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ENERGY AND EXERGY ANALYSIS OF UNMANNED AERIAL VEHICLE ASSIGNED SURVEILLANCE AND RECONNAISSANCE MISSION

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ABSTRACT

Unmanned Aerial Vehicle (UAV) is a creating innovation with a massive potential to change military operations and to empower new civilian applications. The dramatically interest for unmanned systems is generally determined by applications that are dull, dirty and dangerous. The role of surveillance has proven to be important and applicable to a wide range of applications such as target location, map building, border security, pollution monitoring and control, and battle damage assessment. UAVs fit into the scenario of autonomous surveillance perfectly as they involve a low risk factor and facilitate technological advancements, making their use feasible in real world scenarios.

In this paper, we present a surveillance and reconnaissance mission based scenario. Related about the scenario, four different types of UAV assigned for the mission and routes are calculated by TSP (Travelling Salesman Problem) algorithm. Then for each UAV, consuming different type of fuel, energy and exergy analyses were applied. Energy efficiency, exergy efficiency and sustainability index values are calculated. There are a lot of factors must be counted in UAV-Mission Matching/Planning. For that reason, in this paper, we present a new criteria for UAV-Mission Matching/Planning. The results showed that the maximum energy and exergy efficiencies were calculated for UAV W. It burns JP-8 and the results were 91.8% and 93.7%. The maximum sustainability index was found also for UAV W as 15.78. According to the cost figures, the best performance was observed for UAV Y with 5.7 $.

INTRODUCTION

Over the past decade, the quantities and types of Unmanned Aerial Vehicles (UAV) have grown immensely and they promise new ways for both civilian and military applications. Nowadays, the US portfolio over the dimension, application diversity, technological complexity and maintainability costs have reached up to the traditional manned systems Technologies[1].

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During complex mission environments, multiple systems across several platforms such as the air, ground or maritime domains must collaborate and interoperate to effectively perform and fulfil mission tasks. Hence, we project that integration of manned aircraft systems with UAV have the capability to give rise to many research fields, expand the application diversity and fulfil critical missions effectively [2].

Unmanned Aerial Vehicles (UAVs) have seen unprecedented levels of growth in military and civilian application domains. Fixed-wing aircraft, heavier or lighter than air, rotary-wing (rotorcraft, helicopters), vertical take-off and landing (VTOL) unmanned vehicles are being increasingly used in military and civilian domains for surveillance, reconnaissance, mapping, cartography, border patrol, inspection, homeland security, search and rescue, fire detection, agricultural imaging, traffic monitoring, to name just a few application domains [3]. UAV is a creating innovation with a massive potential to change military operations and to empower new civilian applications. The dramatical interest for unmanned systems is generally determined by applications that are dull, dirty and dangerous[4].

UAVs, on the other hand, are often used in intelligence-gathering, surveillance and reconnaissance (ISR) roles, where there is no a priori knowledge of the existence or nature of targets. Given our lack of knowledge regarding the potential diversity, nature and location of any targets that might ‘pop up’ it is also unlikely that we will have a good understanding of the surroundings and hence the potential effect of weapons on non-combatants and infrastructure, except in specific circumstances (e.g. uncluttered environments such as air-air or underwater engagements)[5].

The role of surveillance and reconnaissance have proven to be important and applicable to a wide range of applications such as target location, map building, border security, pollution monitoring and control, and battle damage assessment. UAVs fit into the scenario of autonomous surveillance perfectly as they involve a low risk factor and facilitate technological advancements, making their use feasible in real world scenarios[3].

MISSION ASSIGMENT PROBLEM

In the past few decades in particular, however, there has been an explosion in the miniaturization, maturation, diversity and commercial availability of components and systems engineering techniques required to successfully automate an UAV. To date these advances have come largely in the areas of communications, sensing, signal processing, data and information fusion, systems engineering and integration, launch and recovery, human factors, platform, aero/hydro-dynamics, mobility, collision avoidance, mission planning and re-planning, propulsion, size, and energy storage. However, more recent advances now offer the prospect of levels of autonomy and functionality which for the first time could bring about agile, versatile, persistent, reliable and lethal autonomy with levels of robustness and survivability that could cope with some of the rigours of modern warfare.

Mission Assignment is the process of generating a trajectory or sequence of actions from a specified starting point to a goal position or activity while avoiding obstacles and impediments. In this paper, mission assignment problem with five specific targets is formulated and solved as traveling salesman problem (TSP). For TSP it is necessary to choose a sequence of targets to fly over the target so as to accomplish a specified objective. The mission assignment problem consists of determining an optimal path for each target point to accomplish the goals of the mission in the minimum possible time On general, TSP is a network problem that given a network and a distance associated with each arc, it is necessary to start from a specified originating or depot target, visit each and every other target exactly one, and return to the starting target in the least time manner [6].

Surveillance and reconnaissance mission based scenario is prepared according the target shown in Table 1.

	Target 1	**Target 2**	**Target 3**	**Target 4**	**Target 5**
Target 1	0	16	22	43	24
Target 2	16	0	30	45	31
Target 3	22	30	0	47	52
Target 4	43	45	47	0	14
Target 5	24	31	52	14	0

Table 1*:* Target Distance (in NM)

From the solution, the assignment is: 3 – 1 – 2 – 5 – 4 with the solution of minimum total distance 83 NM.

As explained above, TSP generally focused on time manner. In this paper it is also analyzed energy consuming and obtained exergy analysis for UAVs. For this mission based scenario, it is chosen four different type of UAV detailed in Table 2.

UAV	Fuel Type	Fuel Consumption (lt/hrs)	Total Distance (in NM)	Mission Speed (knots)	Engine Power (kW)	Flight Duration (min.)
X	Avgas 100LL	10,6	83	70	86	71
Y	Jet A-1	4,5	83	65	36	76
Z	100/130 0ctane Fuel	14	83	90	42	55
W	JP-8	12,6	83	125	110	40

Table 2. Flight Characteristics.

ENERGY AND COST ANALYSIS

Gas turbine engines which are commonly used for aircraft propulsion, convert the chemical energy of fuel into thermal energy that is used to run the turbine. According to the first law of thermodynamics, the difference between inlet and outlet energy rate flows of engine can be explained by the heat gain from the fuel.

$$\dot{\boldsymbol{Q}} = \Delta\dot{\boldsymbol{E}} \tag{1}$$

In the energy analysis, the fuel consumed in the UAV engine is taken into consideration.

$$\dot{\boldsymbol{E}}_{\boldsymbol{j}} = \dot{\boldsymbol{m}}_{\boldsymbol{j}}.\boldsymbol{LHV}_{\boldsymbol{j}} \tag{2}$$

Here $\dot{\boldsymbol{E}}_{\boldsymbol{j}}$, $\dot{\boldsymbol{m}}_{\boldsymbol{j}}$ and $\boldsymbol{LHV}_{\boldsymbol{j}}$ stand for the energy rate obtained by the combustion in the engine of j^{th} UAV, mass flow rate of the fuel for j^{th} UAV and heating value of fuel for j^{th} UAV. Energy use during the missions are compared and analyzed for possible improvements. Energy sources in air vehicles with gas turbine or piston engines are fossil fuels. Because of the quick reduction in fossil fuel reserves, low fuel consumption, thus energy use, is a must in all energy sectors (transportation, industry etc.) It is assumed that the lower heating value of a fuel was transferred as the required energy to the UAV and used to complete the mission.

The engine power ($\dot{\boldsymbol{W}}$) of each UAV is considered as the work rate obtained from the engine. The energy efficiency for each UAV can be found by using the following formula.

$$\boldsymbol{\eta}_{\boldsymbol{j}} = \frac{\dot{\boldsymbol{W}}_{\boldsymbol{j}}}{\dot{\boldsymbol{E}}_{\boldsymbol{j}}} \tag{3}$$

Fuel energy is obtained by converting the chemical energy in fuel to the heat energy. Low energy use results with low fuel consumption, thus low costs. The energy analysis findings are presented in Table 3.

UAV	Fuel Type	LHV (MJ/kg)	Combustion Energy Rate (kW)	Energy Efficiency (-)
X	Avgas 100LL	44.2	104.116	0.826
Y	Jet A-1	43.2	43.2	0.833
Z	100/130 0ctane Fuel	43.5	135.333	0.310
W	JP-8	42.8	119.84	0.918

Table 3. Calculated energy results.

The cost rate of a flight by an UAV is calculated as,

$$\dot{\boldsymbol{C}}_{\boldsymbol{j}} = \boldsymbol{c}_{\boldsymbol{j}}.\dot{\boldsymbol{m}}_{\boldsymbol{j}} \tag{4}$$

Similarly the cost of a flight by an UAV,

$$\boldsymbol{C}_{\boldsymbol{j}} = \boldsymbol{c}_{\boldsymbol{j}}.\boldsymbol{m}_{\boldsymbol{j}}.\boldsymbol{t}_{\boldsymbol{j}} \tag{5}$$

where $\dot{C}_j$, c_j, C_j and t_j represent flight cost rate for j[th] UAV, unit cost of fuel, flight cost for j[th] UAV and flight duration of j[th] UAV, respectively. Calculated cost figures for the UAV types are presented in Table 4.

UAV	Fuel Type	Fuel Cost ($/lt)	Flight Cost Rate ($/hr)	Flight Cost ($)
X	Avgas 100LL	1.32	13.99	16.56
Y	Jet A-1	1	4.5	5.7
Z	100/130 0ctane Fuel	1.95	27.3	25.03
W	JP-8	0.71	8.95	5.96

Table 4. Calculated cost figures for the UAV types
(fuel costs are taken from www.airnav.com [7])

EXERGY ANALYSIS

Exergy is defined as the maximum work potential that can be obtained from a system. The exergy rate which can be obtained from a fuel can be explained by chemical exergy portion. Exergy input of a fuel can be found as,

$$\dot{Ex}_j = \dot{m}_j . \varepsilon_j \tag{6}$$

where $\dot{Ex}_j$ is the exergy of fuel for j[th] UAV and ε_j is the specific exergy of the fuel for j[th] UAV. Specific exergy of a fuel is calculated as follows,

$$\varepsilon_j = LHV_j . \varphi_j \tag{7}$$

where φ_j is the chemical exergy factor of the fuel for j[th] UAV. When carrying out the calculations the chemical exergy factors are assumed as 0.98 for the fuels [8].

Exergy efficiency is the true measure of the performance of a thermodynamic system. The rational efficiency, defined as the ratio of useful or desired work obtained from the system to the total quantity of incoming exergy. The incoming exergy is assumed as the chemical exergy of the fuel [9].

Exergy term expresses the quality of the energy. It does not include the portion that results with entropy generation. Thus, the exergy efficiency of each UAV is obtained as follows [10],

$$\psi_j = \frac{\dot{W}_j}{\dot{Ex}_j} \tag{8}$$

The ratio between the power of the engine and the chemical exergy of the fuel will give the true value of the efficiency. Sustainability index (SI), is an expression which aims the supply of clean and affordable clean energy resources to be used in thermodynamic systems [11]. It is defined as,

$$\psi = 1 - \frac{1}{SI} \tag{9}$$

The findings obtained by using exergy analysis are shown in Table 5.

UAV	Fuel Type	Combustion Exergy Rate (kW)	Exergy Efficiency (-)	Sustainability Index (-)
X	Avgas 100LL	102.033	0.843	6.364
Y	Jet A-1	42.336	0.850	6.682
Z	100/130 0ctane Fuel	132.627	0.317	1.463
W	JP-8	117.443	0.937	15.779

Table 5. Calculated exergy results.

CONCLUSION

Considerably, there are a lot of inputs for UAV ISR Mission especially on UAV-Mission Matching/Planning issue. In literature authors and papers are generally focused on some main domains like payload, terrain and obstacle characteristics, autonomous algorithms etc. Yet endurance for UAV vital point for mission effectiveness and it directly depends on fuel consumption. Therefore while taking account the fuel consumption, energy and exergy analysis plays crucial role.

Having said that, in this paper, we present a surveillance and reconnaissance mission based scenario. Related about the scenario, four different types of UAV assigned for the mission and routes are calculated by TSP (Travelling Salesman Problem) algorithm. Then for each UAV, consuming different type of fuel, energy and exergy analyses were applied. Energy efficiency, exergy efficiency and sustainability index values are calculated.

The calculated energy efficiencies, exergy efficiencies and sustainability indices are compared to evaluate the performances of each UAV. The results of energy analysis show that UAV W is the one that has the best performance among the four UAVs. The energy efficiency of UAV W which burns JP-8 is found to be 91.79%. The minimum energy efficiency was calculated for UAV Z. It is 31% and it uses 100/130 Octane Fuel.

To obtain cost figures, fuel costs, flight durations and fuel consumptions were taken into consideration. To complete the mission, the maximum flight cost was calculated for UAV Z. It is approximately 25 $. Because it burns the fuel which has the maximum fuel cost. The cheapest flight belongs to UAV Y which burns Jet-A-1. It took 5.7 $ to complete the mission.

According to the exergy efficiencies, UAV W has the lowest exergy destruction. As a result it has the highest sustainability index. The exergy efficiency and sustainability index for UAV W were found to be 93.66% and 15.78, respectively. The minimum exergy efficiency and sustainability index value belong to UAV Z. They were calculated as 31.7% and 1.46. This means that it is not energy and cost effective to use 100/130 Octane Fuel using UAV engine to do the mission.

When performing an UAV mission with different fuels and engine types, the exergy efficiency and sustainability index values can give the researcher the opportunity to decide the most energy and money saving option. Thus low fossil fuel consumption will yield low carbon emission and more clean environment. As a future study, we plan to analyze the environmental effects of completing such a mission.

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