(b_i - c) - \sum_{i=0}^{n}(a_i - d)} \tag{2}$$

Where *n* is the maximum number of membership function levels, a_i and b_i are rating values, *c & d* are set to be same for deffuzzification of the linguistic terms.

We then obtain a set of defuzzified values for each rank and their grey relational coefficient as presented in Table Ⅱ.

TABLE II. DEFUZZIFIED VALUE & RELATIONAL COEFFICIENT

Linguistic terms	a0	b0	a1=b1	Defuzzified K	Grey relation γ
very low	0	0.3	0.15	0.1956	1
low	0.2	0.5	0.35	0.3695	0.79
moderate	0.4	0.8	0.6	0.5833	0.63
high	0.7	1	0.85	0.8043	0.52
very high	0.9	1	1	0.9523	0.47

B. Grey theory

Grey relational analysis was applied to factor in the relationship between the variables. Firstly, a comparative series is built-up, the failure mode can be presented as:

$$x = [x_n] = [x_n(i)] \tag{3}$$

Where $[x_n]$ are failure mode series and $[x_n(i)]$ are decision factors series of the failure mode.

The difference between comparative series and the standard series has been calculated by:

$$DF = [DF_n(i)] = [\|x_0(i) - x_n(i)\|] \tag{4}$$

Where $[DF_n(i)]$ are the deference between comparative and standard series, $[\|x_0(i) - x_n(i)\|]$ are the difference between decision factors.

The grey relational coefficient can be calculated by comparison of the decision factors and standard series:

$$\gamma(x_0(i), x_n(i)) = (\min_n \min_i |x_0(i) - x_n(i)| + \xi \min_n \min_i |x_0(i) - x_n(i)|) / (|x_0(i) - x_n(i)| + \xi \min_n \min_i |x_0(i) - x_n(i)|) \quad (5)$$

Where $x_0(i)$ and $x_n(i)$ is the maximum or minimum value in the standard series and comparative series respectively. ξ is an identifier. For more detailed calculation and explanation can refer to [14].

Three parameters were given as a weightage coefficient since the severity, occurrence, and difficulty of detection are not equally important. In this paper, the weightage coefficients are:

TABLE III. WEIGHTAGE COEFFICIENT

β_s	β_o	β_d
0.5	0.4	0.1

The relational coefficients are then factored by the weightage coefficients to give the optimal degree of relation $\Gamma = \sum_i \beta_i \gamma_i$.

III. FE SIMULATION

Finite element method is a generally used numerical method for solving mathematical physics and engineering problems. It also widely used in industries. By dividing the system into small elements, with the applying of boundary conditions, complex engineering problem can be solved numerically. In this case, a commercial FE simulation software Comsol is employed to do the structure analysis of UAV. Solid mechanics module is used.

The boundary condition is set according to the real condition as presented in Fig. 2. The three faces connected to the rotor arms were set to be fixed constraints and the loads applied are downward loads, which includes the body and payload weight.

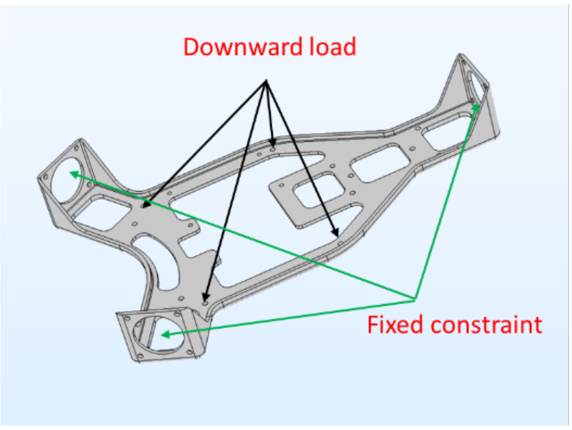


Figure 2. Boundary conditions

The model is meshed into small elements as shown in Fig. 3. Triangular prism elements were used in the simulation. Extra fine meshes was applied. There were totally 559002 elements.

Figure 3. FE simulation mesh

IV. CASE STUDY

To demonstrate the usefulness of the proposed failure analysis and FE simulation, a case study is applied for a UAV. To have a clear understanding of the UAV system failure, all the failures are categorized into six groups as shown in Fig. 4.

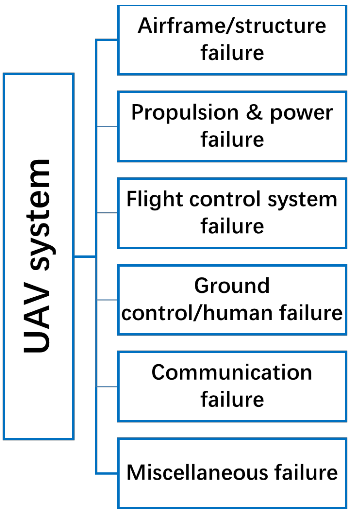


Figure 4. UAV subsystem failures

A. FMEA analysis

By applying the FMEA analysis and grey theory, the risk levels of UAV parts and subsystems has been determined. For an example, Table Ⅳ shows the risk level of UAV battery.

TABLE IV. RANKING RESULTS WITH GREY METHOD OF UAV BATTERY

Components	Failure mode	S	O	D	Γ	Rank
UAV Battery	Puncture/ Crack	VH	VL	VL	0.74	19
	Overheat	H	H	M	0.54	3
	Water damage	H	M	H	0.57	6

Components	**Failure mode**	**S**	**O**	**D**	**Γ**	**Rank**
	Run out of charge	VH	VH	L	0.50	1

Ranking by the subsystem levels have also been done as shown in Table Ⅴ.

TABLE V. RANKING RESULTS OF UAV SUBSYSTEMS

Subsystems	**Γ**	**Rank**
Structure (fuselage, landing gear)	0.9	4
Battery	0.59	1
Avionics (flight controller & communications)	0.76	3
Rotor arm (motors, ESCs & arm structure)	0.7	2

From these results, we can determine that the battery and rotors are more important, since they are the parts that keep the UAV airborne; failures of these could cause catastrophic failure of the UAV.

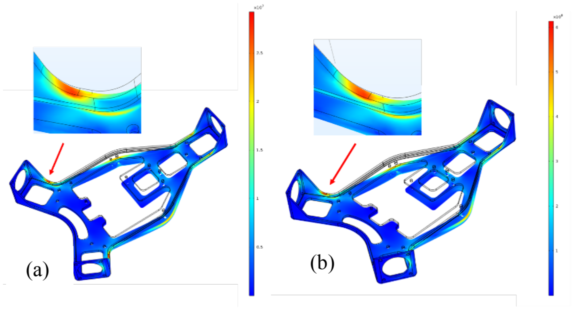
B. *FE simulation*

A 3D FE model was built-up. The fuselage was made of Al 7076 T6. The material property put in simulation is shown in Table Ⅵ.

TABLE VI. MATERIAL PROPERTY OF AL 7076 T6 [15]

Material properties	**Value**
Young's modulus	71.7 Gpa
Ultimate tensile strength	572 MPa
Poisson's ratio	0.33
Tensile yield strength	503 Mpa
Elongation at break	11%
Density	2810 kg/m^3

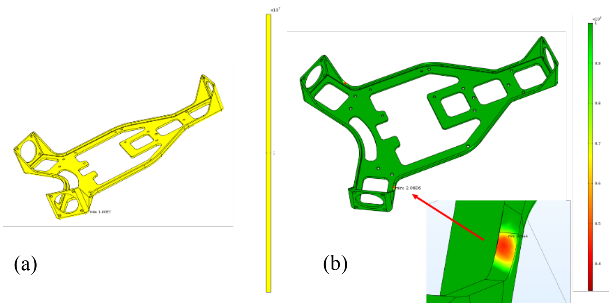
At a normal load of 5 kg, the maximum stress occurred at the corner which is 27.1 MPa as shown in Fig. 5 (a). With the ultimate tensile strength of 572 MPa, the simulated maximum load the fuselage can support is around 105 kg.



(a) (b)

Figure 5. Simulated stress distribution at load of 5 kg & 105 kg respectively.

Fatigue life simulation was conducted on the fuselage at different loads: 5 kg, 50 kg & 75 kg. At a normal load of 5 kg, the simulated fatigue life cycle was up to 10^7. When the load increased to 50 kg, the simulated fatigue life cycle is still up to 10^7. While when the load further increased to 75 kg, the fatigue life cycle is reduced to 2.06 x 10^6 as shown in Fig. 6 (b). The fracture point occurred at the maximum stress concentration corner.



(a) (b)

Figure 6. Fatigue simulation at load of 50 kg and 75 kg respectively.

V. CLOSING REMARKS AND FUTURE WORK

In this paper, the failure analysis and FE simulation of a small UAV were conducted. For FMEA reliability analysis, the UAV system was divided into several subsystems. Using fuzzy logic and grey relational analysis, the failure modes were ranked. The battery failure & motor failure were found to be the most important failures that need to be focused on. FE simulation was conducted on the UAV fuselage at different load levels: 5 kg, 50 kg & 75 kg. At 5 kg, the maximum stress occurred at a corner of the fuselage, which is 27.1 MPa. The maximum load the fuselage can support was simulated up to 105 kg with the ultimate tensile limit of the material. The fatigue life at different load levels were simulated. At a load of 5 kg and 50 kg, the fatigue life was up to 10^7, and when the load increased to 75 kg, the fatigue life cycle was reduced to 2.06 x 10^6.

With the FMEA analysis, the potential failures and risk levels are identified. The critical component and subsystems are identified. The strength limit of the fuselage has been simulated out. The fatigue simulation enables predictive maintenance and replacement of the fuselage.

For future works, the stress distribution and fatigue simulation will be conducted on more parts including rotor arms and landing gears. Impact simulation will be applied on landing gears. Structure vibration will be simulated. Experiment will be conducted to test the reliability of the UAV system. The experiment results will be compared with the simulation results. In addition, based on FMEA analysis more focus will move to battery and rotor arm failures. Beside FE analysis, data analysis will be developed and applied for the failure analysis.

REFERENCES

[1] G. Kandaswamy and P. Balamuralidhar, "Health Monitoring and Failure Detection of Electronic and Structural Components in Small Unmanned Aerial Vehicles," *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering,* vol. 11, pp. 1080-1089, June 2017.

[2] (2003). *Unmanned Aerial Vehicle Reliability Study*. Available: https://www.uvsr.org/Documentatie%20UVS/Publicatii-internationale/ReliabilityStudy-2003.pdf

[3] P. Freeman and G. J. Balas, "Actuation failure modes and effects analysis for a small UAV," in *2014 American Control Conference*, Portland, 2014, pp. 1292-1297.

[4] E. Petritoli, F. Leccese, and L. Ciani, "Reliability and Maintenance Analysis of Unmanned Aerial Vehicles," *Sensors (Basel, Switzerland),* vol. 18, no. 9, p. 3171, 2018.

[5] Hendarko, T. Indriyanto, Syardianto, and F. A. Maulana, "Determination of UAV pre-flight Checklist for flight test purpose using qualitative failure analysis," *IOP Conference Series: Materials Science and Engineering,* vol. 352, p. 012007, May 2018.

[6] B. J. d. O. M. Franco and L. C. S. Goes, "Failure analysis methods in unmanned aerial vehicle (UAV) applications," in *19th International Congress of Mechanical Engineering*, Brasilia, DF, 2007.

[7] J. B. Bowles and C. E. Peláez, "Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis," *Reliability Engineering & System Safety,* vol. 50, no. 2, pp. 203-213, Jan 1995.

[8] C.-B. Liu, *Aircraft fuel tank system fire disaster analysis based on FMEA and FTA*. 2013, pp. 99-102.

[9] H. Pang, T. Yu, and B. Song, "Failure mechanism analysis and reliability assessment of an aircraft slat," *Engineering Failure Analysis,* vol. 60, pp. 261-279, Jan 2016.

[10] J. Tang, P. Xi, B. Zhang, and B. Hu, "A finite element parametric modeling technique of aircraft wing structures," *Chinese Journal of Aeronautics,* vol. 26, no. 5, pp. 1202-1210, Oct 2013.

[11] X. Liu, J. Guo, C. Bai, X. Sun, and R. Mou, "Drop test and crash simulation of a civil airplane fuselage section," *Chinese Journal of Aeronautics,* vol. 28, no. 2, pp. 447-456, April 2015.

[12] A. Deepak, P. M, and D. L Prabhakara, *FE based Crash Simulation of belly landing of a light transport aircraft*. 2015.

[13] A. Pillay and J. Wang, "Modified failure mode and effects analysis using approximate reasoning," *Reliability Engineering & System Safety,* vol. 79, no. 1, pp. 69-85, Jan 2003.

[14] S. K. Moon, H. S. Oh, J. A. Venture, J. K. Kim, and Y.-J. Yoon, "Service reliability improvement in manufacturing and operating systems," *International Journal of Precision Engineering and Manufacturing,* journal article vol. 14, no. 8, pp. 1401-1406, Aug. 2013.

[15] A. I. H. Committee, *Properties and Selection: Nonferrous Alloys and Special- Purpose Materials*. ASM International, 1990.