MECSOL 2022 - Proceedings of the8thInternational Symposium on Solid Mechanics
M.L. Bittencourt, J.Labaki, L.C.M. Vieira Jr. and E. Mesquita(Editors), CampinasSP, Brazil, October17th to 19th, 2022

Generative Design of a Cargo Drone

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Abstract: With the emergency of industry 4.0, drones are taking an even more expressive position in the market because of its capacity to perform diverse tasks. Their applications depend mainly on the structural configuration (rotary or fixed wings) and the number of motors. Most of the engineering development on drones is currently leveraged by CAD/CAE computational tools, which provides more agility to generate new designs. Recent computational tools for structural optimization together with new technologies of additive manufacturing bring a great potential to generate very complex structures with organic design and structurally optimized in a short space of time. This work aims to explore the design of a cargo drone using generative design tool. A literature review is carried out in order to understand the requirements. Some alternatives of drone structures are created using generative design, of which one is selected based on maximum structural efficiency, manufacturing capability, safety and functionality.

Keywords: Generative Design, Drone, Structural Optimization, Additive Manufacturing, CAE

INTRODUCTION

Drones or UAVs (Unmanned Aerial Vehicles) (Hassanalian and Abdelkefi, 2017) are aircraft capable of flying without a human pilot or passenger on board, they can be autonomous or controlled by a remote operator. Drones are an emergent technology of Industry 4.0: they are multifunctional, easy to transport and can be quickly prepared to fly. Therefore, they are used toaerialtransport of small packages, scan areas to create maps, supervise systems and inspect unhealthy areas for humans among other functions (Vergouw et al.,2016).

Drones can be classified into two main cathegories according to how they generate lift: fixed wing drones or rotary wing drones.

Fixed wing drones (Fig. 1) have aerodynamic fundamentals similar to those of airplanes: they use one or two motors to accelerate the aircraft, thus increasing the airspeed to generate lift. As this kind of drone uses fixed wings, the control systems are similar to airplanes (Homa, 2010): ailerons, rudder and elevator allowtheaircraft model to perform roll (rotation about the longitudinal axis), pitch (rotation about the transverse axis), and yaw (rotation about the vertical axis) movements.

Figure 1– Fixed wing drone Penguin B (left) and Rotary wing drone FJI Mavick 2 (right)

The multi-rotor drones (Fig. 1) are similar to helicopters, which use rotating wings (propellers) to generate lift. This type of drone usually uses four rotors (hence the name multi-rotor), andtheycan have more. Each one of these rotors isnecessaryto have flight stability. Since they do not depend on the speed of the incident air to generate lift, this drone can perform helicopter-like manouvers: hover in the air, operate at low speed and rotate around its own axis.

Due to the growing technological development in the last decades, computational toolshavebecomepart of engineering applications since the 1960s (Tornincasa and Di Monaco, 2010). Nowadays, these applications have only increased and spread to several areas of engineeringso becoming fundamental and indispensable for the engineer's work. For mechanical and structural designtasks, CAD (Computer Aided Drawing) and CAE (Computer Aided

Engineering) tools are essential for the 3D modeling of mechanical structures, creation of technical drawings, prediction of stresses and strains induced by mechanical loadings among other applications. This set of computational tools ends up increasing the quality of the final product and reducing the occurrence of structural problems in the manufacturing stages.

Also, thanks to the advances in computer processing and the CAD codes' development, the first additive manufacturing technologies have begun to be developed in the 1980s and 1990s (Bandyopadhyay et al.,2020). Additive manufacturing consists in the fabrication of parts directly from its CAD model without the need of a specific tool. This is why they are considered as digital manufacturing technologies. Additive manufacturing basically involves the layering of material (using diverse methods) according to the 3D CAD model until the complete 3D geometry of the physical part is generated. It allows generating parts with complex geometries which would be difficult/impossible to be manufactured by other methodsrelatively quick and at low unit cost. Both computational advances and the capability to manufacture complex geometry parts have forwardedthe development of new tools for structural engineering optimization. Nowadays, several increasingly sophisticated engineering tools for structural optimization are launched on the international market, most of them are based on topological optimization fundamentals, but they are also based on newer technologies such as artificial intelligence algorithms, this is the case of generative design.

GENERATIVE DESIGN OF DRONE STRUCTURE

Generative Design

One of the most complete tools for structural optimization in mechanical design is Generative Design (Arozi, 2021). In generative design, the structure design is created from the project requirements such as mechanical loadings, displacement constraints, manufacturing methods, material, among other requirements (Autodesk, 2021). Based on this information, the generative design code proposes several design alternatives for the structure that meet the established requirements. It makes the creative design process more efficient by including structurally optimized geometries (i.e., maximizing the mechanical strength and minimizing the weight of the structure) that would not be possible to develop with traditional methods.

Along with additive manufacturing technologies, generative design tools have great potential to transform the way the engineer does mechanical design today. This is because generative design tools help generating structurally optimized designs while additive manufacturing technologies make possible manufacturing them.

Drone Design

In this work,the aim is to create a four-rotor rotary-wing drone (considering a general X configuration) capable of carrying a payload with maximum volume of about 350×270×230mm^{3}and 1.5 kg maximum mass. This aircraft was designed using the generative design module of the Autodesk Fusion360 software. This work involves the design of three subtructures of the drone: the arms, the frame and the landing gear.

Initially, it was considered to generate the drone structure divided into 3 parts: a frame and two landing gears. In this specific case, the only function of the landing gear was to guarantee a safe landing far from the ground, while the frame would hold the four rotors, protect the electronic components and carry the payload. In this frame model, the frame would be composed of two parallel rectangular perforated platforms (perforated to reduce the mass and to facilitate the assembly of electronic components).The payload also would be attached to platform bottom using these holes, while the landing gears would be attached to a side support located between the two platforms. However, the holes of the platform ended up weakening the structure so limiting the transportation of small payloads attached in the bottom of the platform. For this reason, the payload is now attached to four landing gears (located below the engines) so allowing the reduction of the platform weight (perforated octagonal platform) (Fig. 2).

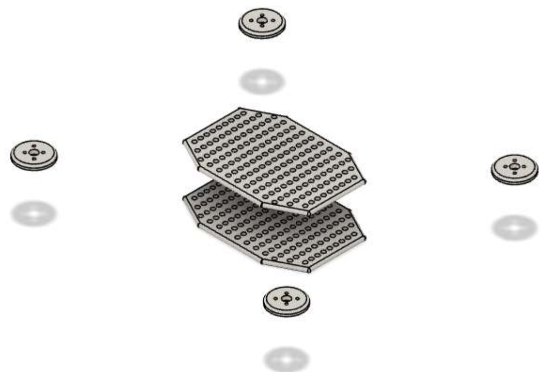

Figure 2 – Isometric view of the preserved geometries of the second frame prototype.

Although this model met all the project requirements adequately, the size of the resulting structure frame is larger than the printing volume of common commercial 3D printing machines, which makes it difficult to manufacture. Therefore, it was necessary to create a new model in which the structureframe is divided into five parts: the central frame, responsible for protecting the electronic components, and four arms, responsible for holding the landing gear and the engines. This work covers the design processes of these components.

Preserve and obstacle geometries

The preserve geometries are considered regions kept as part of the resulting geometry, they are necessary because mechanical stresses and constraints are applied on them. In the case of the frame, the preserve geometries are defined by the octagonal platforms (Fig. 3). In the case of the drone arm, it involves the connection surface to the motorandtwo pins that connect the arm to the drone frame (Fig. 4). Finally, in the case of the landing gear, it involves the surface that connects to the arm, the surface where the payload is attached, and the surface that contact to the ground (Fig. 5).

The obstacle geometriesare the regions that cannot be occupied by the structure to be generated. In the case of the frame (Fig. 3) these regions are all the holes both platforms, all the volume between the two platforms, the volume occupied by the payload (with a20 mm offset from the lower platform), the areas occupied by the drone arms and the areas in the front and rear faces of the frame.In the case of the drone arm (Fig. 4), these regions are that occupied by engine and propeller, landing gear, frame, screws that will connect the arm to the frame, screws that will connect the landing gear to the arm and some of the holes to avoid collision with the landing gear.In the case of the landing gear (Fig. 5), these regions are that occupied bypayload, drone arm, bolts that connect the landing gear to the arm and the ground.

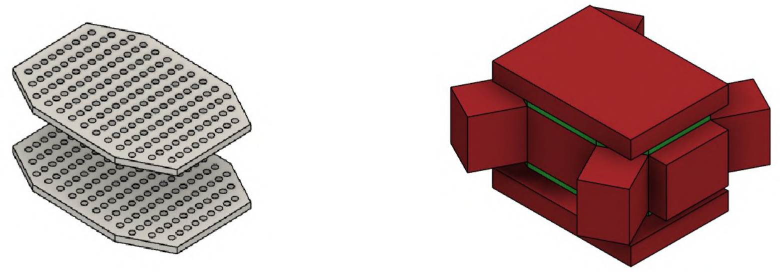

Figure 3 – Isometric views of the preserve (left) and obstacle (right) geometries of the frame model.

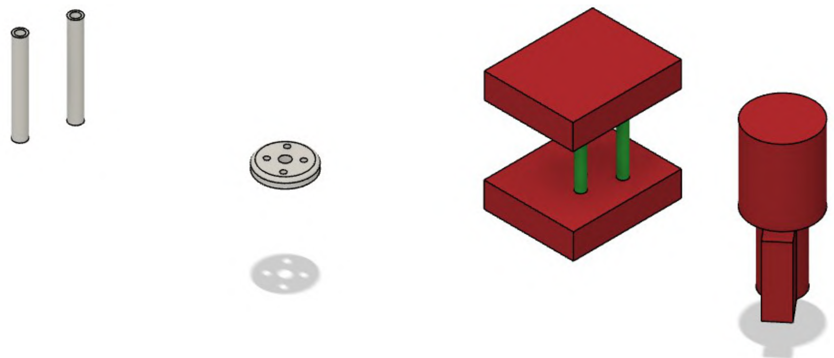

Figure 4 – Isometric views of the preserve (left) and obstacle (right) geometries of the drone arm model.

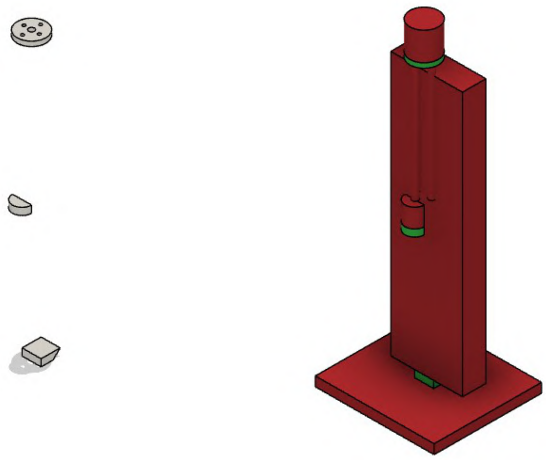

Figure 5 - Isometric views of preserve (left) and obstacle (right) geometries of the landing gear model.

Materials

Initially, a literature review was carried out in order to understand the behavior of potential materials to be used to build the drone structure using additive manufacturing processes based on powder bed fusion technology (PA12) and fused material deposition (PLA and ABS). It is worth mentioning that the mechanical properties of these materials depend on the manufacturing direction when the component is made using a process of additive manufacturing. Thus, in order to create a drone capable of operating safely without occurrence of structural damage, even in extreme operation cases, a safety factor of 2.0 was set considering the material's yield stress as reference maximum stress.

The values of yield stress for the aforementioned materials were raised in the literature review. Thus, Song et al. (2017) identified that the maximum stress value of PLA is 54.84 MPa for parts built in the XY plane, 0° orientation, 0.2 mm layer thickness, extrusion speed of 60 mm/s, extruder temperature of 220°C and 1.46 % porosity. Samykano et al. (2019) identified that the maximum stress of ABS is 22.2 MPa for parts built in the XY plane with 65° orientation, 0.4 mm layer thickness and 20% porosity. Finally, Lammens, De Baere and Van Paepegem (2016) found that the maximum stress of PA12 is 35 MPa for parts built in the XY or XZ plane.

Load cases

An essential step when creating a part using generative design is to determine the forces that act on the structural part during its operation (Autodesk, 2022). With this information, it is possible to define the case studies, a set of forces and constraints that act on the part at a given situation. Thus, the loads acting in each component of the drone were discussed below. Furthermore, a quantitative evaluation of the value of these loads is compiled in the Appendix A. These values can be used in all case studies considered in the work and listed in Table 1.

Frame

Is the central component of the drone, it is responsible for carrying most of the electronic components and must be able to withstand the stresses induced in the connection with the drone arms.Therefore, the frame is subjected to the weight of the electronic components distributed on its two platforms and to the forces induced by flight manouvers: take-off (the drone's moment of ascent when the four motors operate at maximum power), pitch (movement of leaning forward or backward in which the front pair of motors has different power than the rear pair of motors), roll (movement of leaning to the right or left in which the right pair of motors has different power than the left pair of motors), yaw (movement of rotating clockwise or counterclockwise around the vertical axis in which the pairs of motors of each diagonal have different powers), turns (moment in which the drone performs at the same time the movements of pitch and roll), landing (in which its weight is transferred to the arm and supported on the landing gear) and also acollision (when two arms of the drone collide against a rigid structure while the drone is at a maximum speed of 6 m/s).

Arm

Is the component responsible for holding the landing gear and the rotor generating the thrust that sustains the aircraft in flight.Thus, the arm is subjected to the forces induced by flight manouvers: takeoff (maximum engine power) and landing (in which the weight of the frame and components acts on the arm fasteners and the normal landing gear acts below the engine). Other flight maneuver cases were disregarded since the thrust and torque generated by the engine are lower than in the case of takeoff.Other load cases incuded in the analysis are: arm drop (in which case the arm falls off during assembly of the drone), collision (drone arm collides against a rigid body) and when the drone is lifted(hand manipulation) only by one arm (weight of the frame, components and other arms act on the arm fasteners).

Landing Gear

Is the component responsible for allowing the drone to land safely with a certain distance from the ground and to carry the payload. Because of this, the landing gear is subjected to the forces induced during the landing case, in which the weight of the frame, the arm and the electronic components act on its upper side, the weight of the payload acts on specific fasteners and the normal force of the ground acts on its base.

Table 1- Description of case studies

Case Study	Description
Take off*	When the drone leaves the ground
Take off 2**	When the drone leaves the ground
Pitch forward ***	Movement in which the drone moves forward
Pitch back****	Movement in which the drone moves backward
Roll right	Movement in which the drone turns right
Roll left	Movement in which the drone turns left
Yaw clockwise	When the drone hovers and rotates clockwise around its vertical axis
Yaw anticlockwise	When the drone hovers and rotates anticlockwise around its vertical axis
Forward and right turn	Movement in which the drone moves forward and turns right at the same time
Forward and left turn	Movement in which the drone moves forward and turns left at the same time
Backward and right turn	Movement in which the drone moves backward and turns right at the same time
Backward and left turn	Movement in which the drone moves backward and turns left at the same time
Landing	When the drone touches the ground
Colision	Two drone arms collide against a rigid body at 6 m/s

- Take off*: Four rotors at maximum power (generating maximum thrust and torque) +structureweith +weight of the landing gear, payload and electronics.
- Take off 2**:Identical to the previous one, but the armssupport the torque in both directions (torque occurs counterclockwise).
- Pitch forward ***: Front rotors have less power than rear rotors, they have less torquesogenerating two different torques in the center of the frame. As in the previous case, the weight of landing gear, payload and electronics are also included.
- Pitch backward****: Rear rotor have less power than front rotors, they have less torques so generating two different torques at the center of the frame.As in the previous case, the weight of landing gear, payload and electronics are also included.

Generative design outcomes and selection

After defining preserve and obstacle geometries, materials and case studies as well as processing this information in the design generative module of the Autodesk Fusion 360 software, the results were generated and analyzed. The main criterion to choose the best alternative of structure design is based on the lowest structure mass and higher safety factor (above or equal to 2.0).

As can be seen in Tables 2, 3 and 4, all the components analyzed have a safety factor equal or above 2.0 and (except for the ABS landing gear) all resulting structures are lightweight. Low weight makes them perfect structural parts for use in the aeronautical applications. Since all models (frame, arm and landing gear) have identical safety factor, the design alternatives with the lowest mass were chosen, i.e., those made of PA12 material.The complete lightweight design configuration of the drone considering all structural parts created in this work using generative design are presented in Figs. 9 and 10.

Table 2 – Frame results

Material	Minimum safety factor	Mass (kg)	Maximum displacement (m)
PA12	2.0	0.147	0.0057
ABS	2.0	0.159	0.0096
PLA	2.0	0.170	0.0024

Figure 6 – Designs generative of frame using PA12 (left), ABS (center) and PLA (right).

Table 3 – Drone armresults

Material	Minimum safety factor	Mass (kg)	Maximum displacement (m)
PA12	2.0	0.016	0.0046
ABS	2.0	0.018	0.0105
PLA	2.02	0.021	0.0033

Figure 7 – Designs generative of drone arm using PA12 (left), ABS (center) and PLA (right).

Table 4 – Landing gear results

Material	Minimum safety factor	Mass (kg)	Maximum displacement (m)
PA12	2.0	0.015	0.0017
ABS	32.0	0.174	0.0005
PLA	45.0	0.053	0.0002

Figure 8 – Designs generative of landing gear using PA12 (left), ABS (center) and PLA (right).

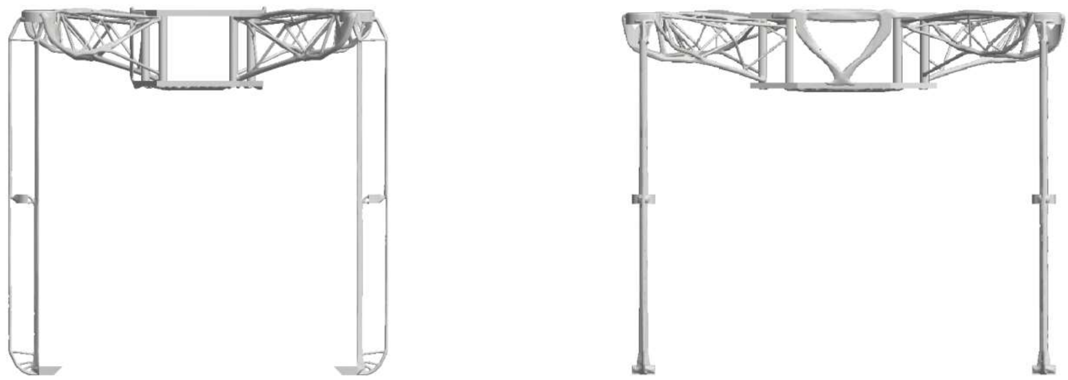

Figure 9 – Front and side views of drone assembly

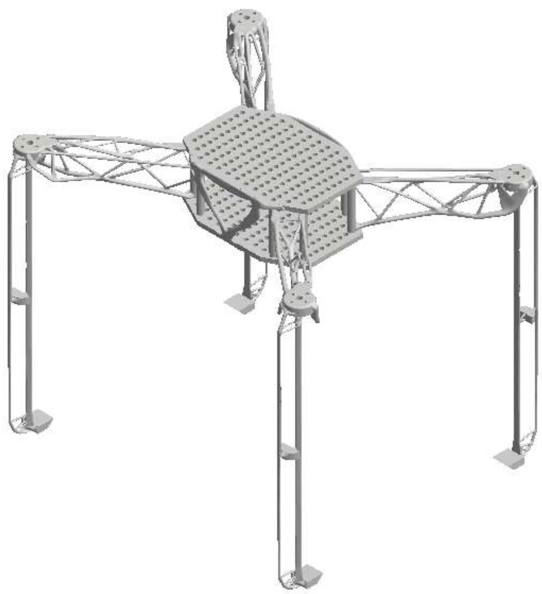

Figure 10 –Isometric view of drone assembly

CONCLUSIONS

Considering the alternatives of design generated for the frame, arm and landing gear strutures, it can be clearly observed that generative design is a powerful tool for the mechanical design of aircraft structures, such as drones. However,this computational tool is only able to generate structures that withstand real service loadingswhena accurate evaluation of the acting loads and material properties is carry out by the engineer.So, the engineer needs to know clearly the different loading situations of the structure to send this information as input to the generative design code.

Disregarding information of crucial load case in the generative design analysis can potentially lead to generate structures prone to structural failure occurrence.

It is also important to take into account the general size of the structure to be created by generative design so to be able to be manufactured.So, the maximum building volume of the 3D printing machine can notbedisregarded during the design stage.

So, it can be concluded that it is possible to design a cargo drone using the generative design tool based on additive manufacturing that can competewithcommercial drones designed by conventional design means in terms of mechanical resistance, organic design, cost and design flexibility. Thus, with the present evolution of additive manufacturing technologies and increasing processing speed of computers, it can be expected that generative design becomes more and more common in educational and hobbist environments.

In future works, computational structural analyses(FEA) of the drone parts here presented are to be performedwiththe aim to validate the structural integrity during the flying maneuvers revised in this work. It is also planned to manufacture them using additive manufacturing technologies as well as toperformexperimental tests of these drone parts.

APPENDIX A: Evaluation of loads

a.1. Evaluation of loads induced by take-off motions

The first loading is the maximum rotor thrust (E_{max}), which can be calculated from the mass that the rotor can lift and the acceleration of gravity. So, using Newton's second law:$E_{max} = m \times g \rightarrow E_{max} = 1.52\ kg \times 9.81 \frac{m}{s^2} = 14.92\ N$.

As the other rotors, the brushless rotor also generates a torque when operating. According to Hendershot and Miller (2010), the maximum torque value (T_{max}) is given by:

$$T_{max} = K_t \times I_{max} \rightarrow T_{max} = \frac{60}{2 \times \pi \times KV} \times I_{max} \rightarrow T_{max} = \frac{60}{2 \times \pi \times KV} Nm/A \times 60\ A \rightarrow T_{max} = 0.88148Nm$$

K_T is the motor torque constant, I_{MAX} is the maximum motor current during operation, and KV is the motor-specific RPM/Volts ratio.

a.2. Evaluation of loads induced by roll, pitch and yaw motions

With the maximum torque and maximum thrust values, it can be calculated the magnitudes of motor torques and thrusts at other situations. For pitch, yaw and roll motions (Fig. 11), it is necessary that the pairs of rotors have different thrusts. Thus, it was adopted: $E_{max} = 1.5\ \times E \rightarrow 14.92\ N = 1.5\ \times E \rightarrow E = 9.95N$ and $T_{max} = 1.5\ \times T \rightarrow 0.88148\ N.m = 1.5\ \times T \rightarrow T = 0.58766N.m$

a.3. Evaluation of loads induced by turning manouvers

For the turning movements (Fig. 11), it was adopted:
Rotor 1 (side of turning manouver) has weight 1.0 of the motor power
Rotor 2 (rotor located diagonally opposed torotor 1) has weight of 2.0rotors
Rotors3 and 4 (remaining rotors) have weight 1.5
Thus:

$E_{max} = 2\ \times E_{min} \rightarrow 14.92\ N = 2\ \times E \rightarrow E_{min} = 7.46N$

$E_{min} \times 1.5 = E_{med} \rightarrow E_{med} = 1.5\ \times 7.46N \rightarrow E_{med} = 11.19N$

$T_{max} = 2\ \times T_{min} \rightarrow 0.88148Nm = 2 \times T_{min} \rightarrow T_{min} = 0.44074Nm$

$T_{min} \times 1.5 = T_{med} \rightarrow 0.44074Nm = 1.5 \times T_{med} \rightarrow T_{med} = 0.66111Nm$

Where E_{MIN} is the minimum thrust that the rotor will generate, E_{MED} is the median thrust, T_{MIN} is the minimum torque that the rotor will generate and T_{MED} is the median torque.

According to Burggräf et al. (2019), the difference in thrust and torque of drone rotors can generate up to three different torques in its structure and these are responsible for roll, pitch and yaw motions and, when combined, are responsible for cornering motions.

$$[\tau_\phi \quad \tau_\theta \quad \tau_\psi] = [l \times (F_d - F_b) \quad l \times (F_a - F_c) \quad (\tau_b + \tau_d) - (\tau_a + \tau_c)]$$

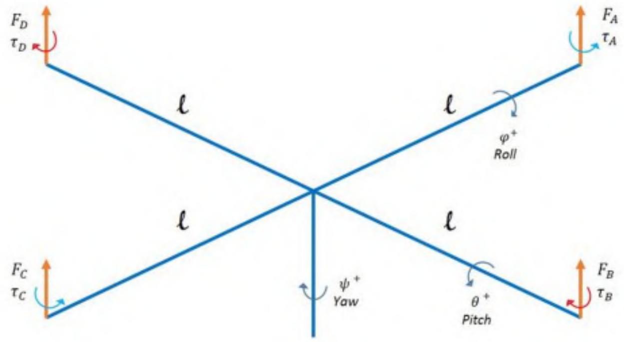

Figure 11– Forces and moments in an ideal quadcopter

a.4. Evaluation of weight loads

With the mass value of the payload, it is possible to determine its weight force (W_{PL}): $W_{PL} = m \times g \rightarrow W_{PL} = 1.5kg \times 9.81\ m/s^2 \rightarrow W_{PL} = 14.92N$

Since the payload will be attached to the four landing gears, its weight will be divided equally between them.

In addition, the weight of the electronic components must be calculated. On the lower plataform will be allocated the battery, the Foxeer camera and the telemetry receiver. Therefore, the force weight of these components ($W_{EC\ LP}$) can be calculated as: $W_{ECLP} = m \times g \rightarrow W_{ECLP} = 0.6726\ kg \times 9.81\ m/s^2 \rightarrow W_{ECLP} = 6.6N$. On the upper platform will be allocated the remaining components, which will have a weight $W_{EC\ UP}$ given by:

$W_{ECUP} = m \times g \rightarrow W_{ECUP} = 0.2396\ kg \times 9.81\ m/s^2 \rightarrow W_{ECUP} = 2.36N$.

Calculating the estimated weight force of each landing gear (W_{LG}):

$W_{LG} = m \times g \rightarrow W_{LG} = 0.06\ kg \times 9.81\ m/s^2 \rightarrow W_{LG} = 0.59N$.

a.5. Evaluation of load induced by collision

Finally, calculating the force (F_c) acting on the drone during impact by varying its amount of movement and considering such force constant with time, we have:

$$I = \Delta P = \int_{t_i}^{t_f} F_c(t)dt \rightarrow m \times \Delta v = F_c \times (t_f - t_i)$$

Considering that the collision will be enough to completely stop the drone (with an initial flight speed of 6 m/s), the collision start time (t_i) as 0 s and the end time (t_f) as 0.085s (due to the difficulty in finding information about collisions involving drones, it wasused the information obtained from Warner's (2004) work about collisions between cars and poles), we will have: $3.6 \times (6-0) = F_c \times (0.085 - 0) \rightarrow F_c = 254{,}18N$

Since the impact force will be applied to both arms that will suffer the collision, this force will be divided equally between both arms.

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