Model-Based Development of Multirotor UAV Power Profiles for Performance Investigation of Different Flight Missions

Mika Suwe, Anna de Groot, Martje Forner, and Claudia Werner

Flensburg University of Applied Sciences

Abstract

In this study, a model is developed for a comparative assessment of three flight missions of multirotor unmanned aerial vehicles (UAVs) based on their power profiles in order to identify future technical research priorities and possible improvements in operational management. The model describes the missions (transport, facade inspection, drone show) based on the maneuver-specific parameters for hovering flight, vertical flight, and horizontal flight and calculates the respective power profiles of the missions based on the input parameters of a reference UAV with a battery-powered electric motor. The power profiles of the investigated missions show that the maximum powers occur during accelerated climb in each case. The greatest difference in maximum power occurs between the transport mission and the facade inspection. Considering the small difference in the respective payload, the significantly higher maximum power during the transport mission can mainly be attributed to the higher acceleration assumed for this mission. Consequently, the necessary power can be influenced by the choice of maximum acceleration. This also applies to the drone show, but the difference in power cannot only be linked to the acceleration since for the considered mission the mass differs significantly because no payload is needed. Concerning the different maneuvers, horizontal flight with constant flight speed has the largest time share and the largest energy requirement in all missions. Accordingly, this is where the greatest potential for energy savings is seen. It is shown that an ideal speed for minimizing the energy demand in horizontal flight results for each total mass.

Keywords: multirotor UAV, power profile, flight mission, electric flight, flight performance

1 Introduction

Unmanned aerial vehicles (UAVs) have been gaining more and more importance in recent years and are used in numerous civil applications. In the transportation sector, they are used to deliver goods, e.g., medical materials. In the sector of monitoring they can help to observe agricultural or forest areas as well as buildings, traffic, or air pollution (Boukoberine et al., 2019). In the event sector, they are able to replace fireworks by drone shows (Lanteigne et al., 2017; Vergouw et al., 2016).

The energy needed to perform these missions can be supplied by various power systems. Most commonly discussed are conventional internal combustion engines, batteries, or fuel cells (Donateo et al., 2017). To comparatively evaluate different mission types and select the UAV and power system for each mission, the power and energy demands of the UAV during the mission need to be known. They can be determined either through measurements which would accurately portray the
power demand of an individual UAV for one specific mission, or through models. Models can offer a more general approach, allowing multiple UAVs and mission types to be compared. In order to provide an accurate description of UAV operations, the models should be validated using appropriate measurements.

Various models representing the power demand of drones can be found in the literature. In Maekawa et al. (2017), only the power requirement of horizontal flight is modeled as a function of payload. However, this does not allow one to simulate a flight mission as a whole or even to compare flight missions among each other. In Liu et al. (2017), the power requirement of basic maneuvers (vertical climb/descend, horizontal straight line) with constant speed is determined. This approach does not consider power spikes caused by acceleration maneuvers. Abdilla et al. (2015) and Abeywickrama et al. (2018) use empirical data from individual UAVs to build their models, making them applicable only to the measured UAV. Also, none of the models presented analyzes the energy and power demand for various possible mission types.

This paper introduces a model applicable to various multirotor UAVs and flight missions. To represent the three main UAV application sectors, three different flight missions are analyzed: a delivery mission, a facade monitoring mission, and a drone show. A battery-powered multirotor UAV based on manufacturer data is used as a reference UAV. Based on this model, the generated power profiles, which include power spikes caused by acceleration, are analyzed for each mission to reveal potential optimization approaches. The calculation of a maximum and average power for each mission can be used in future work to evaluate possible power systems and configurations. Experimental validation of the presented model by measurements is planned for further future work.

2 Model

To achieve the goal of creating mission-based power profiles for multirotor UAV flights, a model was developed. This modeling approach should be able to:

- generate a power profile that incorporates the power needed to perform typical UAV maneuvers;
- include possible power spikes caused by acceleration to determine a maximum power requirement; and
- show the total energy and average power needed to perform the defined mission.

The model allows a basic evaluation of the defined mission requirements for the UAV and its power system. The discrete power profile that assigns each performed maneuver a constant power can show the maneuvers that require the most propulsion power. This allows the identification of optimization factors to reduce power requirements for specific maneuvers. While not all power spikes that will occur in real flight due to, for example, wind will be reproduced, the maximum power requirement is included by considering acceleration maneuvers. This maximum power is an important factor in evaluating and configuring the power system of a UAV. The total energy needed can highlight requirements for the power system energy storage. The average power during the mission will show the individual mission with the lowest energy requirement per unit of time and help identify factors that contribute to high average powers.

![Figure 1. Model description with input and output parameters.](image-url)
The modeling process to create power profiles for various missions is illustrated in Figure 1. The inputs are divided into UAV-based parameters and mission-based parameters. From those, the required rotor power $P_R$ to perform the respective mission can be determined via a flight mechanical model. The theory of the flight mechanical model is described in Sections 2.1 to 2.4. To include losses in the propeller, the motor, and other components, a power train efficiency $\eta_{PT}$ is multiplied to the rotor power. Thus, the required electrical power $P_{el,required}$ for the respective mission is calculated and can be analyzed when plotted over the mission time. The calculations performed in this model are implemented in Microsoft Excel.

Because of growing complexity, the flight mechanical model is limited to the maneuver- and UAV-specific input variables. The following aspects are not included in the model:

- The impact of microclimate (wind, temperature, pressure, and humidity) on the required power.
- The impact of user behavior on mission parameters like speed and acceleration.
- The exact description of extraordinary maneuvers like loops.
- Some in-flight effects that cannot be modeled by the simplified power theory (e.g., the ground effect).

The disregard of these aspects means that the created power profiles will not exactly match the power profile of a real UAV flight that is performed in unstable weather conditions and possibly controlled by a human operator. While the power profile produced by this model assigns each maneuver a constant power, in reality there will be fluctuations in power level even when performing the same maneuver. When modeling flights that include extraordinary maneuvers, the model can only include a simplified version of these maneuvers whose power requirement might not match the power requirement of the extraordinary maneuver.

In addition, the described model has not yet been validated via tests and measurements. This validation and examinations of the impact of the disregarded effects on the UAV flight behavior are to be the subjects of future works.

2.1 Power Theory

The basic principle of multirotor flight is the generation of lift via rotational rotor movements. In contrast to fixed-wing UAVs, which require a minimum velocity to generate enough lift, multirotor UAVs can hover in the air due to the constant rotation of the rotor blades and have better maneuverability (González-Jorge et al., 2017).

The herein used power theory for multirotor UAVs is taken from helicopter theory (Bittner, 2014). As shown in Figure 2, the rotor is simplified as an infinitely flat circular disk that is able to induce a velocity to the air and therefore produce thrust. The airflow through the rotor disk is considered to be uniformly distributed over the disk area.

This approach neglects some fluid mechanical effects:

- The non-uniform flow through the rotor area.
- Profile drag from the rotor blades.
- Blade tip losses.
- The compressibility of the air.

These effects can lead to a higher-than-calculated required rotor power. They can be considered by including a propeller efficiency. In this work, the propeller efficiency is included in the power train efficiency $\eta_{PT}$.

Figure 2 describes three planes. Plane 0 is the air velocity $v_0$ and pressure $p_0$ far enough over the rotor disk that it is unaffected by it. Plane 1 describes the velocity $v_1$ and pressure $p_1$ in the rotor plane, where the air has been accelerated. Plane 2 is the air velocity $v_2$ at which the pressure has been equalized to its original value.
The rotor power $P_R$ can be described by the thrust $F_T$ and the air velocity $v_1$ in the rotor plane:

$$P_R = F_T \cdot v_1$$  \hspace{0.5cm} (2.1)

The difference between the unaffected air velocity $v_0$ and its velocity in the rotor plane is called induced velocity $v_i$:

$$v_i = v_0 + v_1$$  \hspace{0.5cm} (2.2)

Therefore, the rotor power is split into the induced power $P_{vi}$ and the so-called parasitic power $P_{v0}$, which stems from the unaffected air velocity:

$$P_R = F_T \cdot (v_0 + v_i) = P_{v0} + P_{vi}$$  \hspace{0.5cm} (2.3)

The induced velocity can be determined via the thrust and the air mass flow through the rotor $m_L$, which is described by the air density $\rho_L$, the rotor area $A_R$, and the velocity $v_i$:

$$F_T = 2 \cdot m_L \cdot v_i = 2 \cdot \rho_L \cdot A_R \cdot (v_0 + v_i) \cdot v_i$$  \hspace{0.5cm} (2.4)

$$v_i = \frac{-v_0}{2} \pm \sqrt{\left(\frac{v_0}{2}\right)^2 + \frac{F_T}{2 \cdot \rho_L \cdot A_R}}$$  \hspace{0.5cm} (2.5)

### 2.2 Thrust

From equations (2.3) and (2.5) the thrust needs to be determined in order to calculate the rotor power. In this approach, the thrust is made up of three different forces.

The weight of the UAV $F_G$ is dependent on its mass $m_{uav}$ and the gravitational acceleration $g$:

$$F_G = m_{uav} \cdot g$$  \hspace{0.5cm} (2.6)

The drag $F_D$ is defined via the flight velocity $v_{flight}$, the projected area $A_{proj}$, and the drag coefficient $c_D$ of the UAV:

$$F_D = \frac{1}{2} \cdot \rho_L \cdot A_{proj} \cdot c_D \cdot v_{flight}^2$$  \hspace{0.5cm} (2.7)

The inertial force $F_I$ is dependent on the mass and acceleration $a$ of the aircraft:

$$F_I = m_{uav} \cdot a$$  \hspace{0.5cm} (2.8)

To determine the thrust, these three forces can be added up:

$$F_T = F_G + F_I + F_D$$  \hspace{0.5cm} (2.9)

### 2.3 Maneuvers

This approach defines individual maneuvers that the UAV can perform. By combining the individual maneuvers, specific flight missions can be built. This modular system allows the definition of missions which are variable at will. For each maneuver, there are different possible directions of the forces. The considered maneuvers are:

- Hover flight.
- Horizontal flight.
- Vertical flight (climb/descend).

For horizontal flight and vertical flight, the UAV can move with either constant velocity or constant acceleration. The distribution of forces for each of these maneuvers is shown via simplified drafts of a UAV in Figure 3.

For the simplest maneuver to describe, hovering, the velocity $v_0$ can be set to zero. Also, the thrust needs only to overcome the weight $F_G$ of the UAV. From equations (2.3) and (2.5), the required rotor power for hover is:

$$P_{R,hover} = F_G \cdot \sqrt{\frac{F_G}{2 \cdot \rho_L \cdot A_R}}$$  \hspace{0.5cm} (2.10)

For vertical flight, the velocity $v_0$ is set equal to the flight velocity. The thrust is determined by adding up the weight, drag, and inertia. Based on flight direction, drag and inertia can be negative or positive.

In horizontal flight, the UAV is tilted by a pitch angle $\alpha$ to produce forward thrust. The angle is determined via the ratio of drag and inertia to weight. For horizontal flight, this model takes into account only the air velocity that is flowing perpendicular to the rotor plane. It can be calculated from the flight velocity and $\alpha$.

### 2.4 Power Train Efficiency

The methodology described in the previous sections allows for the calculation of the ideal rotor power needed to perform different maneuvers. However, this ideal power is not equal to the power demanded of the UAV’s energy supply. This power can be determined by considering losses in the power train, which includes the propeller, the motor, as well as the electronic speed controller.

According to Abdilla et al. (2015), multiple studies in the literature (Beekman, 2010; Mulgaonkar & Kumar, 2014; Neitzke, 2013; Wagner et al., 2011) have adopted a constant value for an efficiency encompassing the whole power train. This approach was also chosen for this work. Therefore, the power demanded by the energy supply $P_{el,required}$ is calculated via the power train efficiency $\eta_{PT}$ and the ideal rotor power $P_R$:

$$P_{el,required} = \frac{P_R}{\eta_{PT}}$$  \hspace{0.5cm} (2.11)

To find a constant value for the power train efficiency, technical data from several multirotor UAVs were compared and a power train efficiency for each individual UAV was calculated from the maximum flight duration...
given, the ideal rotor power during hovering $P_{R, \text{Hover}}$ (calculated from the given weight and propeller diameter as shown in equation (2.10)), and the energy saved in the respective UAV’s energy storage (see equation (2.12)). This approach assumes that the maximum flight duration is the maximum duration for which the UAV can perform the hover maneuver, since the maximum flight time is also described as “hover time” in some datasheets (DJI Official, 2020a). Since hover is the maneuver with the lowest power demand (besides descend), it would make sense that the maximum flight time is reached when constantly hovering.

Using this approach for 15 individual UAVs results in the power train efficiencies shown over the empty takeoff weight in Figure 4. It can be seen that most efficiencies occur in the range of 40 to 45%, the average of all values being 40.6%. The arrow-marked value is based on the same manufacturer data as the reference drone (DJI Official, 2020a) used in this work to calculate the power profiles. Its power train efficiency is 43.5%, which is also the value chosen for the power train efficiency in this work.

In practice, each of the components encompassed in the power train efficiency would have its own efficiency curve, which would vary depending on various factors such as airflow velocity and direction, the propeller and motor rotational speed, and performed maneuvers during the flight. Taking all of these factors into account would improve the accuracy of the power train efficiency and should be considered in further research.

2.5 Flight Missions

This paper compares three flight missions that represent the transportation sector, the monitoring sector, and the event sector, respectively, which were identified as the three main sectors for UAVs in civil application. In the following sections the parameters for the missions are described.

2.5.1 Delivery flight mission

The delivery mission represents the transportation sector. The delivered goods could be medicines or commercial packages. The UAV is to deliver a package from point A to point B and then return to point A without a load. To do this, the UAV first climbs to the desired flight altitude. Upon reaching the flight altitude, the UAV first hovers and then transitions to horizontal flight. This is flown at constant speed until the target point is reached. After another short hover, the UAV descends and lands. The return flight is done in the same way but without a payload. The exact flight path can be seen in Figure 5.

The payload for this mission is supposed to be a 200 x 200 x 200 mm³ package with a weight of 2 kg. The assumed flight distance is 5 km each way, for a total of 10 km. A flight altitude of 120 m was chosen for the specific parameters of the mission, as this is the maximum flight altitude for drone flights with typical everyday applications according to European drone regulations (Drohnen.de, 2021). In the USA, the allowed flight altitude is also limited to 122 m (Logistik-Watchblog, 2021). The maximum speed has been set at 12 m/s.

The mission parameters for a one-way flight for the delivery mission are presented in Table 1. The “climb,” “descent,” and “hor. flight” maneuvers are flown with
The horizontal flight is flown at a constant velocity of 12 m/s. The accelerated maneuvers are performed with constant acceleration.

2.5.2 Inspection of a building facade

When choosing a monitoring sector flight mission, that of inspection of a building facade was chosen. Similar missions would be the inspection of power lines, bridges, or roads. These are carried out to be able to record possible damage to the structure with the aid of cameras. For the inspection of a building facade, the flight path can be either vertical column-wise or, as chosen in this case, stock-wise horizontal (Eschmann et al., n.d.). The exact flight path is shown in Figure 6.

To represent the mission in the model, a five-story square building was assumed. The height of the building is 15 m, and the width is 50 m, so the total area is 3000 m². To capture a floor, the UAV should fly around it at a distance of 3.5 m and with a speed of 2 m/s (Roca et al., 2013). The payload during the mission is a 1.6 kg camera.
The visible projection area of the camera is assumed to be 200 $\times$ 100 mm$^2$ during horizontal flight. For vertical maneuvers, the projection surface of the UAV is not affected, so the payload is only considered when calculating the horizontal drag coefficient.

A summary of the full mission parameters for the facade inspection is shown in Table 2. The parameters for the inspection of the third to fifth floor are equal to those for the second floor.

### 2.5.3 Drone show

The drone show represents the event sector. A drone show is an air show that can be of various types, including outdoor and indoor performances. The drone show considered here is adapted from a show performed at the 2016 CES trade fair from Parrot (Computer Bild, 2021). The show was three minutes in duration and was performed by eight multirotor drones to recorded music. Maneuvers such as climbing, descending, hovering, flips, and loops were performed (Computer Bild, 2021). To be able to include them in the modeling of the mission, the loops and flips, which are rollovers in a vertical direction, are described by a sequence of simply describable maneuvers:

- Hover (2 s).
- Vertical climb acceleration (0.5 s).
- Vertical descent free fall (0.3 s).
- Vertical descent deceleration (0.7 s).
- Hover (1.5 s).

The difference between flip and looping here is only that the first hover in flip is only 1 second. The total length of
The show is 185 seconds (Computer Bild, 2021). For the drone show, there is no additional payload for the UAV to carry.

A summary of the full mission parameters for the drone show is shown in Table 3. After some initial maneuvers which include a lot of hovering and horizontal flight, the drone performs five loops. Following are various horizontal flight maneuvers until the show ends with a flip and the landing.

### 2.6 UAV

To apply the modeling process described in Figure 1, a reference multirotor UAV is needed in addition to the mission-specific parameters described in the previous section. Here, a basic UAV with only one energy source and no energy management system is defined as a reference. This makes it possible to simulate the UAV-specific input variables in a useful way without focusing on the UAV itself.

The selected UAV is, based on data from DJI Official (2020a) as well as own calculations, a battery-powered hexacopter with an empty weight of 10 kg. The rotor diameter is set to 21 inches (0.5334 m). Further UAV-specific input parameters of the flight model are summarized in Table 4. The takeoff weight is calculated from the UAV empty weight plus the mission-dependent payload according to Section 2.1. The total rotor area is calculated from the number of rotors and the rotor diameter. The assumed UAV dimension inspired by DJI Official (2020a) and the mission-specific payloads from Section 2.1 is converted into \( n \) simple geometric shapes \( A_i \) with determined drag coefficients \( c_i \). This allows an approximate determination of mission-specific drag coefficients for horizontal and vertical flight (Dubs, 1987):

\[
c_W = \frac{\sum_{i=1}^{n} (c_i \cdot A_i)}{\sum_{i=1}^{n} A_i}
\]  

(2.13)

It is assumed that the payload is located underneath the UAV and is invisible when viewed from above. Thus, only the projection area and the drag coefficient for horizontal flight are influenced by the payload.

The overall efficiency of the drivetrain \( \eta_{PT} \) is calculated using the stored energy in the battery \( E_s \), the given maximum hover time \( t_{max, Hover} \), and the required rotor power for hover.

### 3 Results

Applying the mission profiles described to the power theory and following the process outlined in Figure 1, power profiles can be established for the three missions.

Figure 7 plots the delivery mission power profile over time. It is noticeable that the maximum power of about 3700 W occurs in the first 0.6 seconds of the mission during the accelerated climb (with \( a = 5 \) m/s\(^2\)). After the accelerated climb, the UAV continues to climb at a constant speed of 3 m/s for 39.7 seconds. According to the power theory from Section 2.2, the inertial force dependent on the acceleration is zero during this time and the required power decreases by 43.4% to approximately 2093 W. During the subsequent hover, the required power decreases further to approximately 1619 W. This corresponds to approximately 43.8% of the maximum power and describes the power required to overcome gravity. After 50.3 seconds, the second power peak occurs. This is caused by the horizontal flight with an acceleration of...
3 m/s² and amounts to approximately 2591 W. From 54.3 seconds, the starting process is finished, and the UAV moves with a constant speed of 12 m/s in a horizontal direction. This maneuver is flown for 414.7 seconds, significantly longer than those previously described. During this time, a constant power of about 1802 W is required and a distance of about 4976 m is covered. After 469 seconds, the UAV reaches the delivery target and hovers for 10 seconds before descending. During the descent, a power of approximately 1047 W is required, which corresponds to the minimum power of the outbound flight. After 503 seconds, the delivery is finished, and the UAV begins the return flight. The power profile of the return flight mirrors that of the delivery flight. However, the power requirements are lower by an average of 24.0% due to the lower mass (−16.07%) after the payload is dropped. According to Table 5, the average power of the delivery mission is approximately 1569 W, which is the same as the average of the two unaccelerated horizontal flights, with a deviation of −8 W. The transport mission is completed after a total of 1006 seconds. The total power requirement of the mission is about 438.5 Wh according to Table 5.

Table 3
Mission parameters for the drone show.

<table>
<thead>
<tr>
<th>Course of the show</th>
<th>Maneuver</th>
<th>tmaneuver in s</th>
<th>vflight in m/s</th>
<th>aflight in m/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial maneuvers</td>
<td>Accelerated climb</td>
<td>1.0</td>
<td>4.0</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Hover</td>
<td>0.5</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Accelerated hor. flight</td>
<td>1.0</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Hover</td>
<td>0.5</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Accelerated hor. flight</td>
<td>0.5</td>
<td>1.0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Hor. flight</td>
<td>17.5</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Accelerated climb</td>
<td>1.0</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Accelerated hor. flight</td>
<td>2.0</td>
<td>2.0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Hor. flight</td>
<td>4.5</td>
<td>2.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Hover</td>
<td>33.0</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Descent</td>
<td>1.0</td>
<td>−1.0</td>
<td>0</td>
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<tr>
<td>First loop</td>
<td>Hover</td>
<td>2.0</td>
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<td>0</td>
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<tr>
<td></td>
<td>Accelerated climb</td>
<td>0.5</td>
<td>2.5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Accelerated descent</td>
<td>0.3</td>
<td>−2.9</td>
<td>−9.80665</td>
</tr>
<tr>
<td></td>
<td>Decelerated descent</td>
<td>0.7</td>
<td>0.0</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Hover</td>
<td>1.5</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>More loops</td>
<td>...</td>
<td>...</td>
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<td>Various maneuvers</td>
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<tr>
<td>Flip</td>
<td>Hover</td>
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<td>0.0</td>
<td>0</td>
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<td></td>
<td>Accelerated climb</td>
<td>0.5</td>
<td>2.5</td>
<td>5</td>
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<tr>
<td></td>
<td>Accelerated descent</td>
<td>0.3</td>
<td>−2.9</td>
<td>−9.80665</td>
</tr>
<tr>
<td></td>
<td>Decelerated descent</td>
<td>0.7</td>
<td>0.0</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Hover</td>
<td>1.5</td>
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<td>0</td>
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<td>Circular flight</td>
<td>Accelerated hor. flight</td>
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<td>2</td>
</tr>
<tr>
<td></td>
<td>Hor. flight</td>
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<tr>
<td></td>
<td>Hover</td>
<td>1.0</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>Landing</td>
<td>Accelerated descent</td>
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<td>−2.9</td>
<td>−9.80665</td>
</tr>
<tr>
<td></td>
<td>Decelerated descent</td>
<td>0.7</td>
<td>0.0</td>
<td>5</td>
</tr>
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Table 4
UAV parameters based on own calculations and referring to DJI Official (2020a).

<table>
<thead>
<tr>
<th></th>
<th>Transport</th>
<th>Monitoring</th>
<th>Drone Show</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of propellers</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Propeller diameter</td>
<td>21&quot; (0.5334 m)</td>
<td>21&quot; (0.5334 m)</td>
<td>21&quot; (0.5334 m)</td>
</tr>
<tr>
<td>Total rotor area</td>
<td>1.341 m²</td>
<td>1.341 m²</td>
<td>1.341 m²</td>
</tr>
<tr>
<td>Stored energy</td>
<td>779.76 Wh</td>
<td>779.76 Wh</td>
<td>779.76 Wh</td>
</tr>
<tr>
<td>Power train efficiency</td>
<td>43.5 %</td>
<td>43.5 %</td>
<td>43.5 %</td>
</tr>
<tr>
<td>Takeoff weight</td>
<td>12 kg</td>
<td>11.6 kg</td>
<td>10 kg</td>
</tr>
<tr>
<td>Projected area, horizontal</td>
<td>0.129 m²</td>
<td>0.109 m²</td>
<td>0.089 m²</td>
</tr>
<tr>
<td>Projected area, vertical</td>
<td>0.131 m²</td>
<td>0.131 m²</td>
<td>0.131 m²</td>
</tr>
<tr>
<td>Drag coefficient horizontal</td>
<td>1.040</td>
<td>1.038</td>
<td>1.013</td>
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<tr>
<td>Drag coefficient vertical</td>
<td>1.003</td>
<td>1.003</td>
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</tbody>
</table>
Figure 8 shows the power profile for the facade inspection. Here, the power requirements of the mission are repeated for each of the total five floors, resulting in a strikingly regular curve. As with the transport mission, the maximum power occurs during the accelerated climb (in this case with $a = 1 \text{ m/s}^2$). The maximum power is about 1932 W and is already needed during the first second of the mission to reach the first floor. After 122.5 seconds, the maximum power occurs the second time. At this point, the inspection of the first floor is completed and the climb to the second floor begins. Each of the accelerated climbing maneuvers is followed by a short time window of 1 second again, during which the UAV ascends at a constant speed of 1 m/s. This maneuver requires a power of about 1677 W, which is about 85.4% of the maximum power. The unaccelerated climb is followed by hovering (for the first time after 2 seconds). For this maneuver, the UAV requires a constant power of about 1539 W, which corresponds to about 79.7% of the maximum power. This percentage is significantly higher than for the transport mission. Accordingly, here overcoming the weight force has a significantly higher proportion of the maximum power requirement than is the case for the transport mission (43.8%). Reasons for this are the significantly lower accelerations and velocities. After hovering, the UAV enters horizontal flight. During this process, it initially accelerates at 2 m/s$^2$, resulting in a power demand of approximately 1643 W. Unlike the transport mission, in this case the power for the unaccelerated climb is higher than for the horizontal acceleration. Thus, a shift in the power ratios of the individual maneuvers occurs here. After the ascent, the UAV circles the building in horizontal flight. This requires a power of about 1540 W. The power requirement for horizontal flight is thus only about 6.5% higher than the power requirement for hovering. This can be explained by the low speed of 2 m/s. After a total of 614.5 seconds, the inspection of the five floors is completed and the UAV starts descending. As with the transport mission, the minimum power is required during this maneuver. This is about 1000 W for the facade inspection. After a total of 619 seconds, the facade inspection is completed.

Table 5

<table>
<thead>
<tr>
<th>Mission</th>
<th>$P_{\text{max}}$ in W</th>
<th>$P_{\text{avg}}$ in W</th>
<th>$E_{\text{mission}}$ in Wh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>3700</td>
<td>1569</td>
<td>438.49</td>
</tr>
<tr>
<td>Facade inspection</td>
<td>1932</td>
<td>1544</td>
<td>265.40</td>
</tr>
<tr>
<td>Drone show</td>
<td>2823</td>
<td>1284</td>
<td>65.98</td>
</tr>
</tbody>
</table>

Figure 9 depicts the power requirements of the drone show. As with the two previously discussed missions, the maximum power occurs during the accelerated climb (in this case at 4 m/s$^2$). Here, the maximum power is about 2823 W, which is just under 220% of the average power.
(1284 W according to Table 5). As in the previous missions, the accelerated climb is part of the launch process. It occurs for the first time during the first second of the mission. It also precedes every loop (the first time after 62.5 seconds) and flip (from 175.5 seconds). The second highest power is required during deceleration from free fall. Here, free fall and braking from free fall are maneuvers that are not flown during either the transport mission or the facade inspection. During free fall, the minimum power of the mission occurs. It is approximately 0 W (the first time during the first loop after 65.3 seconds). The free fall is followed by deceleration with negative acceleration due to gravity (approximately \(-9.81 \text{ m/s}^2\)). During this process a power of about 2285 W is demanded, which is the second highest power demand of the mission. Also notable in this mission is the landing procedure (starting at 184 seconds):
this is implemented by an accelerated climb, followed by free fall and deceleration from it, thus demanding all power extremes within 1 second. Overall, the average power of the drone show of 1284 W is significantly lower than that of the transport mission or the facade inspection. This is mainly due to the fact that the drone does not carry any additional payload during the drone show.

Figure 10 presents the three previously discussed power profiles of the missions plotted in one diagram. It is clear that the missions differ greatly not only in their curve profiles but also in their total flight time. Thereby, the transport mission with a total of 1006 seconds is significantly longer than the facade inspection (619 seconds) or the drone show (185 seconds). However, this is not due to the restrictions of the power system but to the mission requirements: While the transport has to cover a total distance of 10 km, the drone show involves a comparatively short time, which serves pure entertainment.

The distribution of maneuvers over the entire mission time is shown in Figure 11. The distribution of energy required to perform the various maneuvers is shown in Figure 12. The level-flight maneuver has the largest time and energy fraction for all three missions (ranging from about 55% for the drone show to 84% for the delivery mission). For the delivery mission, the climb maneuver has the second largest time and energy fraction at approximately 9.6%. For the facade inspection, hovering flight is the second most performed maneuver with a share of about 8.9%, while descending flight has a very small share (about 1%). In the case of the drone show, the share of hovering flight is comparatively large at about 34%. This is due to the fact that the individual drones have to wait for the other drones to perform some maneuvers. The drone show is also the only mission where descent has a larger time and energy fraction (about 5.3%) than climb (5.2%). This is partly caused by the high energy demand during deceleration after free fall.

The developed flight mechanical model can be applied to other missions as long as they can be described in terms of the flight maneuvers (vertical flight, horizontal flight, and hovering). However, the results discussed are as individual as the missions themselves and cannot be generalized to other missions in the same sectors (transport, monitoring, and event).

4 Discussion

For this paper, a flight mechanics model was successfully developed, which allows calculation of the performance profiles for different missions. As a result, the model-based power profiles of the three flight missions can be reproduced based on maneuver-specific parameters using a reference drone. This leads to the possibility of comparing the requirements of the missions. In addition, optimization approaches for UAV design and operations management as well as possible future development priorities can be identified.

As already shown in Section 3, the considered flight missions differ in their regularity of power demand, maximum power, and total flight time.

According to Figure 10, the modeled power profile of the delivery mission is characterized by long periods of constant power demand. These are due to traveling comparatively long, straight distances at constant speed and...
without altitude difference. In this context, the outward and return flights exhibit different load demands, which can be explained by the influence of the payload on the forces to be overcome. According to Section 2.2, the weight force and the inertia force are influenced by the mass of the payload, while the shape and size of the payload influence the resistance force. Assuming that the mass of the payload cannot be influenced, the shape and size of the projection surface and the location of attachment would be the adjusting factors for reducing the power requirements at this point. In the modeled delivery mission, neglecting wind strength and direction as well as possible obstacles results in comparatively constant power demand during nonaccelerated horizontal flight. If the parameters just mentioned were taken into account, route-dependent load peaks and load sinks are expected when covering the route by reacting to wind and obstacles. The load peaks and load sinks would be route-dependent without any symmetry.

According to Figure 10, the power demand of the UAV during facade inspection can be described by a constant base load with periodically recurring peak loads. This strong regularity is due to the symmetry of the building: the UAV climbs floor by floor and always overcomes the same height. Between the individual climbing flights, the same distance is covered, oriented around the perimeter of the building. By neglecting wind strength and wind direction, the power demand of the UAV is constant while circling a floor. With wind as an input parameter, the power profile would be affected as follows: the UAV would fly partly downwind and partly upwind and would accordingly require different power for the same maneuver. In addition, the UAV might have to compensate crosswinds and react to sudden wind changes when reaching the edges of the building. If it is also assumed that wind shading by the environment decreases upward, increasing wind strengths can be expected for the upper floors. Thus, a profile would be conceivable in which a qualitative progression recurs periodically and a stepwise increase in load demand by floor occurs. If the inspection object lacks symmetry (e.g., a wind turbine) or if the wind strength or direction changes during the mission, the periodic recurrence of the load peaks would have to be reconsidered. However, if we stay with the modeled power profile for facade inspection, it is noticeable that the highest power demands are required for climbing, while for descending, powers far below the base load are sufficient. Thus, for facade inspections in the future, it could be investigated to what extent starting from the building roof and reversing the sequence in the inspection of the floors could lead to a possible reduction of the installed power. If this were the case, there would be the potential at this point to reduce the overall mass of the UAV and its cost by minimizing the installed power. However, such considerations would only be effective if climb flights could be avoided over the entire mission.

According to Figure 9, the power profile of the drone show is characterized by a very irregular power demand with comparatively frequent load peaks and load troughs. This places special demands on the power supply and the energy management system, which must respond to the varying demands. If the drone show is assumed to be an indoor event, the neglect of wind plays only a minor role in
this case. For the simulation of the power profile, the same UAV was used for the show as for the previously discussed missions. This leads to the fact that the power profiles only depend on the mission, which is intended in the context of this study. Nevertheless, it should be noted that UAVs with smaller dimensions and lower weight are normally used in the event sector.

Figure 9 clearly shows how strongly the maneuvers differ in their power requirements and in their total flight time. This leads to strongly differing energy requirements, which are summarized in Table 3. Accordingly, the transport mission stands out due to high energy requirements, so energy density is a promising factor in the optimization of energy supply.

With the maximum powers shown in Table 2, it is noticeable that the facade monitoring has the lowest maximum power with 1932 W. The transport mission, on the other hand, requires a maximum power of 3700 W, which corresponds to about 190% of the maximum power of the monitoring mission. However, the total weight of the UAV differs by only about 3% when the maximum power occurs. The large difference of the maximum power can be explained by the differently assumed accelerations during the climb. In terms of operational management, the acceleration is therefore a possible optimization parameter, which can lead to a reduction of the installed power and thus to a minimization of the total mass and the investment costs.

Figure 11 shows the share of flight maneuvers in the total flight time of the missions considered. According to Figures 10 and 11, the nonaccelerated horizontal flight takes the most time in the three flight missions considered. Not least for this reason, according to Figure 12, the proportional energy requirement for this maneuver is also the greatest in all three missions. Based on this observation, it can be assumed that the optimization of the UAV and its operational management for horizontal flight has a comparatively large impact on the total energy requirement of a mission. Due to the promising optimization potential, nonaccelerated horizontal flight will be examined in more detail below. The investigation is based on the delivery mission.

The energy requirement for horizontal flight results from the power requirement of the UAV and the necessary flight time to cover the required distance. According to Figure 13, the power requirement of the UAV depends on the flight speed as well as the payload, which can be understood in this case as representative of the mass and the projection surface of the UAV. It is striking at this point that the power requirement is relatively constant for very low flight speeds up to 5 m/s. Thereafter, the power increases exponentially with increase in airspeed. For the same absolute change in velocity, the power requirement of the UAV with payload changes more than that of the UAV without payload. The influence of the UAV design (shape and mass) therefore increases with increasing flight speed.

According to Figure 14, the energy requirement for covering a distance is not only linked to the power requirement: between energy and power requirements, the
flight time is the third speed-dependent variable. As a result, the optimization of the energy demand results in an optimal flight speed, which deviates from the flight speed with the lowest power demand. For the UAV with payload, the lowest energy requirement would be achieved at a flight speed of approximately 19 m/s. For the UAV without payload, this would be achieved at a flight speed of approximately 18 m/s.

Figure 13. Power requirement as a function of flight speed.

Figure 14. Energy requirement as a function of flight speed.
According to the above considerations, an optimization of the operational management for the transport mission by adjusting the flight speed is conceivable. There is also potential for optimization at this point for the drone show and building inspection. For the monitoring mission, the camera requirements for the flight speed would have to be examined in this context. For the drone show, the extent to which changes in flight speed can be reconciled with the show would have to be clarified.

According to Figures 13 and 14, the dimensions and the mass—represented by the payload—are further factors influencing the power and energy requirements of the UAV. In this context, Figure 15 depicts the forces acting on the UAV during nonaccelerated horizontal flight. According to equation (2.8), the inertial force does not play a role in nonaccelerated maneuvers and is accordingly not shown.

Here it becomes clear that in nonaccelerated horizontal flight, by far the largest force acting on the UAV is the weight force $F_G$. Accordingly, relative changes in mass would lead to comparatively high absolute changes in relation to the acting forces. In contrast to the weight force, the drag force $F_D$ is relatively small, so that a percentage reduction in the drag coefficient and the projection area would only lead to comparatively small absolute changes. However, since it is not possible to directly infer the changes in power demand and energy demand from the acting forces, the effects on these two factors would have to be investigated further.

As already indicated in the previous sections, it is clear from the modeled power profiles from Section 3 that the missions investigated place very different demands on the UAV’s energy supply. In this context, the missions differ in their maximum power and total energy requirements. In addition, it is conceivable that the power supply system must be able to respond to the fluctuating load requirements at different rates: while for an event the responsiveness requirements strongly depend on the drone show, for transportation and building inspection it would be more conceivable to do without fast responsiveness as part of an optimization process. The characteristics and suitability of different energy sources for different UAV missions therefore represent an interesting field of research, which will be the focus of further investigations in future.

5 Conclusion and Outlook

This investigation has described a modeling process to create power profiles for multirotor UAVs. This process was used to create, compare, and analyze the power profiles of three different flight missions of a multirotor battery electric UAV. This model considers the power theory of a multirotor UAV, including the induced forces on the UAV, the maneuvers specified by the different flight missions, as well as the assumed UAV parameters. The resulting power profiles have not yet been validated by measurements and test flights. This validation could also be used to quantify environmental and microclimate impacts on UAV flights, as these impacts are neglected in these investigations.

The results show that the highest power demands occur during climb and acceleration maneuvers. Therefore, adapting the maximum acceleration for each mission could flatten the power peaks. With the knowledge of the impact
of the climb maneuver on the power profile, further studies could consider investigating different operation management systems to avoid unnecessary climbing, e.g., starting the UAV from the top of a building instead of the ground.

The most time- and energy-consuming maneuver in all three missions is the horizontal flight. Therefore, there is a potential in optimizing the horizontal flight energy and power demand. The main influence on the power demand is the speed of the UAV and the payload. The power demand increases exponentially after a certain UAV speed. For the energy demand, the flight time also had to be taken into consideration. With this taken into account, an optimal flight speed for the delivery mission during the horizontal flight can be identified. This approach can be implemented to optimize the mission parameters for other missions. Since the payload has a big influence on the power and energy demands, the optimization of the overall mass of the UAV is identified as a potential optimization parameter for future research.

As already indicated, the power curves of the three missions are very different. The delivery mission has long constant power demands with only high power peaks during the climb, the facade inspection mission has a constant power demands with only high power peaks during the climb, the facade inspection mission has a constant power demand with periodically recurring peak powers, and the drone show has a variable power curve. Therefore, these power profiles can be used to determine lists of requirements for possible alternative power trains and energy sources and to evaluate these alternatives. These requirements include the supply of peak power and basic power demands and the dynamic performance of the power trains. The evaluation of alternative power trains and energy sources (e.g., fuel cells) is to be done in further research.

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