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Propulsion System Model of a Mini UAV System

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I. INTRODUCTION

This paper is about the propulsion system model, which is developed using combination of flight test data and software analysis, for a mini UAV system (MUAS-2) developed jointly by ASELSAN Inc. and the Aerospace Engineering Department of the Middle East Technical University. Simulation is a critical and very important phase while developing the autopilot algorithms and a good system model is very important for testing the algorithm and tuning the gains of the autopilot. Dynamic modeling of the propulsion system which is the combination of the Propeller System and the Electric Motor System is very time consuming, expensive and requires much work load such as wind tunnel tests and experimental setups like test benches. To make everything easier and faster, propulsion system model of the MUAS-2 is developed using the *Propeller Model* and the *Polynomial Based Motor Model* as described in this paper. While developing the propulsion system model, neither the wind tunnel tests nor the test benches are used. Everything is investigated using analysis softwares and RC (Remote Controlled) flight test data.

MUAS-2 is designed for reconnaissance and surveillance operations. It has a high wing and T-tail configuration with a pusher type electric motor propulsion system. Main specifications of the MUAS-2 are listed as follows:

- Man portable modular design
- Hand launched
- Parachute or Belly landing
- Airbag system
- Low noise signature
- 2-axis stabilized gimbal system
- Light weight
- Long endurance (up to 2 hrs)

Physical characteristics of MUAS-2:

- 3 m Wingspan
- 1.3 m Length
- 7.75 kg total take off weight with payload

The integration of the electric propulsion motor systems and propellers into a mini UAV plays a significant role in the performance, mission success capability and endurance of the unmanned aerial vehicle. In order to achieve the given requirements for a specific mission, the selection of the proper engine-propeller combination is a crucial step during the design of an UAV [1]. After the discussion, AXI 4120/14 model has been chosen as the motor of the UAV system. Two different CAM Carbon Folding propellers with sizes of 12x8 and 13x8 respectively, both containing 4 blades have also been chosen to match this motor. The 12x8 propeller will operate below 3000 m level (ASL) whereas 13x8 is considered for altitudes above that level. Since Ankara is at about 1000 m altitude (MSL) and the flight test data is obtained at this altitude, propulsion system model stated in this paper is investigated with the 12x8 size propeller.

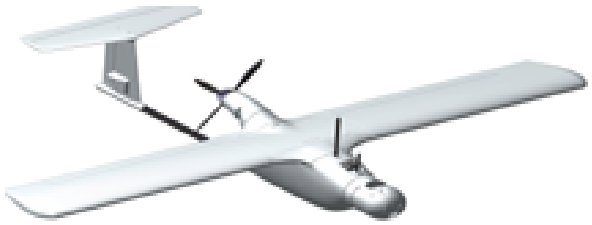

Figure 1 – MUAS-2

II. PROPULSION SYSTEM MODEL

Propulsion system model is prepared using the combination of flight test data with the theoretical results obtained from the commercially available software “MotoCalc”. Phoenix Ice Lite 100 Engine Speed Controller unit (ESC), has the capability to record several parameters during the flight such as: the Throttle PWM, Power Output, Power Input, RPM, Current, internal temperature of the ESC etc.

During the flight tests, data is collected at a rate of 5 Hz and *Figure 2* shows a typical graphical representation of the recorded data during a typical flight. In this figure, Throttle PWM, Power Input, Current and RPM values are shown with different colors. Since the ESC is powered on before the flight, beginning of the figure is smooth. After the flight starts, the parameters chosen to be recorded are shown on the graph.

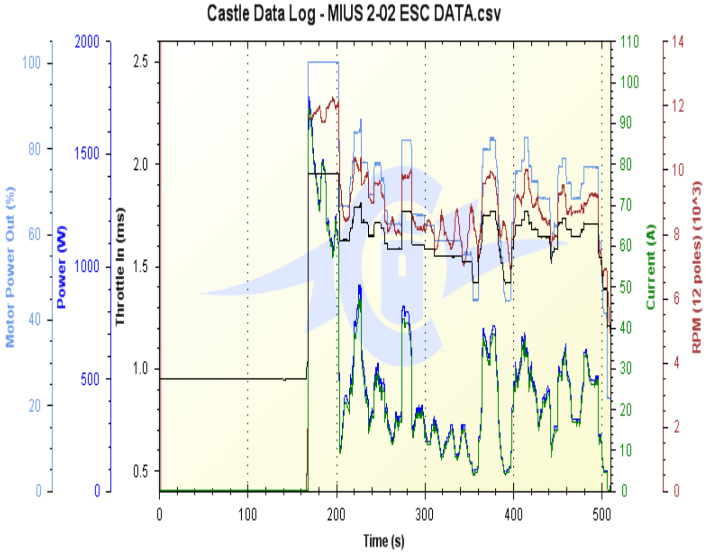

Figure 2 – Recorded ESC Data

Propulsion System Model includes 2 subsystem models:

- Propeller Model
- Electric Motor Model:
    i. Polynomial Based Motor Model (PBMM)
    ii. Krause's Motor Model

Since the input and output power of the electronic speed controller (ESC) is recorded and the losses in the ESC change with the level of current which is also related to the throttle level and the airspeed of the UAV due to the dynamic loading acting on the motor shaft, it is not modeled separately. However, the power output of the ESC is included in the PBMM as a polynomial where throttle is the input. For the Krause's motor model, which is also investigated in this paper to compare the results of the

PBMM, losses in the ESC are included in the efficiency look-up table since the ESC is used during the experiments done by the manufacturer.

A. Propeller Model

While a propeller is a physically simple device, its performance characteristics are complex. Power coefficient, thrust coefficient, propeller moment and propeller thrust are the main performance characteristics [2]. Propeller moment and propeller thrust are the outputs of the propeller model. Therefore, thrust and power coefficients (Ct and Cp) should be determined accurately to have a realistic dynamic model. Hence, look up tables are generated according to the results obtained from the analysis run in MotoCalc. Ct and Cp values are calculated according to the following equations:

$$C_t = \frac{T\pi^2}{4R^4(\frac{2\pi\omega}{60})^2\rho}$$

$$C_p = \frac{P\pi^3}{4R^5(\frac{2\pi\omega}{60})^3\rho}$$

In these equations:

T = Thrust (kg)
P = Power (Watt)
ρ = Density of air (kg/m^3)
ω = Rotational Velocity (rpm)

For different level flight altitudes and airspeeds C_t and C_p are calculated. Then, according to the calculated values, look up tables are formed in Matlab-SIMULINK. Following figure shows the SIMULINK propeller model.

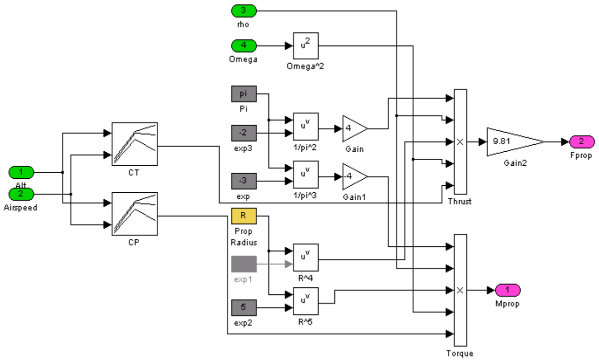

Figure 3 – Propeller Model

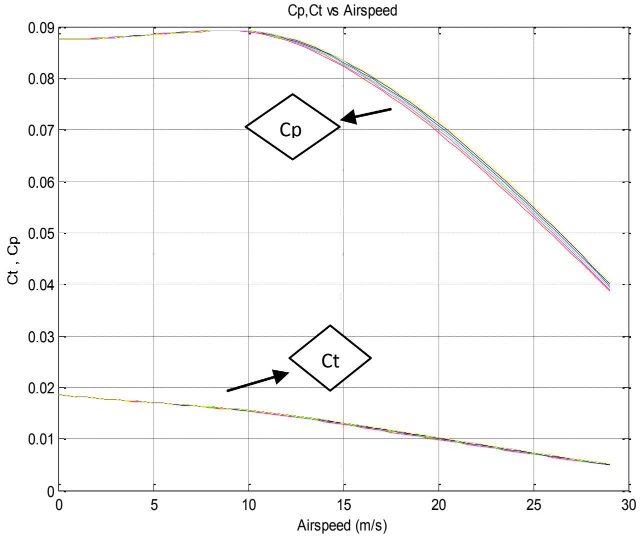

Figure 4 – Ct and Cp vs Airspeed

B. Electric Motor Model

Electric motor model of the MUAS-2 system is developed using Polynomial Based Motor Model (PBMM) which requires only flight data which can be recorded on the ESC and the MotoCalc software results. Also, to compare the results of the PBMM, Krause's motor model, which requires some parameters provided by the manufacturer and test results of the motor, is additionally investigated in this paper.

i. *Polynomial Based Motor Model (PBMM)*

Efficiency is a very important parameter in modeling the performance of an electric motor. Airspeed and the throttle level are the two parameters that cause the main changes in the efficiency of the motor. Therefore, efficiency of the motor is the main consideration of this model.

The output of the electric motor model is the torque of the shaft which drives the propeller. Hence, the shaft efficiency of the motor should be modeled accurately. To have an accurate model for the electric motor, flight test data and the dynamic (in-flight) analysis results are combined. A SIMULINK model of the motor is obtained as shown in *Figure 5*.

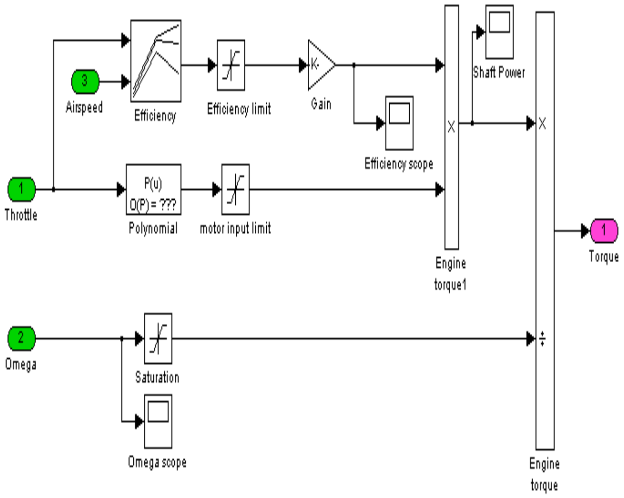

Figure 5 – Electric Motor Model

The input power of the motor is the data obtained from the ESC which is the power output. As can be seen in *Figure 4,* the "Shaft Power" of the electric motor is obtained by multiplying the Power Output with the efficiency of the motor. Since the RPM data can be obtained using ESC log data, torque of the shaft to drive the propeller is determined from the model as:

$$\textbf{Shaft Power} \qquad P_s = P_e * e_s \qquad (1)$$

$$\textbf{Torque} \qquad T = P_s/\omega \qquad (2)$$

Where:

P_s: is the shaft power
P_e: is the engine power
ω: is the rotational speed of the engine

To model the electric power that is transferred to the electric motor, throttle PWM signal recorded on the ESC is used as an input and it is scaled to between 0 and 100. The Curve Fitting Tool in MATLAB (cftool) is used to fit the data with a cubic polynomial as shown in *Figure 6.*

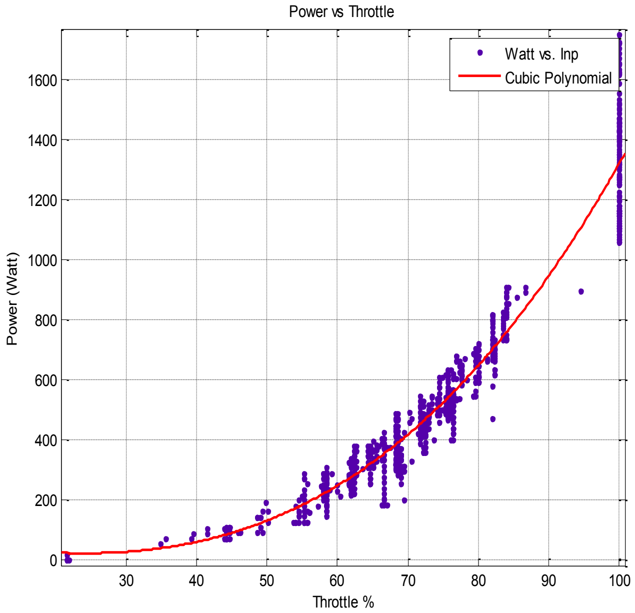

Figure 6 – Power vs Throttle

Third_order_fit = Linear model Poly3:
Third_order_fit (x) = p1*x^3 + p2*x^2 + p3*x + p4
Coefficients (with 95% confidence bounds):
p1 = 0.001254 (0.0007881, 0.001719)
p2 = 0.04039 (-0.05421, 0.135)
p3 = -4.18 (-10.33, 1.97)
p4 = 83.18 (-46.06, 212.4)

As mentioned earlier, there is a huge difference between the electric power transferred to the electric motor and the output power of the electric motor which is in fact the shaft power. Therefore, the efficiency look-up table which is dependent on the airspeed and the throttle level is created in MATLAB using the results of the analysis run in MotoCalc software. Furthermore, the shaft power is calculated using the efficiency as mentioned in eq (1). However, the efficiency values are not available for low throttle settings and high airspeed values since the analysis were only done for level flight conditions. So, linear extrapolation technique is used to complete the look-up table. *Figure 7* shows the graphical representation of the efficiency values. Finally, the torque of the electric motor is calculated and added to the model using the formula given in eq. (2).

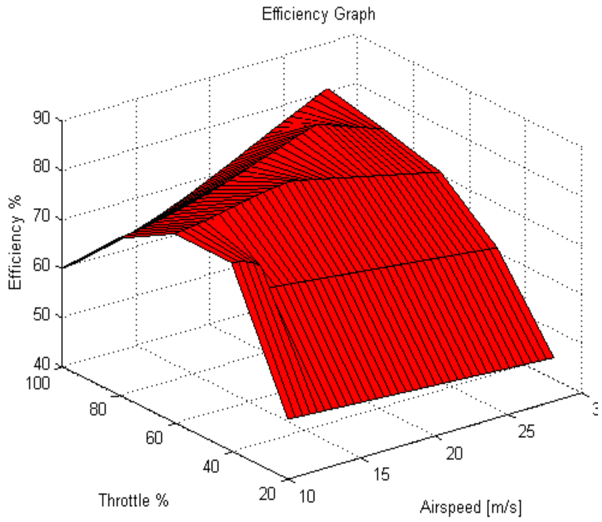

Figure 7 – Efficiency Graph

ii. Krause's Motor Model

Since the manufacturer of the electric motor supplied limited data, Roerig's and Krause's motor model is thought as suitable to simulate the motor. According to Joel Yourkowski's thesis, Roerig's model and a "simplified" model given by Krause were evaluated and Krause's model proved more accurate than Roerig's [3]. Therefore, Krause's model is chosen as an alternative motor model for our system model. However, some modifications are needed because of the test conditions and data obtained from the motor manufacturer. Main assumptions and the approximations used in the model are emphasized below:

- Empirical efficiency matrix is used to account for various losses in the motor [3].
- The efficiency of the ESC used by the manufacturer is thought as the same with the one used in MUAS-2 system.
- The rotor reference frame voltage and the current are approximated as:

$$V_{dc} = \frac{\pi}{2} V_{qs}^{r}$$

$$I_{dc} = \frac{3}{\pi} I_{qs}^{r}$$

Where:

$\boldsymbol{V_{dc}}$: DC voltage (V)
$\boldsymbol{I_{dc}}$: DC current (Amp)
$\boldsymbol{V_{qs}^{r}}$: Reference frame voltage (V)
$\boldsymbol{I_{qs}^{r}}$: Reference frame current (Amp)

- Losses due to the armature windings are included in both efficiency matrix and motor model. Therefore, it is externally added into the model as an equivalent torque [3]. The equivalent torque value is approximated as:

$$T_{cu} = \frac{P}{2} \left(\frac{\frac{3}{2} V_{dc}^{2} r_{a}}{\omega_{r}} \right)$$

Where:

T_{cu}: Equivalent torque due to the copper losses (Nm)
P: Number of poles of the motor
ω_r: Rotational speed of the motor (rad/s)
r_a: Winding resistance of the motor (ohm)
V_{dc}: DC voltage input (V)

- The input voltage of the motor is constant over the time.

In *Figure 8,* simplified Krause's Motor Model is shown.

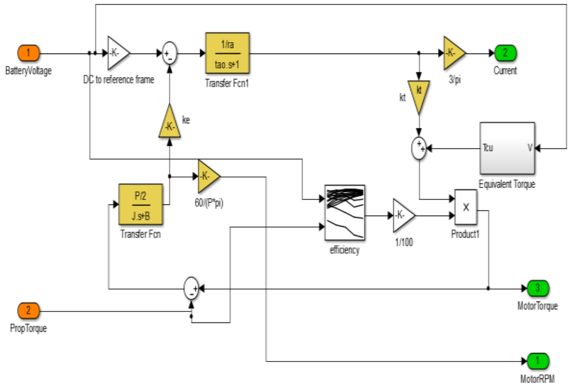

Figure 8 – Simplified Krause's Motor Model

The manufacturer of the motor (AXI 4120/14) provides the following data which are used in the SIMULINK model shown in *Figure 7.*

	Value	***Unit***
Torque Constant, k_t	0.015	N.m/A
Winding Resistance, r_a	0.041	ohm
# of magnetic poles, P	14	-
Rotor inertia, J	5.1x10^{-5}	kg.m^2

Table 1 – Motor data provided by the manufacturer

Also, for different voltage levels, rpm, efficiency, current, power input and power output versus torque graphs are provided by the manufacturer. For 18 V input voltage, the graph shown in *Figure 9* can be seen as an example. The efficiency matrix used in the SIMULINK model is tabulated using the input voltages (10V, 12V … 18V), applied torques and the corresponding efficiencies. It is also shown in *Figure 10* as an efficiency graph of the electric motor.

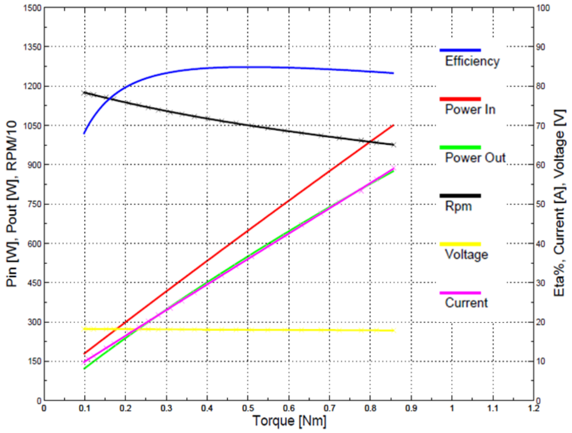

Figure 9 – Test data provided by the manufacturer

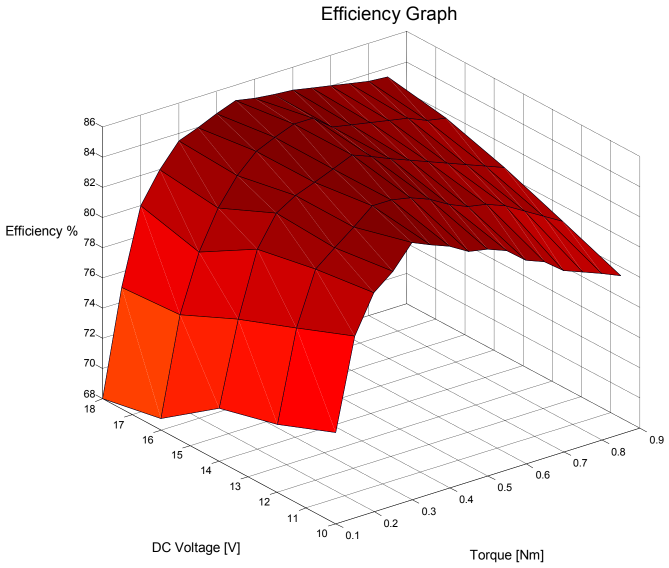

Figure 10 – Efficiency graph of the motor

To compare the simulation results, the same inputs are used as in the data provided by the manufacturer which are the applied voltage and the load torque. To compare the results, *Table 2 and Table 3* are prepared.

		Test Results	**Model Results**	
Voltage (V)	**Torque (Nm)**	**Current (Amp)**	**Current (Amp)**	**Difference %**
12	0.2	15	14.12	5.33
12	0.5	35	34.35	1.86
12	0.8	54.5	57.34	5.21
14	0.2	15.5	14.25	8.06
14	0.5	35	34.04	2.74
14	0.8	54.5	56.46	0.07
16	0.2	15.75	14.65	6.98
16	0.5	35.6	33.85	4.92
16	0.8	54.6	55.78	2.16
18	0.2	16.5	14.47	12.3
18	0.5	35.8	34.14	4.64
18	0.8	55.35	55.45	0.18

Table 2 – Comparison of the current results

		Test Results	**Model Results**	
Voltage (V)	**Torque (Nm)**	**RPM**	**RPM**	**Difference %**
12	0.2	7495	7593	1.31
12	0.5	6750	6656	1.39
12	0.8	6300	5590	11.27
14	0.2	8617	8962	4.00
14	0.5	7950	8044	1.18
14	0.8	7300	7005	4.01
16	0.2	10075	10318	2.41
16	0.5	9300	9428	1.38
16	0.8	8550	8411	1.63
18	0.2	11362	11701	2.98
18	0.5	10575	10789	2.02
18	0.8	9863	9801	0.63

Table 3 – Comparison of the rpm results

The average differences for the current values are 4.54% and 2.85% for the rpm values. Also, the maximum differences are 12.3% for the current values and 11.27% for the rpm values. Experimental errors, reading errors and the approximations made in the model are the main reasons of these differences.

III. CONCLUSION

The comparison of the simulation results described in this paper and the commercially available software (MotoCalc) results are tabulated in *Table 4.* Since the Krause's model is compared with the test results in *Table 2 and Table 3,* PBMM and MotoCalc results are compared with the Krause's motor model for different airspeeds which are the possible cruise speeds that the aircraft can be trimmed at.

				PBMM-Krause	MotoCalc-Krause
	Throttle %			Difference %	Difference %
Airspeed (m/s)	Krause	PBMM	MotoCalc		
17	39.58	40.75	56	2.96	41.49
19	45.36	46.51	62	2.54	36.68
21	52.14	53.27	68	2.17	30.42
23	60.04	61.14	75	1.83	24.92
25	69.29	70.36	82	1.54	18.34

Table 4 – Comparison of the throttle levels at varying airspeeds

As can be seen in *Table 4,* the results obtained using the PBMM are very close to the simulation results obtained using the Krause's motor model. However, there are large differences between the Krause's model and the MotoCalc. Finally, to record the throttle levels while the aircraft flies at level, RC (Remote Controlled) flight test is organized. In *Figure 11,* recorded flight data during the flight test can be seen and it can be summarized for the level flight as follows:

Altitude ***: ~1183 m.***
Airspeed ***: ~21 m/s***
Throttle Level ***: ~54.95 %***

The propulsion system model which consists of the *Propeller Model* and the *Polynomial Based Motor Model* described in this paper can be used to design an autopilot for the MUAS-2 and it is observed that for the level flight conditions, there is only 3% difference in the throttle level between the simulation results and the flight test data while the results of the software analysis without the combination of the flight test data gives up to 30% difference. This accuracy is good enough to design and tune the propulsion related loops of the autopilot algorithms without the need of any complex tests and long time periods.

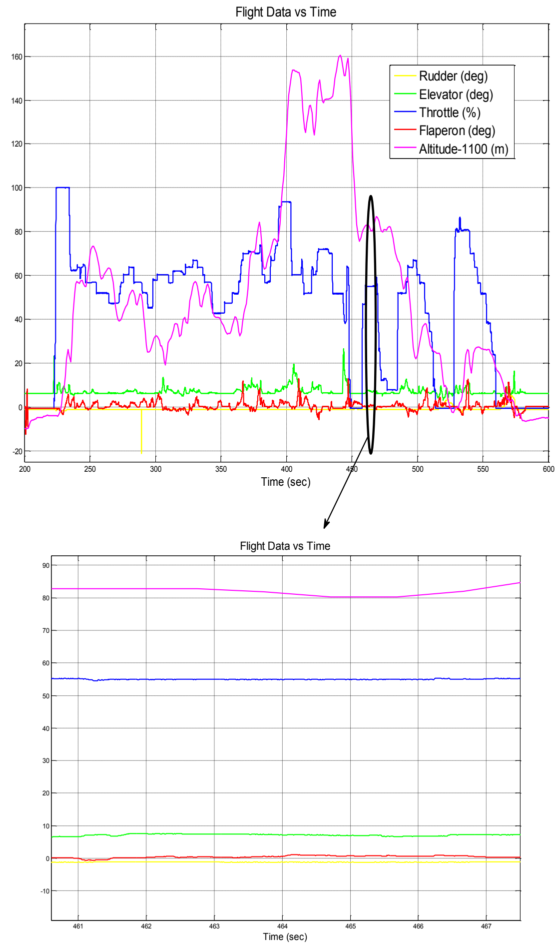

Figure 11 – Recorded flight data

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