QUADROTORS: A REVIEW ABOUT FUNCTIONALITIES AND COMPONENTS

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Abstract: Quadrotors are a kind of unmanned aerial vehicle (UAV) with 4 propellers that have been utilized for civilian and military porpoises. This paper brings the study of the state of the art about quadrotors, making a review about the main components of the vehicle and main functionalities, like control, trajectory planning and localization.

Keywords: Quadrotors; Components; Control; Trajectory Planning; Localization.

QUADROTORES: UM *REVIEW* SOBRE FUNCIONALIDADES E COMPONENTES

Resumo: Quadrotores são veículos aéreos não tripulados (VANTs) com 4 propulsores que têm sido utilizados para fins civis e militares. Esse artigo traz o estudo do estado da arte sobre quadrotores, fazendo um *review* sobre os principais componentes desse veículo e principais funcionalidades, como controle, planejamento de trajetória e localização.

Palavras-chave: Quadrotores; Componentes; Controle; Planejamento de Trajetória; Localização.

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Atribuído a BIR robotics

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1. INTRODUCTION

The usage of quadrotors, a kind of unmanned aerial vehicle (UAV) with 4 propellers, has been growing in many areas, such as civil, military and academic because they are very agile robots, with great maneuverability and payload, in addition to perform stationary flights and also vertical take-off and landing.

In military applications, they can be used in espionage, monitoring, reconnaissance, and surveillance missions. They do not require an onboard pilot, not putting the operator at risk. Also they can be very small, so they can be used in search and rescue missions in hostile environments, such as in landslide situations.

In the civil area, their use has become very popular for entertainment. Several models are marketed with an exclusively recreational purpose, often equipped with cameras to capture images. In the cinematographic area, they have been used to make videos and aerial photographs, replacing helicopters, which had higher associated costs to perform this type of operation. Their usage has also become popular in precision agriculture [1], to perform crop monitoring, agricultural irrigation, seeding, and pesticide distribution. At the beginning of the year 2022, ANAC (*Agência Nacional de Aviação Civil*) allowed the first delivery with UAVs in Brazil [2]. In the academic environment, quadrotors are used as a platform to test control strategies, given the difficulty of the stabilization and control of this type of vehicle. Also to test trajectory planning techniques. The working space is three-dimensional, making the solutions more complex and expensive.

The quadrotor is a rotary-wing aircraft, so it has a high energy consumption, because it has to sustain its whole weight with the propulsion of its rotors, different from fixed-wing aircrafts, that the horizontal movement helps it to sustain the weight in the air. Due to that, it is ideal to minimize the efforts needed to control the aircraft and study more efficient batteries to maximize the time of flight without recharging. The researches about quadrotors focus nowadays on themes like dynamical control and trajectory planning to optimize the energy cost and to do feasible trajectories without colliding with obstacles. The study about localization is also important to guarantee a correct information to feed back the control and trajectory planning structure. Researches about wireless recharging have been done [3], where the drone can have a recharging station. To reach this kind of station is a good thing that the drone can do that autonomously.

This research presents the main academic studies about the most used techniques applied in the functionalities of control, trajectory planning and localization, found through the BiLi Method, the methodology used in this review. Searches about the main components used in this kind of vehicle were done too.

2. METHODOLOGY

This study of the state of the art was developed mainly from the BiLi method [4], Figure 1, which allows a bibliographic search in a database of scientific articles, publications in journals, books and other sources of scientific knowledge, surveying the publications and the most impactful authors in the researched area. Targeted

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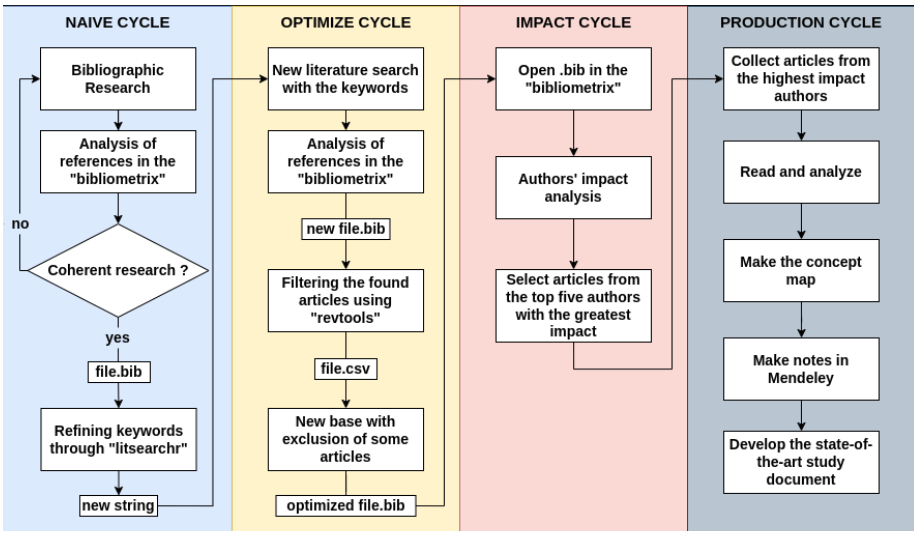
Comentado [26]: cada tópico merece um parágrafo introdutório. favor incluir searches for each theme were carried out in the chosen database. The BILI method is divided into four cycles that happen in sequence. They are called the naive cycle, optimized cycle, impact cycle, and production cycle.

Figure 1 - BiLi Method Schematic



The result of the method is a set of articles of the most impactful authors about the searched themes, where the techniques about control, trajectory planning and localization can be studied and the main components utilized can be found.

The string found in the optimize cycle for control was ("aerial vehicle" OR "quadrotor uav" OR "quadrotor system" OR "quadrotor unmanned" OR "rotor unmanned" OR "unmanned aerial" OR quadrotor) AND ("adaptive control" OR "attitude control" OR "backstepping control" OR "control approach" OR "control design" OR "control strategy" OR "control system" OR “flight control" OR "position control" OR "robust control" OR "sliding mode control" OR "stability analysis" OR "tracking controller") AND ("disturbance rejection" OR “external disturbance" OR "external disturbances") AND ("tracking performance" OR "trajectory tracking" OR "tracking error") AND (“quadrotor” OR “quadcopter”) resulting in 391 articles. After the filter a number of 381 articles was reached.

The string found in the optimize cycle for trajectory planning was (“quadrotor” OR “quadcopter”) AND (“uav” OR “unmanned aerial vehicle” OR “unmanned aerial vehicles” OR “unmanned aerial”) AND (“path planning” OR “trajectory planning” OR “motion planning” OR “planning algorithm”) resulting in 309 articles. After the filter a number of 138 articles was reached.

The string found in the optimize cycle for localization was ("aerial vehicle" OR aircraft OR drone OR "micro aerial" OR quadrotor OR "unmanned aerial") AND ("autonomous navigation" OR localization OR "pose estimation" OR "simultaneous localization" OR slam) AND (reliable OR robust) AND ("inertial measurement unit" OR lidar OR vision-based OR "visual odometry" OR "kalman filter" OR landmark) resulting in 263 articles.

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3. RESULTS AND DISCUSSION

The most important techniques used on the functionalities of control, localization and path planning will be described in the following sections. Also the study about main components evolved in a conception of this kind of vehicle.

3.1 Battery

A major challenge to be faced when working with rotary-wing aircrafts is the autonomy of the battery. Thanks to the large energy consumption that these aircraft have to sustain themselves in the air, the time of flight without recharging is very low.

The most widely used batteries for UAVs are lithium polymer batteries (LiPo). This type of battery has one of the best capacity-to-weight ratios, which is of vital importance for this type of vehicle, since the weight of the batteries can represent up to 50% of the weight of the aircraft, as shown in [4]. LiPo batteries have a regular capacity and a good life cycle. In [5], a study of the energy consumption of multirotors and a modeling for estimating the autonomy of the vehicle operating with LiPo batteries is done.

3.2 Microcontroller

The microcontroller is responsible for performing the communication between components and functionalities and the implementation of the controller that will act on the thrusters. There are several models on the market, with different operating frequencies or clock, flash memory, RAM, EEPROM, and supply voltage. The clock determines how many operations the microprocessor can do per unit of time, the higher the speed, the shorter the time between control actions, making the control more precise. Among the most widely used platforms are Arduino, Raspberry, ARM, PIC, ESP32 and Teensy. The Arduino platform is based on ATmega chips, reaching a maximum frequency of 84 Mhz in its Arduino DUE model, with 96 kB SRAM and 512 kB flash memory [6]. The Raspberry Pi platform uses ARM chips, with its Raspberry Pi 4 model using 4 ARM cores with 1.5 Ghz clock [7]. The Teensy platform is based on ARM chips, its teensy 4.0 model featuring a 600mHz ARM Cortex-M7 chip [8]. As shown in a benchmark that measures the number of operations per second of microcontrollers doing common tasks, shown in Figure 2, but which does not include the Raspberry Pi 4, the Teensy 4.0 comes out as far superior to all other options.

Figura 2 - Microcontrollers Comparison [8]

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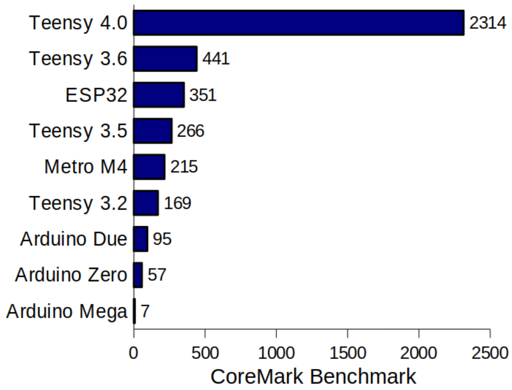

3.3 Localization

Localization is the step responsible for determining where the quadrotor is in the environment. Localization algorithms need to be able to handle noise and generate not only an estimate of the location, but also measure the uncertainty of that estimation. The most suitable technique will vary according to the environment, available sensors, controller processing capacity, mission, among others. In outdoor environments, where we don't have a map, SLAM (simultaneous localization and mapping) methods are more suited.

Using a GPS receiver, a camera and IMU (Inertial Measurement Unit) is sufficient to precisely estimate the pose of the UAV [9]. LIDAR as a localization sensor for drones is not usual due to its high cost, energy requirements, limited view angles, complexity and weight.

The vision-based techniques are split into two main categories: Feature-based and Direct. The first extract a sparse set of salient image features (points, lines, etc.) in each image; match them in successive frames with invariant feature descriptors; robustly recover both camera motion and structure using geometry and finally, refine the pose and structure through re-projection error minimization. The direct approach estimates structure and motion directly from the pixel values in the image, the local intensity gradient magnitude and direction is used in the optimization [9]. Forward, we present some state of the art of algorithms to perform real time localization in a UAV.

SVO (Semi-direct Visual Odometry) is a visual-based technique that uses a camera to track the robot's movement and estimate its position and orientation. It's very efficient and accurate, capable of run in real-time using low power computer (2 cores at 1.6 GHz or more) and can be used in indoor or outdoor environments. The semi-direct approach eliminates the need of costly feature extraction and robust matching techniques for motion estimation. Instead, a direct method is used, which is based directly on the image intensities [9].
ORB-SLAM2 is a feature based method (indirect) that uses the ORB (Oriented FAST and rotated BRIEF) [10] feature because of the speed in which these can be extracted from images and there rotational invariance. Can be used as a complete

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SLAM or just as a localization system (without mapping) for monocular, stereo and RGB-D cameras. The localization only mode is useful when the environment is known. In SLAM mode it computes the view trajectory and generate a sparse 3D reconstruction of the environment, using features like map reuse, loop closing, and re-localization capabilities. The system works in real time on standard central processing (2 cores at 3.5 GHz or more) units and can be used in indoor or outdoor environments [11].

DSO (Direct Sparse Odometry) is a visual-based technique that uses a direct approach for visual odometry. Combining a fully direct probabilistic model with consistent, joint optimization of all model parameters, including geometry-represented as inverse depth in a reference frame and camera motion. This is achieved in real time on simple CPU (1 core at 3.4GHz or more) by omitting the smoothness prior used in other direct methods and instead sampling pixels evenly throughout the images. It combines the benefits of direct methods (seamless ability to use & reconstruct all points instead of only corners) with the flexibility of sparse approaches (efficient, joint optimization of all model parameters), map reuse, loop closing and re-localization capabilities [12].

LSD-SLAM (Large-Scale Direct Monocular SLAM) is a direct algorithm, instead of using key-points (like ORB-SLAM), it directly operates on image intensities both for tracking and mapping. That a allows building large-scale, consistent maps of the environment. Along with highly accurate pose estimation based on direct image alignment, the 3D environment is reconstructed in real-time as pose-graph of keyframes with associated semi-dense depth maps. This leads to higher accuracy and more robustness in sparsely textured environments, and a much denser 3D reconstruction. It's very efficient and can run in real-time on a CPU of 3.5 GHz or more, and even on a modern smart-phone [13].

3.4 Control

Quadrotors have unstable behavior, so they require an appropriate and well-tuned control structure to make possible the path following task. This structure is usually organized in cascaded levels, where the low level is responsible for the rotational speed of the rotors, the intermediate level for altitude and angular velocities, and the high level for linear positions in three-dimensional space. Each level has a type of controller required to perform its tasks. For example, at the low level the most commonly used controller is the PID, given the simplicity of the rotor dynamics. At the intermediate level, linear or nonlinear controllers can be used. Linear controllers require linearization at the operating points to achive a linear model of the vehicle.

In the linear group, the main controllers are the PID, the LQR, and the H∞. The PID controller was one of the first to be developed and is usually used as a parameter by other approaches. Its implementation relies only on empirical adjustments to its parameters, requiring no knowledge of the system dynamics. LQR is based on state feedback, minimizing a cost function that weights the control signal and the reference tracking error. H∞ is also based on state feedback, but it works by minimizing the H∞ norm by solving linear matrix inequalities.

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Comentado [76]: bem ... o tópico é localização mas estamos falando de drones então vcs deveríam se ater a localização em drones mostrando prós e contras de cada exemplo. Vcs estão descrevendo cada modelo, isso é bom mas o foco deve ser em drones

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The main nonlinear controllers are Backstepping, SMC and Fuzzy. Backstepping is a recursive technique based on the Lyapunov criterion, making it a controller capable of stabilizing the aircraft formally. It is commonly used for attitude control and is efficient in maintaining the orientation of the quadrotor even under strong disturbances. SMC (Sliding Mode Control) is also based on Lyapunov's criterion, where switching functions generate trajectories that define a sliding surface. This technique unites robustness with speed of convergence, enabling the aircraft to perform difficult trajectory missions and cope with large parameter variations and disturbances. In the fuzzy technique, belonging functions map inputs and outputs of the system, and can be combined with other control techniques. It has been used for altitude and orientation control using as input the designated power of each engine.

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3.5 Trajectory Planning

Trajectory planning is crucial for the quadrotor to become a completely autonomous platform. Through this functionality the vehicle can calculate a route to move from its current position to a final position without human interference, avoiding collision. The main articles about this functionality found in this study are described as follows.

In [14] a comparison study was done between trajectory planning through a genetic algorithm (GA) and particle swarm optimization (PSO) in simulation. Both techniques presented good solutions in relatively short computational times. As a conclusion it was observed that with statistical significance GA presents better trajectories than PSO. To compare the results the t-test was performed on the cost function.

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In [15] the trajectory planning is made through Artificial Potential Field (APF), which is implemented through an algorithm of simple structure, with a consistent mathematical description and convenient for real-time control, besides having great portability, being able to solve the problem of obstacle avoidance by changing the source of the artificial potential field. The technique can also be used for flight path planning in multiple UAV formations. Despite its many advantages, APF in the standard configuration does not result in the optimal trajectory, and it can be combined with other techniques such as genetic algorithm or evolutionary algorithm to improve its results. APF is based on the idea that the destination acts as an attractive potential field for the UAV, while obstacles act as repulsive potential fields. In this research, APF is reconstructed on constrained optimization introduced with the additional control force.

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In [16], an optimization algorithm derived from Central Force Optimization (CFO), called the Modified Central Force Optimization. CFO is a smart particle optimization algorithm based on the law of gravity, where each solution is a particle. The particles attract each other with the virtual gravitational force. The masses of these particles are dependent on the cost function of each solution. In the CFO metaphor, when a mass is under strong influence, it gets trapped in its gravitational field, which is analogous to finding a maximum value for an objective function. In MCFO concepts from Particle Swarm Optimization (PSO) are added in addition to the genetic algorithm (GA) mutation operator to improve CFO results. The research results showed superior simulation results compared to techniques with the CFO, GA, PSO and random bucket algorithm.

4. CONCLUSION

In this paper the state of the art study of quadrotors was done using the BiLi method. The BiLi method was important to bring the most impactful authors and the most researched areas on the subject, and other searches were made in Scopus more directed to each subject to complement the bibliographic collection. A search was made of the main components too. And finally, the study of the main functionalities involved in quadrotor projects, such as localization, control and trajectory planning.

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