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PREDICTING MAXIMUM ENDURANCE OF A HIGH ALTITUDE LONG ENDURANCE UAV WITH TAGUCHI METHOD

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ABSTRACT

In this study, an application of Taguchi method was done on performance of a high altitude long endurance (HALE) unmanned air vehicle (UAV). General performance characteristics were calculated for UAV with a basic mission profile for a typical reconnaissance mission. Initially, endurance values of UAV were calculated and tabulated in an interval of airspeed and flight altitude. Then, Taguchi method was used to predict the maximum endurance on this interval. Secondly, flight range was calculated was calculated and tabulated at the same interval. On the implementation of the Taguchi method, two parameters in there levels were selected. Airspeed and flight altitude were the two parameters with assumed low, medium and high values. Taguchi method was found to be very effective in estimating the maximum values of flight endurance and the range of the UAV. Based on the response table of Taguchi, Speed was the most significant parameter and the optimum levels of the selected parameters to achieve the highest endurance were speed at level 1 and altitude at level 3. Also the percentage of contribution for speed and altitude was found to be 88.1% and 8.7% respectively.

INTRODUCTION

Unmanned air vehicle (UAV) is defined as “an aircraft which is designed or modified, not to carry a human pilot and is operated through electronic input initiated by the flight controller or by an onboard autonomous flight management control system that does not require flight controller intervention” [1]. In other words, UAV is a plane that can be flown autonomously or remotely to perform specific tasks without any crew inside. Missiles or single-use aircraft are not considered as UAV. There are many types of UAVs, including micro, tactical, strategic and combat [2]. UAVs have increased their use, versatility and variety in many areas of civil and military application. The UAVs are preferred in “dull, dirty and dangerous” missions/duties and they achieved high success in service and demonstration. Typical missions of UAVs include border & costal patrol and monitoring, homeland security, combat, law enforcement & disaster operations, digital mapping & planning/land management, search & rescue, fire detection and firefighting management, communications and broadcast services, precision agriculture and fisheries, ground transportation monitoring and control, satellite augmentation systems, air traffic control support, power transmission line monitoring, environmental research & air quality, management/control, etc. [3].

Starting from 1990s, UAV programs had an increasing momentum than ever before throughout the world. As an example, NASA undertook a program called Environmental Research Technology and Sensor Technology (ERAST), with industrial partners focusing on the development of technologies for drone and unmanned commercial aircraft markets. In this nine-year program, a lot of technologies related with drone, their integrated engines, sensors etc. were developed to perform better in high-altitude and longer distance. In literature, there are numerous studies on the design and optimization of UAV systems for further reading [4-16].

AIRCRAFT PERFORMANCE

Calculations are needed to estimate if an aircraft to accomplish the requirements set forth in the mission profile. For instance, ability to take off and land, carry payloads, fly at required altitudes at speeds, maneuvers, endurance and range, aerodynamic lift and drag etc. are estimated as a part of flight performance calculations. Flight duration, endurance and range can be estimated using equations below:

$$R = \frac{V}{C}\frac{L}{D}\ln\frac{W_{i-1}}{W_i} \tag{1}$$

$$E = \frac{L/D}{C}\ln\frac{W_{i-1}}{W_i} \tag{2}$$

Equation (1) is the modified Breguet range formula for constant velocity and altitude for a jet aircraft. V, the speed of the plane, C, specific fuel consumption; L, lift force; D, drag force; W, aircraft weight. Typically, the velocities required for maximum endurance and maximum range are different. Typically, velocity for maximum range is higher than the velocity for maximum endurance.

As a case study, `Global Hawk` UAV was selected as a model. `Global Hawk` UAV is a high altitude long endurance (HALE) drone which can operate at high-altitude as high as 19.81 km (65000 ft) and can fly typically more than 24 hours. Calculations were done with a genuine computer code developed by the authors. For this study, initially maximum endurance was calculated in hours within an interval of 0.35-0.75 airspeed (Mach) and 9-16 km flight altitude. Endurance results were tabulated in Table 1. Secondly, maximum range was calculated and tabulated in Table 2. Overall results were compared with the literature values available for `Global Hawk` UAV in Table 3. It was shown that the results are in less than 1% deviation with the literature values.

Figure 1: Global Hawk unmanned air vehicle [17]

Table 1. Endurance Data vs. flight speed (Mach) and altitude (km)

Mach/ Altitude	9 km	10 km	11 km	12 km	13 km	14 km	15 km	16 km
0.35	34.5	35.18	**35.25**	35.06				
0.4	30.3	31.76	32.82	33.69	33.94	33.56		
0.45	25.9	27.78	29.45	31.04	32.14	32.69	32.62	
0.5	21.9	23.89	25.84	27.84	29.52	30.76	31.47	31.61
0.55	18.4	20.4	22.41	24.57	26.56	28.26	29.56	30.37
0.6	15.6	17.41	19.35	21.51	23.61	25.56	27.25	28.55
0.65	13.3	14.9	16.71	18.76	20.85	22.89	24.79	26.44

0.7	11.3	12.82	14.46	16.37	18.36	20.39	22.37	24.21
0.75	9.77	11.09	12.58	14.31	16.17	18.12	20.1	22.02

Table 2. Range Data vs. flight speed (Mach) and altitude (km)

Mach/ Altitude	9 km	10 km	11 km	12 km	13 km	14 km	15 km	16 km
0.35	13230	13311	13167	13131	12859	12369		
0.4	13273	13744	14017	14417	14564	14447	14074	
0.45	12781	13540	14162	14955	15521	15823	15842	
0.5	12023	12959	13829	14924	15850	16550	16977	17106
0.55	11172	12198	13217	14512	15710	16744	17549	18073
0.6	10327	11381	12475	13881	15259	16543	17662	18547
0.65	9532	10578	11695	13145	14625	16078	17434	**18618**
0.7	8805	9822	10930	12379	13901	15452	16971	18385
0.75	8149	9126	10206	11626	13150	14745	16362	17938

Table 3. UAV Data

Specifications	**Literature value**	**Calculated value**	**Deviation (%)**
Ferry Range (km)	18520	18618	0.5
Maximum Endurance (hour)	35	35.25	0.7

Taguchi Method

Different optimization methods for different industrial applications have been employed for decades. One of the optimization method to improve the quality is Taguchi method. Taguchi is capable to reduce the number of experiment and will evaluate the selected parameters to determine the optimum levels and their contributions [18].

The main goal of the paper is to determine the optimum level of different parameters affecting the endurance in airplane. In this research, the effect of influence two parameters are evaluated namely, the speed (P_1) and the altitude (P_2) as tabulated in Table 4. To achieve the best configuration for the highest endurance, the Taguchi orthogonal array method is used to optimize the process. The selected parameters are defined in three different levels.

Table 4: selected levels of speed (P_1) and altitude ($\boldsymbol{P_2}$)

	$\boldsymbol{P_1}$ (km/h)	$\boldsymbol{P_2}$ (km)
Level 1	0.35	9
Level 2	0.4	10
Level 3	0.45	11

Selection of the parameter levels and orthogonal array of Taguchi

Based on the number of selected parameters and their levels, the L9 orthogonal array of Taguchi is selected as shown in Table 5.

Table 5: L9 orthogonal array of Taguchi

Test Case	P_1	P_2
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

S/N ratio approach

Taguchi method proposes signal to noise ratio to evaluate different quality characteristics in engineering design, namely the smaller the better, the nominal the best, and the larger the better [18]. Since the objective of this study is to increase the endurance value, larger the better quality characteristic has been applied based on Equation 3 and Equation 4 as follows [19]:

$$MSD = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2} \quad (3)$$

$$S/N = -10\ Log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right) \quad (4)$$

where n is the number of experiments and y is the endurance value (based on the number of experiments).

EXPERIMENTAL SET UP

Orthogonal array of Taguchi and S/N ratio

With reference to the number of parameters and their levels, L9 orthogonal array has been chosen and the selected parameters based on different levels have been tabulated to calculate the endurance value as shown in Table 6. The endurance is calculated based on the mathematical model generated in MATLAB. Also, Signal to noise ratio is calculated for 9 experiments as shown in Table 6.

Table 6: L9 orthogonal array of Taguchi for data collection

Test Cases	P_1**:Speed (km/h)**	P_2**: Altitude (km)**	**Endurance (km)**	**S/N**
1	0.35	9	34.5	30.76
2	0.35	10	35.18	30.93
3	0.35	11	35.25	30.94
4	0.4	9	30.3	29.63

5	0.4	10	31.76	30.04
6	0.4	11	32.82	30.32
7	0.45	9	25.9	28.27
8	0.45	10	27.78	28.87
9	0.45	11	29.45	29.38

S/N Response Table

To determine the optimal levels of the selected parameters, the average S/N ratio of response needs to be calculated as shown in Table 7. With reference to Table 7, the larger value of |ΔT| demonstrates the significance of the parameter and the highest value for each parameter represent the optimal level. The result is a combination of P_1 (level 1) and P_2 (level 3), as the best set of parameters for having higher endurance. The S/N response diagram can be plotted as shown in Figure 2 and Figure 3 based on Table 7.

Table 7: The response Table of S/N ratio

	P_1	P_2
Level 1	**30.87516**	29.55041
Level 2	29.996411	29.94606
Level 3	28.840782	**30.21589**
Difference |ΔT|	2.0343783	0.665477

The data in Table 8 was determined using Analysis of Variance. The relative percentage of contribution of each parameter was calculated by comparing their relative variance. ANOVA computes the quantities such as degrees of freedom, the sums of squares, F-ratio, the pure sum of square and the percentage of contribution [19].

Table 8: Analysis of Variance (ANOVA).

Source	F	S	P %
P_1 (Speed)	2	79.37	88.1
P_2 (Altitude)	2	7.83	8.7
error	4	2.91	3.2
Total	8	90.11	100.0

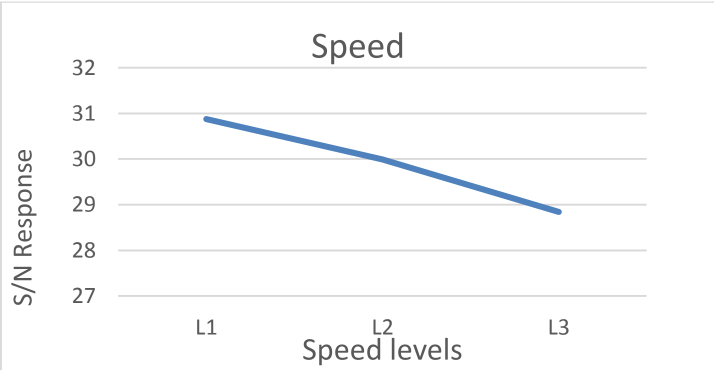

Figure 2: S/N response for speed.

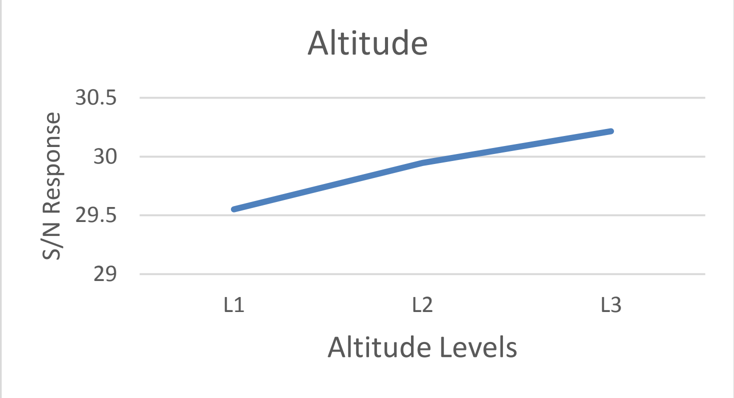

Figure 3: S/N response for altitude.

The calculation of Sum of Square can be written as follows [19]:

$$SS = \left(Ave_1{}^2 + Ave_2{}^2 + Ave_3{}^2 + \cdots\right) - \frac{(Ave_1 + Ave_2 + Ave_3 + \cdots)^2}{N}, \quad (5)$$

$$St = \left(\frac{(\sum Ave_1)^2}{k_{P_1}} + \frac{(\sum Ave_2)^2}{k_{P_1}} + \frac{(\sum Ave_3)^2}{k_{P_1}} + \cdots\right) - \frac{(Ave_1 + Ave_2 + Ave_3 + \cdots)^2}{N}, \quad (6)$$

For the degree of freedom, Equation 7 and Equation 8 were used:

$$F_{P_1} = k_{P_1} - 1, \quad (7)$$

$$F_t = N - 1, \quad (8)$$

where, N is the total number of result for factor P_1 and k_{P_1} stands for the number of level for factor P_1. To determine the error for the degree of freedom, Equation 9 is applied as follows [19]:

$$f_e = f_t - f_{P_1} - f_{P_2} - f_{P_3}, \quad (9)$$

For the percentage of contribution, Equation 10 can be written as follows [19];

$$\mathrm{P}_{\mathrm{P}_1} = \frac{\mathrm{s}_{\mathrm{P}_1}}{\mathrm{s}_\mathrm{T}}, \quad (10)$$

where, s_T is the total sum of square.

Based on Table 8, speed contributes to the endurance with 88.1%, and the altitude contributes with 8.7%. As a result, the speed has the maximum contribution and significantly affects the endurance in comparison with the altitude.

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CONCLUSION

As an aim of this study, an application of Taguchi method was done on performance of a high altitude long endurance (HALE) unmanned air vehicle (UAV). Taguchi optimization method was applied to find the significant parameters and their optimum levels. Based on the number of parameters and their levels, L9 orthogonal array was chosen and larger the better quality characteristics was selected to determine the higher endurance. Based on the response table of Taguchi, Speed was the most significant parameter and the optimum levels of the selected parameters to achieve the highest endurance were speed at level 1 and altitude at level 3. Also the percentage of contribution for speed and altitude was 88.1% and 8.7% respectively.

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