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PERFORMANCE OF 3D PRINTED CONVENTIONAL AND TOROIDAL PROPELLER FOR SMALL MULTIROTOR DRONES

Abstract: *This paper presents a study on the design, fabrication, and performance evaluation of a quadcopter with toroidal propellers manufactured using 3D printing technology. The quadcopter's propellers were designed to have a toroidal shape, which is believed to improve the aerodynamic efficiency of the propellers compared to conventional propellers. To evaluate the performance of the quadcopter, finite element analysis (FEA) was used to simulate the propeller's behavior under different load conditions. In addition, thrust analysis was performed using ANSYS Fluent software to evaluate the thrust produced by the toroidal propeller compared to conventional propeller. These results provide insight into the potential benefits of toroidal propellers and 3D printing technology for the design and development of efficient quadcopters.*

Key words: *Quadcopter drone, toroidal propeller, aerodynamic efficiency, thrust, 3D printing, FEA.*

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) or Unmanned Aerial Systems (UAS), otherwise known as drones, are aircraft that can fly unmanned and without passengers on board [1].

One of the first drone creators was Charles Kettering, who in collaboration with Elmer Sperrym, Orville Wright and Robert Milikanem created in 1915 an aircraft called the "Kettering Bug". It was a primitive automatic aircraft, which, based on the sensors, defined the height (using a barometer) and the distance traveled (depending on the number of engine revolutions) [1].

The use of UAVs is now becoming part of the normal operating procedures for many public and private organizations. Especially in security, surveillance and research applications [2]. The growth of these applications has led to technological improvements in several areas such as sensors, programming technology, digital processing units, energy storage (batteries), etc. [3].

Drones can be classified by the criteria: (flight mode, application domain and energy supply).

The way of which an aircraft, in our case an UAV, can maneuver through the air is either in fixed wing configuration or vertical thrust configuration, also a combination of both is possible.

Another way to differentiates drones is in which field of use they are found.

UAVs used in the military domain are machines capable of loitering for a long time and at a high altitude, tasked with eliminating or spying enemy installations, without the risk of losing any friendly personnel in the process [4].

Drone technology offers enormous benefits and opportunities for a wide range of disciplines. Drones support tasks such as humanitarian work, disaster risk management, research and transportation [4].

In agriculture, drones can provide real-time images and data from sensors in agricultural fields that cannot be quickly accessed on foot or by vehicle (data such as fertilization or crop growth rate) [4].

Aerial delivery of drone drugs to health facilities in remote communities with reduced road infrastructure and heavy relief has been successfully achieved in some African countries Rwanda and Ghana [4].

The applicability of drones does not necessarily have to be found only in critical areas of great interest, for example, commercial drones (quadcopters) can be used to photograph / film private events or even recreational activities such as drone racing.

There are four main sources of energy: traditional aircraft fuel, battery cells, fuel cells and solar cells [5].

A quadcopter is a four-rotor unmanned aerial drone that runs with the same principle as of a helicopter. Vertical lift is generated by the spinning of the propeller's blades pushing the air downward (Figure 1). The Newton's third law states that if an object A applies a force on object B, then object B must apply the same force of equal magnitude, but in opposite direction back on object A, thus in our case the rotor symbolizing the object A, and the air fluid resembling object B [6].

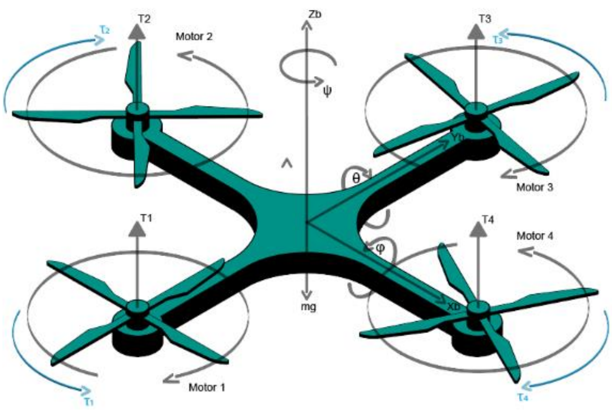

Figure 1 The forces that are present in the dynamic assembly of a quadcopter.

Figure 1 shows the different forces acting on the system (drone) [6], where:

T = Traction (force)
ϕ = Roll angle
θ = Pitch angle
ψ = Yaw angle
m = Mass
ω = Rotation (engine)
τ = Reaction force
g = gravitational acceleration

A quadcopter can be summed up as a complex of varied parts of sensors (Figure 2), some of the most essential's components being:

- Brushless motors or another type of electric motor that is able to produce torque [7];
- Speed controllers, which are coupled to the motors and the sole purposes of them is to control the speed of which the rotor is spinning [8] (Figure 3);
- Propellers have the role of creating lift. Lift is possible because of the difference of pressures created between the propellers. The propellers combined with the motors work together to generate thrust [9].

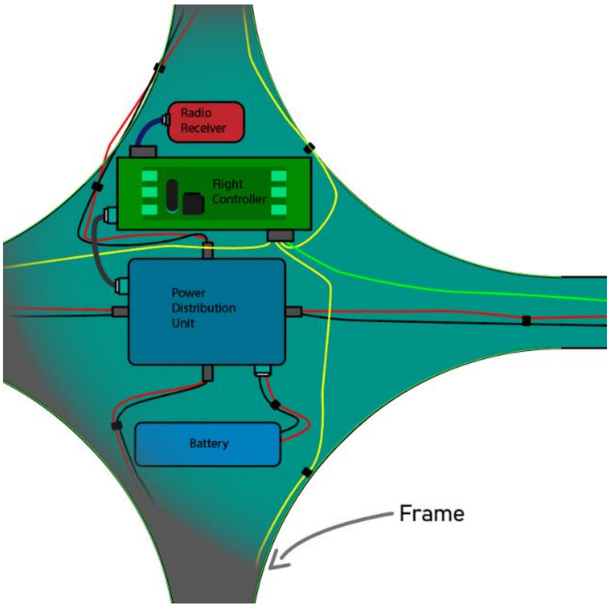

Figure 2 Diagram showcasing the essential components of the main body of a quadcopter.

There are many configurations in which a propeller can take shape. A new concept pioneered by MIT utilizes a toroidal shaped propeller in an attempt to decrease the noise levels heard by the human ear [10].

ESC (electronic speed controllers) purpose is to adjust the speed of the rotors. It does this by utilizing BEC (battery elimination circuit), that basically alternates the voltage being sent to the motor from the power distribution unit [8].

LiPo (Lithium polymer battery) or any other type of energy source that is capable of powering the entire system is a vital part.

The power distribution unit carries the current from the battery throughout the entire airframe and its modules.

Flight controller can be summarized as the brain of the quadcopter. It is capable of analyzing the flight performance through its sensors and to also process input commands [9].

Radio receiver, as the name suggests, it receives radio signals from the emitter.

The air frame represents the main body of any aircraft, with the sole purpose of holding every component together [9].

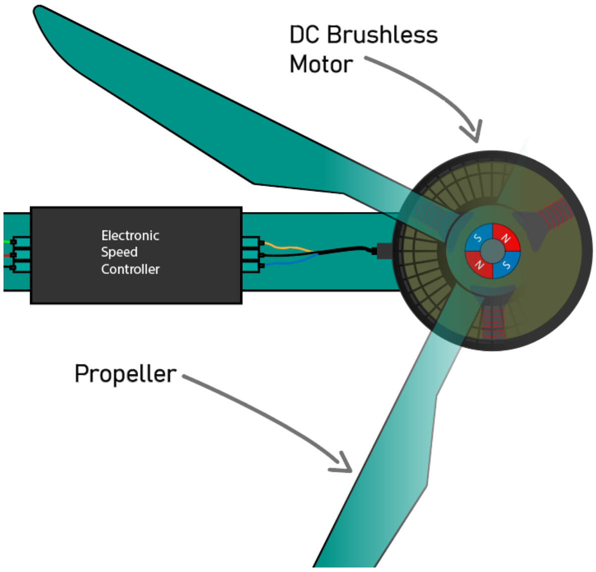

Figure 3 Diagram showcasing the essential components of an arm of a quadcopter.

FDM also known as "fused deposition modelling" is a manufacturing method that is used for prototyping and creating functional parts out of thermoplastic materials such as PLA, PETG, ASA, Nylon [11].

The concept of FDM 3d printing is adding layer by layer of melted plastic material through the extruder onto a heated bed till the desired product takes shape [12].

Well established software programs like Ansys or Nastran are capable of analyzing complex geometries in specific conditions by generating a mesh composed of finite elements.

2. MATERIALS AND METHODS

The chosen propeller designs for this project began from a simple twin blade 6-inch (127mm) propeller with a pitch of 4 inches (101mm), followed by a toroidal propeller design with similar length. The 3d models were realized using Autodesk's Fusion 360 CAD software. The geometrical construction of the conventional propeller was done through the 3 NACA airfoil profiles using the loft command in order the generate the first body of the propeller.

The two NACA profile were acquired from http://airfoiltools.com/ [13].

The second propeller was built by making a profile than "sweeping" it at a certain distance and angle.

After the propeller geometry is made, the model is exported to a .STEP file and loaded into Ansys Fluent for force and velocity analysis. Before generating the mesh, two domains were created, a rotational domain and a static domain, in order to recreate the appropriate flow conditions. The boundaries and relationships created for this paper are similar to those used by Faraz Ahmad et al. in their study [14].

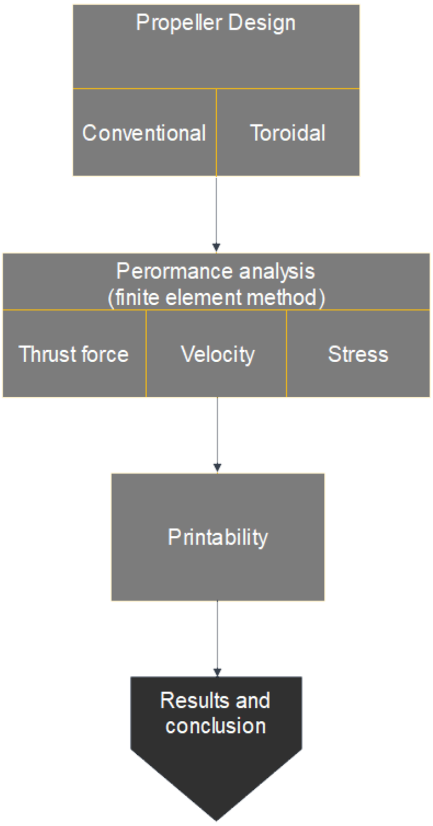

Figure 4 Steps taken in creating and evaluating the propellers.

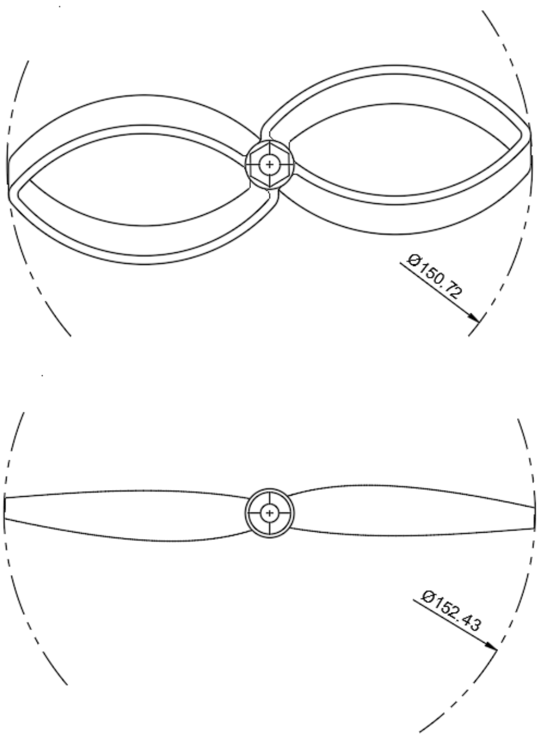

Figure 5 Top view of the designed propellers showcasing their length span.

Figure 6 Isometric view of the propellers.

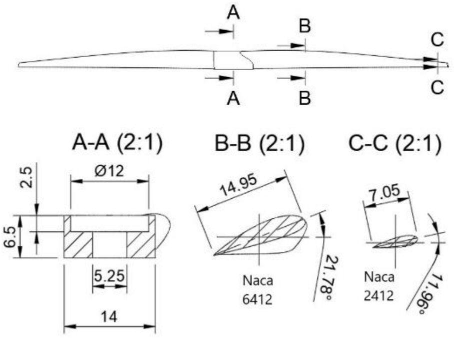

Figure 7 Section view of the NACA profiles used for the first propeller.

A mesh with an element size of 40 mm is added to the rotation domain and a simpler mesh of 80 mm is added to the static domain. An inlet and an outlet are created to facilitate air flow Fig 8.

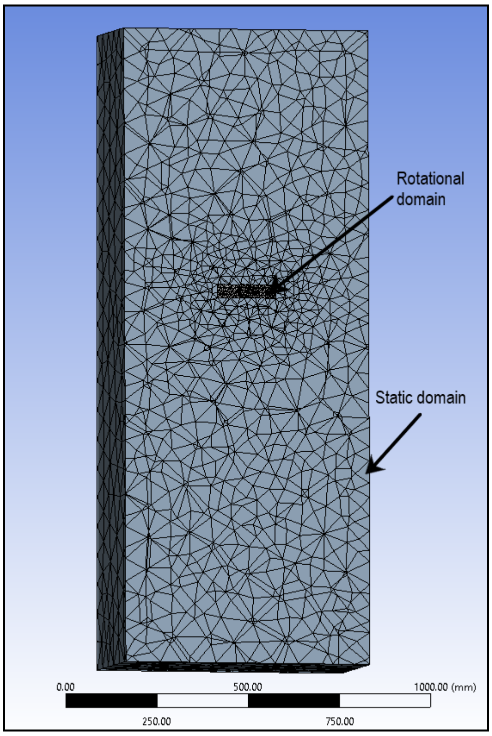

Figure 8 The mesh geometry formed over the first propeller.

The simulation was performed from an angular velocity range of 1,000 to 20,000 revolutions per minute.

An identical process is performed for the toroidal propeller as well.

Table 1

Parameters used for the thrust force analysis.

Parameter	Value
Gravity	9.81 m/s^2
Time	Transient
Viscous model	K-Epsilon (realizable)
Near wall treatment	Scalable wall function
Flying medium	Air
Inlet air velocity	0,1 m/s
Number of iterations	121
Time step size [s]	0.15
Number of time steps	30

Autodesk Nastran was used to perform the centrifugal analysis on the propeller body.

The first step in this study is to assign a material to the propellers, the chosen material being ASA. Acrylonitrile styrene acrylate or abbreviated ASA is a thermoplastic material with the potential to be 3D printed using FDM technology. The mechanical properties of ASA are similar to ABS, with a big difference being the high UV resistance.

A new mesh was created in Fusion 360 with a new set of constraints and loads. The center-bottom plate of the propeller was fixed and a rotational force was added on the Y-axis, Figure 9.

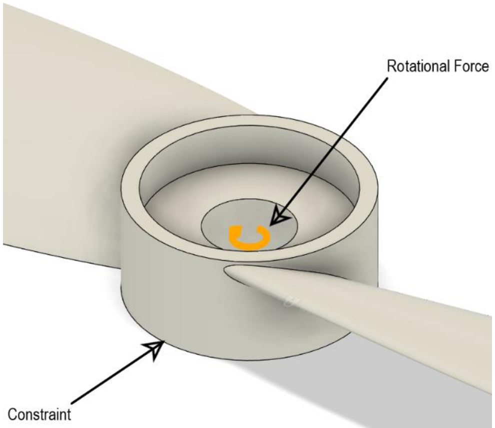

Figure 9 Showcase of the boundary conditions used for the conventional propeller.

Table 2

Parameters used for printing the conventional propeller

Parameter	Value
Layer height	0.15mm
Extruder temperature	250 ° Celsius
Infill density	10%
Bed temperature	90° Celsius
Print speed	40mm/s
Cooling	20%
Support	Grid
Build plate adhesion type	Brim
Draft Shield	On
Coasting	On
Retraction distance	5mm
Flow	95%

Similar conditions were adopted for the analysis of the toroidal propeller.

The two 3d models were exported as .stl files and loaded into the slicer software. The chosen slicing software for the 3d printing process regarding this paper was *Ultimaker Cura*.

10% infill was chosen due to the larger single surface that permits maintaining constant infill pattern.

Table 3

Parameters used for printing the toroidal propeller.

Parameter	Value
Layer height	0.15mm
Extruder temperature	250° Celsius
Infill density	100%
Bed temperature	90° Celsius
Print speed	40mm/s
Cooling	20%
Support	Grid
Build plate adhesion type	Brim
Retraction distance	0.5mm
Flow	110%

The models were printed on a QIDI TECH-Plus II printer, using FormFutura brand ASA ApolloX as material.

3. RESULTS

In this chapter, the results of the analyzes performed using Ansys fluent and Nastran software for the proposed propeller models are presented. Analysis of the propulsion evaluation and the speed gradient.

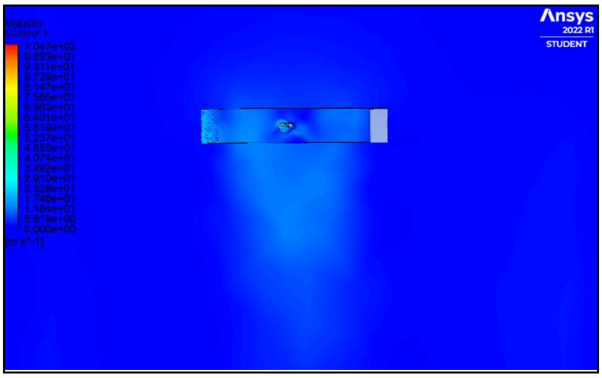

Figure 10 Velocity gradient displayed perpendicularly, illustrating the air flow.

In Figure 10, the air speed differences can be seen in the form of a gradient. The black rectangular outline represents the rotating domain described in the previous chapter. In this image you can see how the propeller works, creating the pressure difference needed to generate lift.

In Figure 11, the blue region represents the minimum angular velocity on the propeller model, and the red region represents the velocity threshold peak. From this data it follows that the geometric model of the propeller conforms from an aerodynamic point of view.

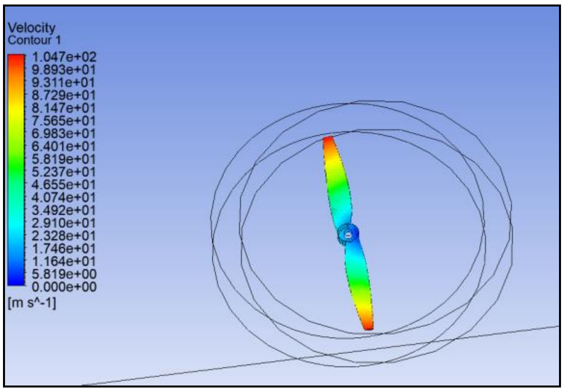

Figure 11 Velocity gradient displayed on the conventional propeller.

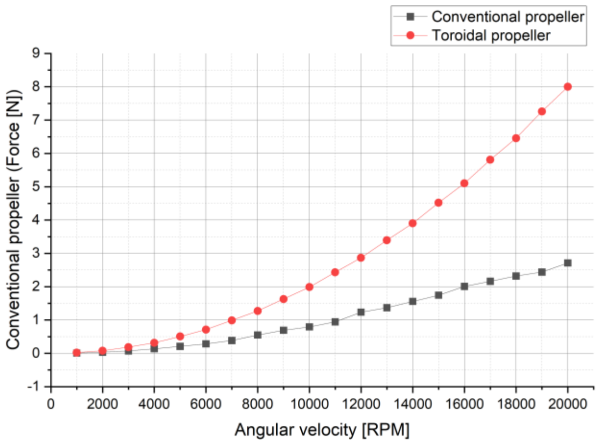

Figure 12 Thrust force generated by the two propellers.

The results of the thrust force analysis are plotted in figure 12, along with each individual load table 4,5.
The conventional designed propeller saw a jump in the generated force capacity, starting from the value of 6000 revolutions per minute. Following the analysis, it can be highlighted that at the value of 12000 RPM the propeller has the highest degree of efficiency, for the selected threshold (Figure 12). The toroidal propeller performs significantly better than its competitor, outputting it at every RPM value. As a sidenote the standard twin blade plateaus a lot sooner than the toroidal one (Figure 12).
Table 4 and 5 illustrate the numerical values registered in the thrust analysis.

Table 4

Thrust results for the conventional propeller.

Angular velocity [RPM]	Force[N]	Load [KgF]
1000	0.0083	0.00084
2000	0.0319	0.00325
3000	0.0717	0.00731
4000	0.1366	0.01392
5000	0.2092	0.02133
6000	0.2836	0.02891
7000	0.3843	0.03918
8000	0.5515	0.05623
9000	0.6919	0.07055
10000	0.79381	0.08094
11000	0.9444	0.09630
12000	1.2351	0.12594
13000	1.3679	0.13948
14000	1.5576	0.15882
15000	1.744	0.17783
16000	2.0077	0.20472
17000	2.1617	0.22042
18000	2.3185	0.23641
19000	2.43715	0.24851
20000	2.7116	0.27650

Table 5

Thrust results for the toroidal propeller.

Angular velocity [RPM]	Force[N]	Load [KgF]
1000	0.021	0.00214
2000	0.0785	0.008004
3000	0.1843	0.018793
4000	0.316	0.03222
5000	0.506	0.05159
6000	0.713	0.07270
7000	0.988	0.10074
8000	1.273	0.12980
9000	1.629	0.16610
10000	1.988	0.20271
11000	2.431	0.24788
12000	2.867	0.29234
13000	3.394	0.34608
14000	3.904	0.39809
15000	4.521	0.46100
16000	5.104	0.52045
17000	5.81	0.5924
18000	6.456	0.65831
19000	7.261	0.74040
20000	7.997	0.81545

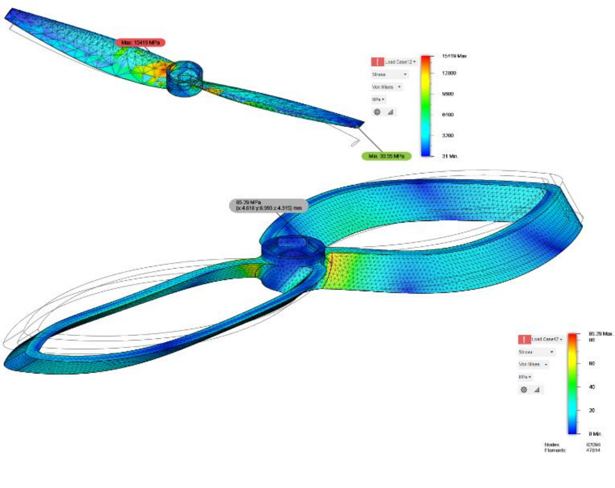

Figure 13 Mesh generated showcasing the breaking point of each propeller at 12000 RPM.

Figure 13 shows the points of maximum mechanical stress suffered by the propellers. The maximum values, for each propeller, are located between the root that connects the hub to the blade.

The results of the 3D printing process are displayed by figure 14 and figure 15.

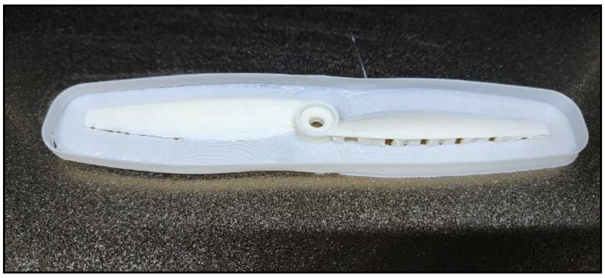

Figure 14 Conventional propeller with the support still attached.

Figure 15 Toroidal 3D printed propeller.

4. CONCLUSIONS

According to the study, the design of both propellers is a capable design and can be used in a quadcopter of small dimensions, but the material chosen cannot tolerate a high value of centrifugal force. A stiffer and stronger material, such as carbon fiber PETG or nylon PA12, would make a suitable replacement for the propeller.

A good guess for the improved thrust of the toroidal version has to do with the toroidal propeller having a larger surface. This improvement doesn't come without a drawback though, for when we compare the volume of material used per propeller, the toroidal propeller outweighs the conventional one by approximately 3 grams. Another positive regarding the toroidal propeller is that the design is simpler and more printable, requiring no support.

There's a very low chance of a 3D printed propeller outperforming an injected molded one, but 3D printing represents a useful tool in prototyping and plotting expectations. The propellers can be printed but require finishing processes, such as removing the support, sand it and balancing it to bring it to a usable stage.

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