

# A Practical Approach to Enhance the Flight Endurance of a Fixed-Wing UAV



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**Abstract** This paper presents a summary of research toward extending the flight duration of fixed-wing unmanned aerial vehicles at ADE. A historical context to extended flight is provided and particular attention is paid to research in establishing the best operating profile for the Reciprocating Piston engine to meet the extended endurance target. With the limitation of the fuel capacity in the UAV, it is imperative to identify and operate the UAV at the lowest fuel consumption regime without compromising the mission objectives. Usage of variable pitch propeller along with operation of mixture control of the engine has resulted in the extension of endurance of up to 12 h. Autonomous flying presents a unique set of challenges whereby the flight computer of the aircraft must command and control the engine to be operated at the best operating regime. The basic mechanisms of variable pitch propeller operation are examined. During the present work, automation tables were evolved to aid the flight control computer.

**Keywords** UAV · Endurance · Variable pitch propellers

## Nomenclature

$c$	Specific fuel consumption
$C_t$	Coefficient of Thrust
$C_L$	Coefficient of Lift
$C_D$	Coefficient of Drag
$E$	Endurance
$m$	Mass flow of air
$T$	Thrust
$\eta$	Propeller Efficiency
$W_o$	Gross Weight of Aircraft

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W1	Empty weight of Aircraft
L/D	Lift to Drag Ratio
V	Forward Velocity
$V_o$	Air Entry velocity
$V_j$	Exit Velocity
VPP	Variable Pitch Propeller
W	UAV weight
FPP	Fixed Pitch Propeller
GCS	Ground Control Station
HST	High Speed Taxi

## 1 Introduction

Unmanned Aerial Vehicles (UAVs) play a vital role in surveillance and reconnaissance operations. The operations are typically dull, dirty, and dangerous in nature. The aircrafts need to be in the air and on target for longer durations to meet the mission objectives.

Historically, attempts have been made to arrive at the best possible operations of small aircrafts to achieve fuel efficiency and thereby stay in air for longer duration, as discussed in Carson et al. Ref. [1]. Carrying additional fuel tanks, using glide potential of the aircraft, operating at high L/D ratio, operating the aircraft engine at best specific fuel consumption, all have been looked at.

Rustom-I, a short-range UAV, is under development at ADE. This UAV is a conversion of twin-seater LongEz aircraft for unmanned applications. The Rustom Flight Control Computer (RFCC) replaces the pilot inside aircraft. The command and control of the aircraft is carried out through a Ground Control Station (GCS).

Lycoming O-320 B3B engine is the powerplant for this UAV. It is a 160 hp, naturally aspirated, carburetor engine using AVGAS 100 LL as fuel.

Fuel tank capacity is 200 Ltrs. The average fuel consumption, during cruise at an altitude of 8000 ft was 23 liter/h. Simple mathematics show, this aircraft cannot achieve 10 h of endurance target in its present configuration. Most efficient use of the available fuel can result in an improved endurance figure.

Description of parameters and their effect on endurance are explained below.

### 1.1 Endurance

By definition, endurance is the amount of time that an airplane can stay in the air on one load of fuel. Equation (1) is the general equation for the endurance  $E$  of an airplane. If detailed variations of  $C_t$ ,  $L/D$ , and  $W$  are known throughout the flight, Eq. (1) can be numerically integrated to obtain an exact result for the endurance.

For preliminary performance analysis, Eq. (1) is usually simplified. Assuming flight at constant  $C_t$  and  $L/D$  the equation becomes

$$E = \int_{W_1}^{W_0} \frac{1}{C} \frac{1}{D} \ln \frac{dWf}{W} \quad (1)$$

Since the specific fuel consumption for propeller-drive airplanes is given in terms of power rather than thrust, the relation between  $c$  and  $C_t$  is

$$C_t = cV / \eta$$

Thus,

$$\text{Endurance } E = \frac{1}{C_t} \frac{1}{D} \ln \frac{W_0}{W_1} \quad (2)$$

Thus from Eq. (2), for achieving maximum endurance of the airplane the following conditions are to be met.

1. Cruise at maximum  $C_L/C_D$ .
2. Select a propeller with the highest propeller efficiency.
3. Operate the UAV at the lowest possible SFC.
4. Carry maximum amount of fuel onboard.

## 1.2 Lift-to-Drag Ratio

Traditionally, maximum Lift-Drag ( $L/D$ ) ratio has been accepted as a primary figure of merit for a given airplane.

The  $L/D$  ratio enters the aircraft endurance calculations in an obvious way as explained in Eq. (2). Neglecting the variations in propeller efficiency (considering the constant-speed propellers to be integrated on this aircraft), it can be shown that the speed which maximizes range, is that corresponding to the best  $L/D$  for a propeller-driven aircraft. However, the speeds corresponding to maximum  $L/D$  ratio, does not seem to be practical for the reasons explained by Carson (1982) Ref. [1].

## 1.3 Propeller Efficiency

Propeller Efficiency is defined as the ratio of useful power converted as thrust to available power. The thrust produced is given by the Eq. (3)

$$T = m(V_j - V_o) \quad (3)$$

Thus, propeller efficiency is  $\eta = 2 / 1 + (V_j / V_o)$ . However, the airplanes operate at different forward speeds. Thus to operate an aircraft at the highest propeller efficiency with a fixed pitch propeller is next to impossible.

### ***1.4 Specific Fuel Consumption***

The specific fuel consumption is a technical figure of merit for an engine which reflects how efficiently the engine is burning fuel and converting it to power. For an internal combustion reciprocating engine, the specific fuel consumption  $c$  is defined as weight of fuel burned per unit power per unit time. The specific fuel consumption is insensitive to changes in altitude and forward velocity as seen in Chap. 3 of Anderson (2010). Ref. [2].

### ***1.5 Variable Pitch Propeller***

Propellers are classified as Fixed Pitch Propellers (FPP) and Variable Pitch Propellers (VPP). The propeller blade angle cannot be changed in FPP. The loss in performance of engines having fixed pitch propellers led to the development of VPP viz., (a) adjustable pitch propeller (b) controllable pitch propeller, and (c) constant speed propeller.

Fixed Pitch Propeller (FPP) is one-piece made of either wood or metal and is used in low-powered aircrafts. The drawback is that the engine output cannot be readily changed to meet the various conditions under which aircraft is flown. During the take-off and climb extra power is needed and propeller of low pitch is desirable. While cruising propeller of high pitch and lower engine output are most effective. When the UAV is in air, the engine has to be throttled back to prevent over speeding with a corresponding loss of power and speed.

In case of Adjustable Pitch Propeller, the angle at which blades are set can be changed while the UAV is on the ground.

Controllable Pitch Propeller, the blades may be rotated while UAV is in flight mode by hydraulic mechanism. It can be two, three, or multi-position system. The angle of blade setting varies with the engine power.

Constant Speed Propellers are equipped with system controller that automatically alters the pitch by hydraulic or electrical mechanism. Centrifugal governor regulates aircraft engine speed by continually varying pitch of propeller to match propeller torque (engine load) to engine developed torque as changes occur in flight conditions Ref. [4].

## 1.6 Lean Mixture Control

Lycoming O-320 is a carburetor fed engine with a provision for mixture control to compensate for the change in density of air at high altitudes. The mixture control lever, when operated regulates the amount of fuel delivered at the venturi of the carburetor for a particular throttle opening. Pilot controls this lean mixture lever, corresponding to the altitude of flying, while monitoring the exhaust gas temperatures and engine rpm as the reference parameters.

## 1.7 Propeller Selection

Lycoming O-320 has been used in aircrafts with various propellers including fixed pitch, variable pitch, constant speed propellers. A constant speed variable pitch propeller, manufactured by MT propellers was selected considering the engine horsepower, gear ratio, ground clearance, UAV operating speeds, and weight of the propeller.

## 2 Engine Control Logic for Uavs

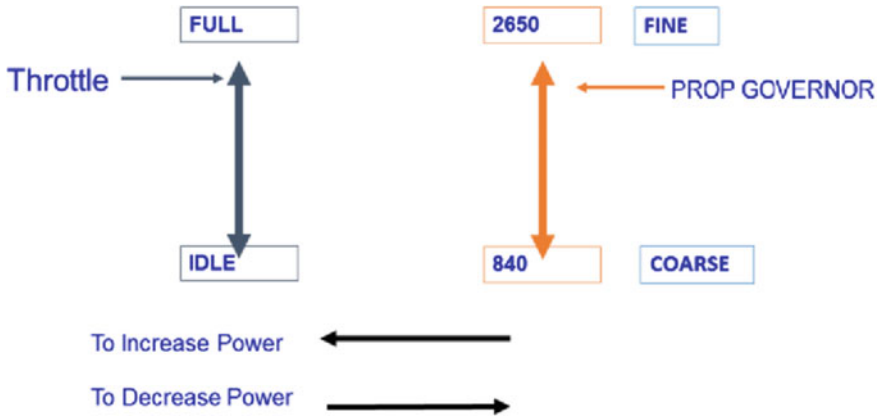
All the three engine controls viz., throttle, propeller rpm, and mixture control were to be operated by the pilots in the sequence established during the ground tests and taxi runs. Also the lookup tables were prepared for automating the propeller rpm and mixture controls for specific forward speeds of the aircraft and cruise altitude. A sample profile for an UAV mission and the engine controls is described below in Fig. 1

## 3 Theoretical Estimation

A higher endurance demanded to carry full fuel, which increased the AUW of the aircraft, which in turn demands higher thrust. Thrust can be increased by using a bigger propeller or high-efficiency propeller. A constant-speed propeller manufactured by MT Propellers, Germany was found suitable for this application. Studies were carried out to estimate the performance of Lycoming O-320 engine (160 Hp) with Fixed Pitch Propeller (FPP) and with Variable Pitch Propeller (VPP). A mission analysis was also carried out using the following conditions of UAV to predict performance improvements of UAV (Fig. 2).

Maximum Take-Off Weight (MTOW)	650 kg, 730 kg, and 780 kg
Altitude ft. AMSL	SL to 14000 ft.





**Fig. 3** Sequence of throttle and rpm control operation

The theoretical analysis shows an improvement in Take-off Ground Roll (TGR) distance and rate of climb of Lycoming O320 engine with VPP than that of Lycoming O-320 engine with FPP.

The analysis result shows that the take-off ground roll distance at sea level for 160 HP engine with Fixed Pitch Propeller (FPP) is 500 m with max AUW of 780 kg. The same engine with Variable Pitch Propeller (VPP) has shown 325 m take-off ground roll distance. The TGR distance has reduced to 175 m for a UAV with VPP. Engine with VPP can provide 35 % increase in take-off ground roll distance.

Rate of Climb (ROC) for 160 HP engine power with FPP at aircraft speed of 100 knots with AUW of 780 kg is 3.8 m/s. In case of same engine with VPP and 780 kg AUW at aircraft speed of 100 knots, the ROC has increased to 4.9 m/s. An increase of 28 % in ROC is observed for the engine with VPP with AUW of 780 kg at speed of 100 Knots.

#### 4 Evaluation of Engine and Propeller on Test Bed

In order to evaluate performance of VPP prior to integration on to the Rustom-1, the VPP system was mounted on test bed engine and carried out performance run for rpm and full static thrust. It is observed that engine was able to attain max speed of 2600 rpm and was able to generate static thrust of 191 kg against 133 kg thrust of two blade fixed pitch propeller as shown in Table 1. Two actuators were used operation of throttle and governor lever.

First step was to establish the throttle vs engine rpm on the test bed. The throttle actuator was commanded in steps after the engine warm-up. The full travel of the actuator was calibrated for the idle and maximum engine rpms. Table 2 was arrived after multiple engine runs on test bed.

**Table 1** Performance of VPP on test bed engine

Propeller	Engine rpm	Thrust Kgf
FPP	2200	133
VPP	2600	191

**Table 2** Throttle versus RPM on test bed

Throttle (%)	RPM	Thrust (Kgf)	Fuel consumption (Ltr/h)
0	840	40	7.4
10	1140	49	8.9
20	1360	90	21.6
30	1880	131	27.9
40	2210	157	35.2
50	2410	175	40.5
60	2500	179	44.7
70	2560	180	46.2
80	2590	182	48.9
90	2610	190	50.4
100	2650	191	52

Next is to evaluate the governor position. The governor actuator was controlled through analog voltage electrical command—10 V to 10 V. Considering the governor travel required and the actuator linear travel available, the governor operation was restricted to—8 V to +8 V. The throttle command and governor actuator were commanded together and in sequence to arrive at the governor position for a selected engine rpm. The governor command vs engine rpm is established as given in Table 3.

All naturally aspirated, carbureted aero engines are equipped with a mixture control lever, to be exercised by the pilot as per the altitude of UAV operation. As the density of air decreases at altitudes, the fuel needs to be metered before its entry into the carburetor (Fig. 4).

The levers in a Marvel Scheibler make carburetor used in the Lycoming O-320 engine is shown in the Annexure-1, Fig. 5. The mixture control lever was adjusted during flight tests at different altitudes and a lookup table was derived which is shown in Table 4.

The sequence of operation is explained below in Fig. 3. To increase power the propeller rpm control is put to fine position first and the throttle is increased to full rpm position next. Similarly to decrease power the throttle is reduced first and propeller rpm control is operated next.



**Table 3** Governor RPM settings based on ground tests and taxi trials

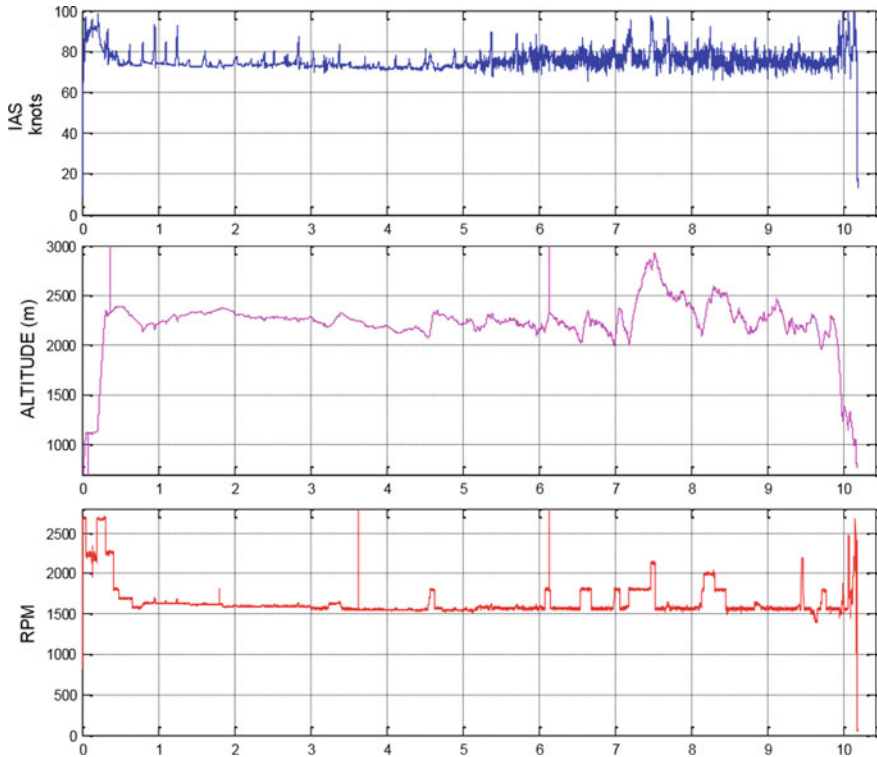
Governor actuator voltage	Engine RPM
8	850
7	1000
6	1100
5	1200
4	1300
3	1400
2	1500
1	1600
0	1725
- 1	1925
- 2	2050
- 3	2200
- 4	2300
- 5	2400
- 6	2500
- 7	2575
- 8	2650

## 5 Flight Tests

Having successfully integrated VPP system to Rustom-1 UAV, it was subjected to LST and HST to check the functional behavior of the VPP system. Subsequent to number of taxi operation the first flight of Rustom-1 with VPP was flown at Kolar Flight Test Range. The critical parameters of VPP engine were observed and analyzed. The parameters are, engine rpm, throttle, fuel flow rate, aircraft speed, altitude, PPC\_POS\_FB, RPM\_DEMAND & RPM\_COMMAND. All engine parameters were within limits.

The governor restricted the max rpm to around 2695. AUTO mode of governor operation was exercised during flight. The series of flight trials of VPP led to the decision to conduct 10 h endurance flight of Rustom-1 UAV for an AUW of 757 kg. Fuel filled 193 liters.

The objective was to fly the UAV at 8000 ft altitude and 75 knots for a duration of 10 h. The engine rpm was maintained at around 1500–1600 during the cruise phase at 8000 ft altitude (Table 5).



**Fig. 4** Plot. 1: Rustom-1 mission profile (X-axis- No. of Hours)

## 6 Results and Discussion

Plot-1 shows the mission profile of the Rustom-1 UAV. An aircraft speed of 73–80 knots was maintained during the cruise operation. The engine rpm was maintained at around 1500–1700 rpm.

Plot-2 shows the cruise of Rustom-1 for 10 h. The engine rpm was maintained by controlling the propeller governor. The Lean mixture control was also operated at 25 %. All engine parameters were within control and no abnormal parameters were noticed. An optimum fuel consumption of 15 l/h was achieved using VPP for maintaining average aircraft speed of 73–80 knots.

Table 6 shows the comparison of Rustom-1 UAV with fixed pitch and variable pitch propellers

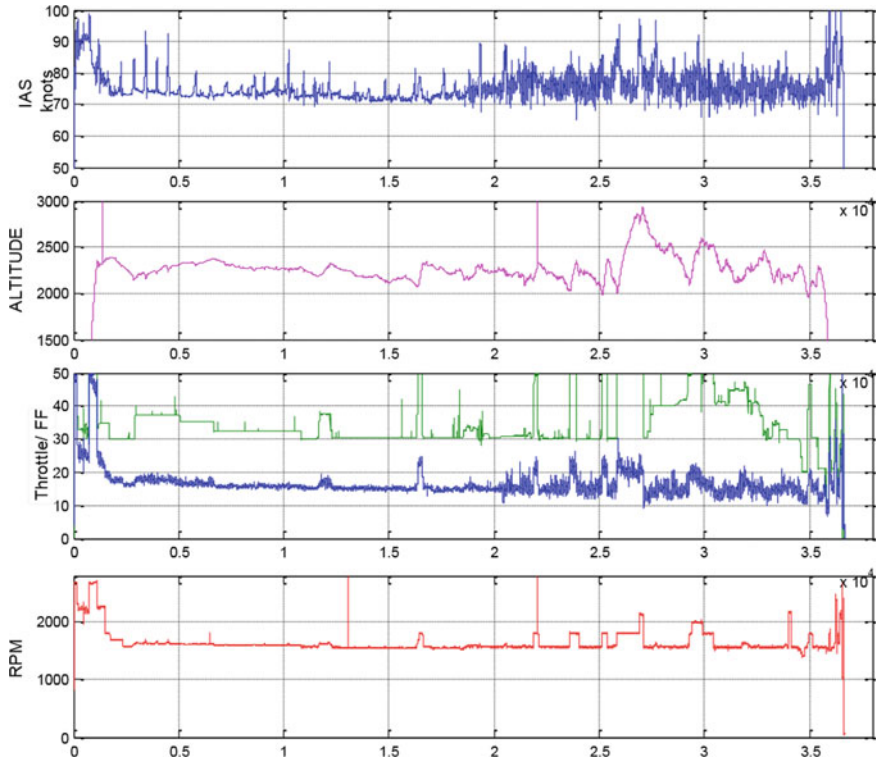


Fig. 5 Plot. 2: Rustom-1 Cruise data

Table 4 Lean mixture control lever setting w.r.t altitude

Altitude (Ft)	<6000	6000–8000		8000–10000		10000–20000	
% Throttle	0–100	<50	50–100	<50	50–100	<50	50–100
LMCU setting (%)	100	50	80	37.5	80	25	50

## 7 Conclusion

A research was initiated to enhance the endurance of Rustom-1 UAV. Higher endurance demanded to carry more fuel, thus increasing the AUW of the aircraft which needed higher thrust from the engine propeller combination. All historical methodologies like carrying additional fuel tanks, selecting an engine with a better SFC were considered. A feasible solution comprising of a variable pitch propeller and mixture control was found encouraging.

**Table 5** Phases of operation of 10 h endurance flight

Phase of flight	Operational conditions	Average Fuel consumption rate	Time (min)
Engine run on Ground	Engine IDLE, MAX Throttle at ~ 12 % 1200 Engine RPM	9 lt/hr	23
Climb to 8000 ft altitude	100 % throttle 100 % LMCU VPP AUTO mode	51.5 lt/h during climb 27 lt/h during cruise @ 1400 m	18
Cruise @ 8000 ft	30–37 % throttle 12.5% LMCU Engine RPM 1600 IAS 71–73 knots	16 lt/h	282
Cruise @ 8000 ft	30–50% throttle 8–15% LMCU Engine RPM 1800~1900 IAS 73–80 knots	15 lt/h	300
Descent and Landing	20 ~ 30% throttle LMCU 100% VPP to AUTO mode	18 lt/h	10

**Table 6** Comparison of flights with FPP and VPP propellers

	R1–42 (with FPP)	R1–55 (with VPP)
AUW	630 kg	757 kg
Fuel Carried	36 kg	140 kg
ROC to 8000 ft	650 ft/min	680 ft/min
Cruise Altitude	8000 ft	8000 ft
Duration of cruise	40 min	~10 h
IAS	80–90 knots	73–80 knots
Engine RPM during cruise	1900–2000	1600–1700
Fuel consumption during Cruise	18 ltr/h	15 ltr/h
Throttle % during cruise	40–50%	35–40%

The ground tests and taxi trials conducted with the VPP has resulted in sufficient data to automate the engine controls for the UAV flight profile.

In conclusion, Rustom-1 UAV, in its newly configured propulsion system has successfully met the endurance requirement of 10 + hours. Lookup tables generated during this work has been extensively used by the pilots in programmed mode flying. The methodology evolved for the selection of best operating points of the aircraft engine, will be utilized for planning the UAV missions in future.

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