Decision-Support Tool for Designing Small Package Delivery Aerial Vehicles (DST-SPDAV)

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***Abstract* - A growing market is the application of multi-rotor vehicles to niche delivery services such as just-in-time spare parts delivery, real-time asset repositioning, rapid food delivery, and remote medical supply delivery. These services are unique in their requirements, meaning there is no single aerial vehicle configuration that is optimal for every scenario. More importantly, these service providers do not have the expertise to design and operate small multi-rotor vehicles that are now feasible due to advances in technology. This is a complex design decision with non-linearities in the design-state-space. This paper presents a decision-support tool to assist small package delivery service providers in configuring the best multi-rotor vehicle for their payload application.**

**   The decision-support tool for the design of multi-rotor small package delivery aerial vehicles (SPDAV) takes inputs such as payload, wind, maximum dimension data, price range, and flight profile, and recommends suitable configurations. The algorithm used to generate the design-state-space consists of two separate models of multi-rotor aircraft: (1) a power consumption model and (2) a full dynamic flight model. The power consumption model evaluates the steady-state performance of the battery, motor, and propeller combinations at hover, 80%, and full throttle to determine systems that satisfy the users' requirements. A dynamic flight model is then applied to these configurations to further account for airframe aerodynamics. A detailed example of the tool for a college campus fast food restaurant is provided.**

Index Terms – Aerodynamics, Dynamic-Model, Multi-Rotor, Power Model, Quadcopter, Tradespace, UAS ,UAV

CONTEXT

I. Multi-Rotor Aerial Vehicles

Modern day advances in batteries, microcontrollers, and lightweight materials have led the unmanned multi-rotor aerial vehicles market away from being hobbyists toys to now mass produced aircraft with commercial applications. Multi-rotors, for the sake of this paper, are rotorcraft with more than two propellers that do not have varying pitch and are capable of vertical takeoff and landing. This allows for easier flight control because movement is achieved by simply deviating the power to propellers, making

programmable flight control a viable capability. The reliability and maintainability is also superior to traditional rotorcraft due to the simpler rotor mechanics from less required moving parts. Multi-rotors are relatively small, with size ranging from one to ten feet tip-to-tip, making them more responsive and easier to change direction. Most importantly, multi-rotors are commercially off the shelf available with a wide variety in custom and pre-built configurations.

A multi-rotor configuration is defined as follows:

- A frame measured in mm from the Center of Gravity to the end of the frame
- Propellers defined diameter (mm) and pitch (N)
- Motors defined by weight and power
- Battery defined by weight and capacity (mAh).

The total vehicle weight is the sum of the weight of all the components. As the vehicle weight increases, the torque required from the rotors increases. As the rotor torque increases, it draws more current, requiring a larger battery. This non-linear interaction is the cause of the design complexity.

II. Small Package Delivery

Large companies such as Amazon, Google, DHL, and Dominos have recognized the capability of the multi-rotor aerial vehicles and have invested in straight-forward package delivery. With their financial and intellectual resources these companies are positioned to leverage this technology.

In addition to package delivery, there exist many other niche delivery services such as just-in-time spare parts delivery, real-time asset repositioning, rapid food delivery, and remote medical supply delivery. These services are unique in their requirements, meaning there is no single aerial vehicle configuration that is optimal for every application. More importantly, these service providers do not have the in-house expertise or financial resources to design and operate small multi-rotor vehicles.

III. Design Engineering Difficulties

Despite having a small set of simple components, the challenge for designing multi-rotors is due to the large amount of possible configurations and the non-linear interactions in the design-space. . Choosing a configuration that meets a set of requirements optimally is not possible without expertise or a decision-support tool. For example,

while evaluating the total payload, one must ensure there is enough power to handle the increased weight. This will then require a battery that is capable of keeping up with the increased need for power. In order to support this larger battery, an adequate frame will be needed. With this now overall increase in total weight one will need more power, and the cycle continues.

IV. Problem Statement

The advances in multi-rotor aerial vehicle technologies have enabled applications for small package delivery. Unlike the large logistics companies with financial and intellectual resources to design and operate these vehicles from a complex and non-linear design-space, enterprises with niche applications (e.g. asset repositioning, spare parts delivery, rapid food or flower delivery) do not have the expertise to design the optimum vehicle to meet the requirements of their application.

STAKEHOLDER ANALYSIS

I. Primary Stakeholders

The primary stakeholders of the DST are the user of the multi-rotor vehicles, the manufacturers of multi-rotors and multi-rotor components, and providers of the niche application. The objective of the end users is to communicate their set of requirements, and then receive a recommendation of which multi-rotor configuration suits them best. Multi-rotor manufacturer's main objective is to maximize their profits from sales of configurations as well as their individual parts. The providers of the niche application aim to build a reliable multi-rotor aerial vehicle with the proper mission suitability for their niche package delivery application.

II. Secondary/Tertiary Stakeholders

The secondary stakeholders of the system are citizens and low altitude air traffic. Both share the same objective of having a safe living environment, however, the citizens want to have the availability of niche small package delivery services. The FAA (Federal Aviation Administration) is considered to be a tertiary stakeholder. Their main objective is to ensure efficient transportation in the increasing density of the National Airspace System (NAS) while maintaining a high level of safety.

III. Win-Win Interaction

The DST can enable the end users to select the right multi-rotor configuration, which reflects on the end user decision regarding the purchase of more accurate parts from the manufacturers. The high expectation of the end user pushes the manufacturers to increase reliability, performance, and maintainability of parts and provide the best multi-rotor configurations. As a result, citizens and low altitude air traffic would maintain a safer environment, and the FAA would be more likely to deliver new regulations that are favorable to the end users, manufacturers, and DST.

REQUIREMENTS FOR THE DST

The DST shall recommend pre-existing configurations of the multi-rotor aircraft that will be able to carry a user-defined payload for a certain distance over a default flight profile. Moreover, the DST shall recommend pre-existing configuration of multi-rotor aircraft that are reliable, operate at a high performance, and are with the end users' budget. Figure 1 shows a block diagram that illustrates the entire functionality of the DST.
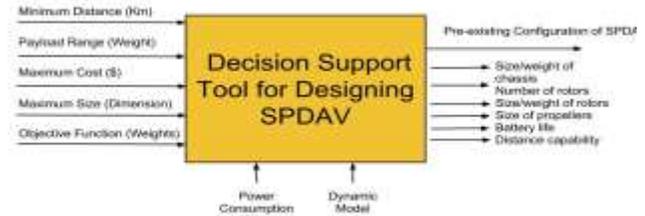

FIGURE 1
INPUTS AND OUTPUTS OF THE DST

IMPLEMENTATION OF THE DST

I. DST Overview

The DST is conducted in two stages – first a power model to identify promising multi-rotor configurations and then a full dynamic model to further characterize the specific performance of these pre-existing configurations.

For the power model, the user defines the distance to travel, payload weight, maximum size, and price range. These factors are then put through a simulation to approximate the power draw, motor temperature, hover characteristics, and flight duration under normal loads. This portion of the simulation is fed either currently manufactured multi-rotor configurations or samples permutations of motor, battery, and propeller combinations. Unreasonable configurations (hovering requires greater than 80% throttle, maximum cost or size exceeded, motor temperature at maximum throttle exceeding 80 degrees Celsius) are removed from further analysis.

The full dynamic model takes these viable configurations and subjects them to a more detailed simulation. The model simulates the multi-rotor's performance over a user defined flight path. Maximum flight distance for a given configuration is found by running the simulation multiple times and applying Newton's method to determine the distance corresponding to a battery drain from 80% to 10% to account for battery degradation and provide a cushion of performance safety. The simulation is conducted for a low wind environment which

is assumed to be 0 mph and package weights corresponding to user inputs.

2. Power Consumption Model

The power consumption model was made using a free body diagram. The free body diagram shows all the forces and angles acting on the vehicle component of the system while it moving. The free body diagram for a quad copter is illustrated in Figures 2.
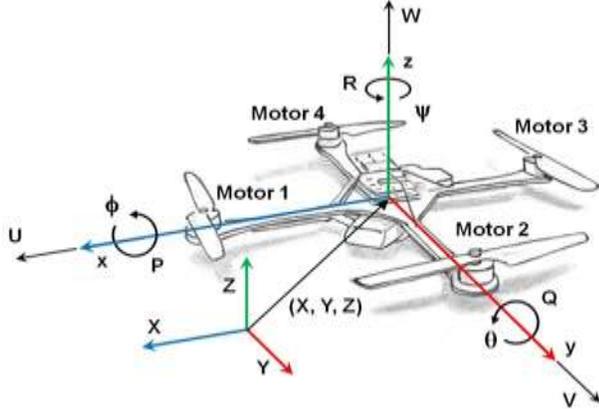

FIGURE 2
FREE BODY DIAGRAM OF QUAD COPTER

The equation used to calculate the hover velocity as a function of thrust using momentum theory is displayed in (1), and the thrust required for lift is calculated using (2)

$$V = \sqrt{\frac{T}{2\rho A}} \tag{1}$$

$$T = \left[\frac{\pi}{2}D^2\rho P^2\right] \tag{2}$$

3. Dynamic Model

The dynamic model consists of the following self-contained modules: Body Geometric and Inertial Calculations, Atmospheric Model, Gravitational Model, Electrical System Model, Motor Model, Battery Model, Throttle Curve Model, Aerodynamic Model, Propeller Model, Rotor Blade Motion, Momentum Theory, Blade Element Theory, and Blade Flapping.

Transformation maticies are used to represent translation and rotation in both coordinate systems. Motion in the body frame is transformed through $\psi - \theta - \phi$ rotations as shown in (3)(4)(5). Combining these transformations yeilds the direction cosine matrix H_B^I (6). For example, velocity measured in the body frame is transformed to the inertial frame as $v_I = H_B^I v_b$.

$$H_I^1(\psi) = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$H_1^2(\theta) = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \tag{4}$$

$$H_2^B(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \tag{5}$$

$$H_B^I(\phi,\theta,\psi) = H_1^I H_2^1 H_B^2 = \begin{bmatrix} \cos\theta\sin\psi & \sin\phi\sin\theta\cos\psi - \sin\psi\cos\phi & \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi \\ \cos\theta\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \cos\phi\sin\theta\cos\psi - \sin\phi\sin\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix} \tag{6}$$

A similar transformation (7) is performed for angular velocities and accelerations where p, q and r are rotational velocities around each translational axis (8).

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = I_{3x3}\begin{bmatrix} \dot\phi \\ 0 \\ 0 \end{bmatrix} + H_2^B\begin{bmatrix} 0 \\ \dot\theta \\ 0 \end{bmatrix} + H_2^B H_1^2\begin{bmatrix} 0 \\ 0 \\ \dot\psi \end{bmatrix} \tag{7}$$

$$L_B^I(\phi,\theta,\psi) = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \tag{8}$$

It should be noted that this transformation matrix yields singular results around $\theta = \frac{\pi}{2}$. The authors deem this limitation acceptable as small package delivery does not typically encounter such aggressive flight maneuvers. Should such maneuvers be desired, a switch to a quaternion representation could be implemented.

Finally, a geodetic axis is used to more accurately approximate local gravity conditions. Transformations are approximated using the WGS84 standard using the following formula (9).

$$x = (N+h)\cos\phi'\cos\lambda' \quad , \quad y = (N+h)\cos\phi'\sin\lambda'$$
$$z = \left(\left(\frac{b^2}{a^2}\right)N + h\right)\sin\phi' \quad \text{where } N = \frac{a}{\sqrt{1-e^2\sin^2\phi}} \tag{9}$$

4. Utility Model

The utility model takes into account the weights obtained from the user with a survey using a Likert scale, the average distance and velocity and the multi-rotor size. It also takes into account the Mean Time between Failure (MTBF) which is associated with motors. Below is the equation used to calculate the utility for all pre-existing configuration.

$$Utility = w1*(Avg\ Dist) + w2*(Avg\ Veloc) + w3*(Size) + w4*(MTBF) \tag{10}$$

Validation of DST-SPDAV

The power consumption model was validated by static performance values of a single rotor. The multi-rotor used in the DST is a Hacker A30-10XL V3, 50A ESC, 4S2P 10000

mAh. The table below shows the result of the experiment comparing three different propellers: 13x6" APC, 11x6" APC, and 11x6" Master Airscrew.

TABLE 1
THRUST AND POWER ANALYSIS DATA

13x6 APC

RPM	Experimental Value	Experimental Value	Calculated Value	% Error	Calculated Value	% Error
4000	540	77	533.2	1.3%	78.74797806	2%
5000	870	139	880.1	1.1%	149.7541499	8%
6000	1300	240	1278.2	1.7%	251.9577462	5%
7000	1780	345	1732.8	2.7%	368.9757116	7%
8000	2300	500	2237.7	2.7%	535.4084598	7%

11x6 APC

RPM	Experimental Value	Experimental Value	Calculated Value	% Error	Calculated Value	% Error
4000	350	49.3	340.6	2.7%	50.71154535	3%
5000	514	86.9	497.8	3.2%	93.96503289	8%
6000	738	140.5	716.0	3.0%	145.4464136	4%
7000	1000	197.9	950.1	5.3%	214.8534171	9%
8000	1330	299.8	1305.5	1.8%	311.6385688	4%

11x6 Master Airscrew

RPM	Experimental Value	Experimental Value	Calculated Value	% Error	Calculated Value	% Error
4000	326	45.152	318.4	2.9%	47.02786077	4%
5000	486	74.0775	481.6	0.9%	79.12783442	7%
6000	740	122.6159	732.7	1.0%	134.2580536	9%
7000	950	176.375	930.3	2.1%	182.4279857	3%
8000	1300	293.2058	1260.9	3.0%	307.7366684	5%

The thrust comparison showed very close similarities between the DST output and experimental values. In fact, the margin of error across the three types of propellers used was at most five percent. The power comparison, again, showed close similarities between the DST output and experimental values. The margin of error across the three types of propellers used was at most just under ten percent.

CASE STUDY : GMU FAST FOOD RESTAURANT

Different end users would present different requirements when making the decision of which multi-rotor air vehicle or configuration would meet their needs. Therefore, their requirements have to be specified in order for the decision support tool to present the best alternative. In this paper, the use case that is being evaluated is a Fast Food restaurant on George Mason University's campus. For this particular case, its requirements are as follows:

- A payload range between 1.0 Kg and 4.0 Kg.
- A minimum distance of 2.0 km (4.0 km round trip).
- A maximum cost of $20,000.
- A maximum width of 1700 mm (from tip to tip).
- The Fast Food restaurant filled a survey that uses a Likert Scale to get the weights for each value evaluated on the utility function.

The assumptions taken into account are that the multi-rotor will not fly above people; it would be autonomous, easily programmable and monitored from the ground. The flight path would also not traverse areas that are inhabited like flying over trees and other areas not used by humans. In order to meet these requirements, the simulation evaluated the following 5 UAVs:

TABLE 2
EVALUATED CONFIGURATION SPECIFICATIONS

	Rotors	Total Weight (g)	Battery (mAh)	Propeller	Motor (Kv)	Width (mm)	MTBF (hours)
DJI-S800	6	4400	15000 (6S)	15x4" APC	415	1180	100
FAE-960H	6	9500	16000 (4S)x2	18x6" APC	480	1420	160
X8-HLM	8	3250	10000 (4S)	10x4.7" APC	880	1350	150
OFM-GQ8	8	6500	16000 (6S)	17x5.8" APC	420	1530	160
HL48	8	7800	16000 (6S)	15x4" APC	520	1450	160

On the other hand, the costs of each multirotor aircraft differ as well. The costs for both hexacopters DJI-S800 and FAE-960H are $3,399 and $9,988 respectively, while for the three octocopters X8-HLM, OFM-GQ8 and HL48 are $2,467, $10,299 and $15,000 as well.

The results after running the simulation were that both the hexacopter DJI-S800 and the octocopter X8-HLM are not able to perform with a payload of 4.0 kg with a distance of 4.0 km round trip. Those were taken out from the following graph:
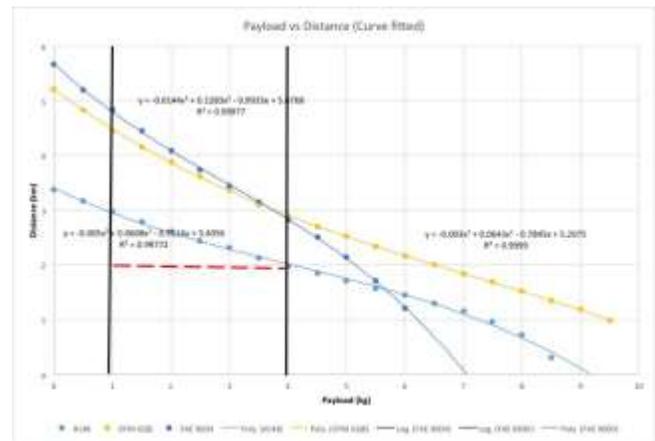

FIGURE 3
PAYLOAD VS DISTANCE PERFORMANCE CURVE

As seen in the graph, there are 3 different off-the-shelf multi-rotor aircrafts that could be used in order to meet the requirements given by the end user. The graph shows the distances (round trip divided by 2) that each UAV could flight within a specific range of payload. On the other hand, the second graph shows the velocity that each UAV would take to deliver the same range of payload as well.
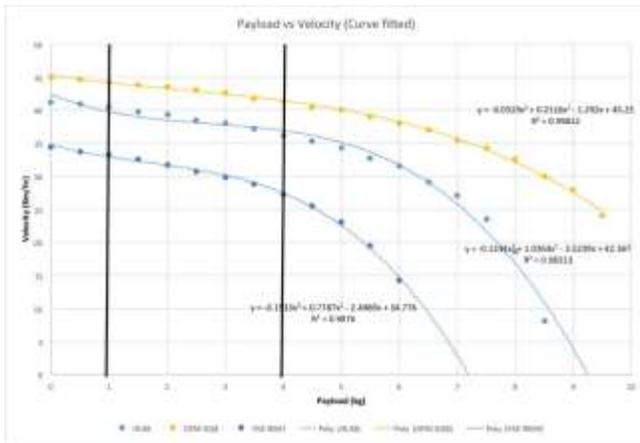
FIGURE 4
PAYLOAD VS VELOCITY PERFORMANCE CURVE

With these two graphs as outputs, both the average distance to fly, and the average velocity that would take for each multi-rotor aircraft to deliver a payload between 1.0 and 4.0 kilograms were calculated by using the equations found when fitting the curves obtained by running the simulation:

TABLE 3
THRUST AND POWER ANALYSIS DATA

Model	Average Distance (Km)	Average Velocity (Km/h)
FAE-960H	3.8	30.3
OFM-GQ8	3.7	42.8
HL48	2.5	38.3

It can be seen that although the first two models present a similar average distance, the first one moves slower than the second one. This is related to their weights and battery capacity.

Normalizing each of the four parameters taken into account and multiplying them by the weights obtained from the survey filled by the end user, the utility score of each multi-rotor aircraft was calculated:

TABLE 4
UTILITY ANALYSIS

	Distance	Velocity	Size	MTBF	
Weights	0.40	0.30	0.10	0.20	Utility Score
FAE-960H	1.00	0.71	0.16	1.00	0.829
OFM-GQ8	0.97	1.00	0.10	1.00	0.898
HL48	0.66	0.90	0.15	1.00	0.749

Finally, the utility vs. cost plot can be graphed as the final output for the end user. The graph shows that spending more money in an aircraft does not result in a better utility score.

FIGURE 5
UTILITY ANALYSIS

As it can be seen on the graph, the Octocopter that provides the best utility value is the OFM-GQ8 with a cost of $10,299.

A comparison in costs of working with a delivery person or a multi-rotor air vehicle is conducted. The assumptions for this case were that on hours with high demand (for example from 6pm to 10pm) the fast food restaurant makes 20 deliveries in total and pays $8/hour to the delivery guy charging a $2 delivery fee. This means that for 20 deliveries they make $8 a day because they make $40 on delivery but they pay $32 to the delivery guy.

On the other hand, they could get the Octocopter mentioned before (OFM-GQ8) that can deliver a maximum of 6 kilograms on a range distance from 0 to 4 kilometers (round trip). In this case, the cost of the multi-rotor air vehicle is $10,299 and it can perform with a mean time between failures of 160 hours. That means that every 160 hours they would have to change the rotors of the UAV, which will be a fixed cost of $1900. With that in mind, it was found that the hourly cost of using the Octocopter would be $11.88, which gives us a delivery cost of $2.38 (following the assumption of 20 deliveries in 4 hours). Another assumption made was that the delivery fee should be higher because people will not have to tip any delivery guy and it was fixed to $5 per delivery. It can be seen that the company would be making $100 with a delivery cost of $47.50 ($2.38 times 20), which will give them a profit of $52.50 a day. The following graph shows the break-even point between the two scenarios explained above:

FIGURE 6
CASE STUDY : BREAKEVEN POINT

As it can be seen, the break-even point is at 8 months of working with the UAV and it actually presents a money difference of $16,400 (profit) after 2 years between the two scenarios shown before.

BUSINESS CASE FOR DST-SPDAV

When running the simulation for the case study shown before, the aerodynamic stage needed 17.5 hours of computational power on a desktop with 2 Xenon processors working with 2.6GHz. For that reason a software package is being evaluated as a business case instead of an online service. This software would accept all the inputs explained before and it would output a trade-off analysis, similar to one shown on the use case mentioned before, to aid the user to choose the best possible configuration.

The costs incurred on this case are based on the development of the software package: $10,000 (hiring a software developer to do the job with a hourly rate of $50/hour) and monthly updates and bug fixes for $250 a month.

An estimate of the potential sales is derived from the traffic to the website (www.ecalc.ch) that offers a similar service, but geared towards design engineers and hobbyists. If 0.001% of the estimated traffic purchase the software, using a triangular distribution with a minimum value of 0 (where nobody purchases the software), a maximum of 73 (0.001% of 73000) and an average of 36, a Monte Carlo simulation with 1000 iterations yields an average of the net present value for after one year. The chosen discount rate was 3% (return of investment) and it was evaluated with 0%, 10% and 20% growth for the demand.
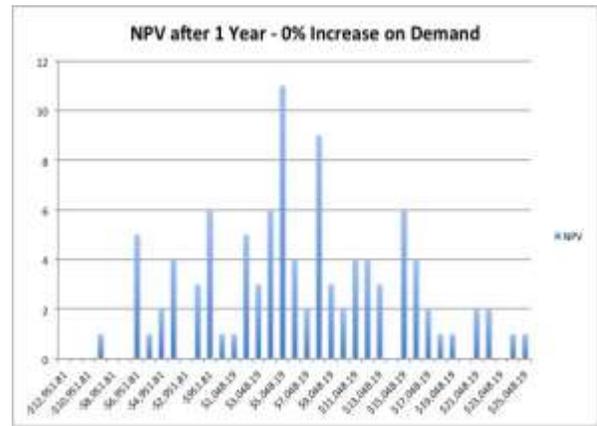

FIGURE 7
BUSINESS CASE : NET PRESENT VALUE

The resulting average NPVs were: 0%-$6,378, 10%-$9,800, and 20%-$12,251 all of which are positive, which means that DST is feasible with a 3% rate of return in the three cases evaluated.

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