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Review article

PID control of quadrotor UAVs: A survey☆

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ABSTRACT

The proportional–integral–derivative (PID) control is the most common control approach used in industrial and commercial mechatronics products. The PID control has been relevant across history since it is useful and intuitive in practical implementations. The selection of three parameters involving the present, past, and future of the system makes it simple and efficient. Unmanned aerial vehicles (UAVs) such as quadrotors have become very common and helpful in many tasks such as surveillance, mapping, and inspection, among others. Quadrotors present highly nonlinear and coupled dynamics that can be stabilized using four control inputs. These facts have prompted the attention of many control practitioners and theoretical specialists. The literature reveals that PID control has been the natural choice to stabilize quadrotor UAVs since its simplicity and robustness. The advantages of the PID control have been considered to perform combinations with other techniques. This paper surveys applications of PID control structures in quadrotor UAVs paying attention to linear, nonlinear, discontinuous, fractional order, intelligent and adaptive schemes. Future directions of PID control are also discussed, and open problems are highlighted.

1. Introduction

Since the beginning of the 2000s, the development of functional quadrotor unmanned aerial vehicles (UAVs) has become a very prolific topic since they can be applied to various tasks, from entertainment to military applications.

With the advancement of electronic technology, the development of long-duration batteries, low-cost inertial measurement units, high-speed microprocessors, and commercial and laboratory-built prototypes, quadrotor UAVs are every time more typical. At the same time, the community of control systems scientists has been more attracted to this topic since quadrotors present complex and nonlinear dynamics while having four input forces which are the thrust provided by each propeller connected to each rotor at a fixed pitch angle.

Essentially, the way of controlling a quadrotor is by varying the speed of each rotor, which implies that the delivered force by each propeller also varies. As described in Zhang et al. (2009): when the rotating velocities of all four motors are increased at the same amount, the quadrotor will fly upwards. When the left and right rotors operate at different speeds, the quadrotor will tilt around its longitudinal axis and fly rightward or leftward, depending on which motor rotates faster. Similarly, the quadrotor will tilt around its transverse axis and fly forward and backward depending on the front and rear motors. The yaw rotation is caused by the difference between the angular momentum generated by these two pairs of rotors. Therefore, the roll, pitch, and yaw angles, and total thrust can be utilized as the control variables for the onboard control of the quadrotor.

It is noteworthy that nonlinear second-order differential equations govern that quadrotor UAVs. The lack of damping terms and four control inputs are the main reasons for making the dynamics of the quadrotor UAV open-loop unstable.

Throughout history, the natural form of controlling a second-order system has been through the PID control since it reduces steady-state error and compensates for some disturbances. Besides, it adds a damping effect to the closed-loop dynamics. The PID control is a longevous control scheme in electrical, mechanical, and electronic systems. Furthermore, the PID control has been the predilection in commercial control boards and autopilots such as Pixhawk and ArduPilot. The practice has demonstrated that quadrotor UAVs can efficiently perform under PID control. As was mentioned in Lim et al. (2012): Most flight controllers implement PID controllers to stabilize the quadrotor, although the structure of the PID controllers varies slightly among the proposals. Besides, concerning commercial autopilots (Chao et al., 2010): Most commercial autopilots use traditional PID controllers because they are easily implemented on many off-the-shelf quadrotor platforms. For example, an autopilot for quadrotor UAVs based on PID control was developed in Zhih et al. (2015).

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The importance of PID control is still recognized since many scientific forums consider special sessions on the topic. Recently, an important conference devoted exclusively to the application of PID control was organized (IFAC, 2018).

Some surveys related to the modeling and control of quadrotor UAVs have been given in Li and Song (2012), Mo and Farid (2019), Nascimento and Saska (2019), Ozbek et al. (2015), Rubí et al. (2020), which address many types of control methodologies. Still, the importance and role of PID control should be recognized.

This manuscript is devoted to surveying and analyzing the scientific work concerning the design and application of PID control structures on quadrotor UAVs. It is worthwhile to notice that the number of research on the PID-type algorithms is so large that a manuscript devoted exclusively to enlisting and analyzing the history, trend, and future of the PID control of quadrotors is required.

1.1. Historical perspective

As explained earlier, the natural choice for controlling a second-order system subject to model uncertainties and external disturbances is the PID algorithm. Its application to the quadrotor UAV is not an exception. Studies in stabilizing the quadrotor UAV and applying the PID control seem to date back to 2004. To the best of our knowledge, the first application of the PID control in quadrotors was a discussion on the gain tuning in Bouabdallah et al. (2004), starting so the study of PID controllers for quadrotors in the context of scientific manuscripts.

Between 2004 and 2012, a few studies were reported, which aimed to present numerical comparisons without discussing real-time implementations nor the closed-loop stability. The formal study of the PID controllers in closed-loop with quadrotors UAVs started in 2010, where the first formal studies and criteria for gain tuning were given. Let us shortly comment on two examples: in González-Vázquez and Moreno-Valenzuela (2010), a stable time-scale separation introduced by a PID scheme was discussed, one first result based on Lyapunov's stability theory was provided in Lee et al. (2012).

The first papers reporting experimental results on PID control applied to a quadrotor UAV were the works Al-Younes et al. (2010), Bouabdallah et al. (2004), Campos et al. (2005), Hoffmann et al. (2010), Yang et al. (2010), Zhang et al. (2009). Although many control algorithms with experimental validation were reported during the last 25 years, it was a fact that a PID controller could stabilize the system experimentally. Nonetheless, theoretical studies with real-time experimental validation were not given attention until around 2010.

Summarizing, since 2010, it has been a significant increase concerning the formal study and experimental verification of PID control schemes for quadrotors. This manuscript is devoted to presenting a critical examination in this regard.

1.2. Contribution

Relevant surveys on methodologies to control quadrotors have been published. However, it is important to pay attention to the fact that the PID control is the most used control approach in commercial and laboratory-built quadrotors.

This manuscript presents an analysis of the PID-based control structures reported for the most common flight task and applications of quadrotor UAVs. The techniques are classified, and open problems are discussed.

1.3. Paper organization

This paper is organized as follows. Section 2 is devoted to the quadrotor dynamic model description. Sections 3.1 to 3.8 deal with linear, nonlinear, adaptive, event-based, gain scheduling, fault-tolerant, factional order, and intelligent PID control strategies. A few works combining model predictive control and PID control for quadrotors are commented in Section 3.9. A brief description of some PID-based techniques used in formation control, consensus, and cooperative systems for quadrotors is given in Section 3.10. The results of a set of simulations implementing some of the most common PID control schemes addressing the trajectory tracking task are presented and discussed in Section 4. Open problems and future directions are discussed in Section 5. Finally, conclusions are given in Section 6 (see Figs. 2 and 3).

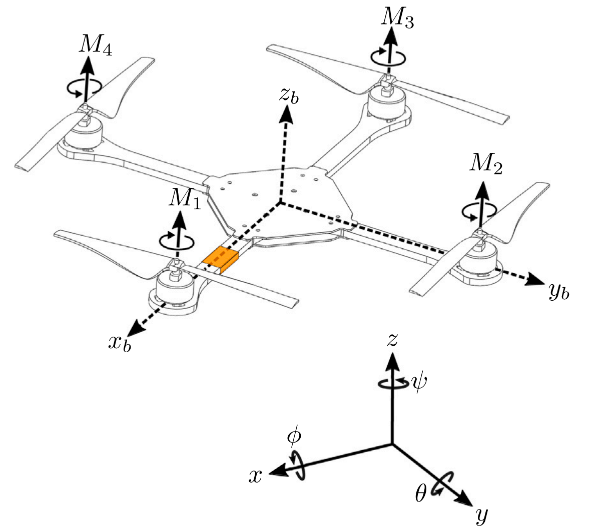

Fig. 1. Quadrotor with inertial reference frame (solid lines) and body reference frame (dashed lines).

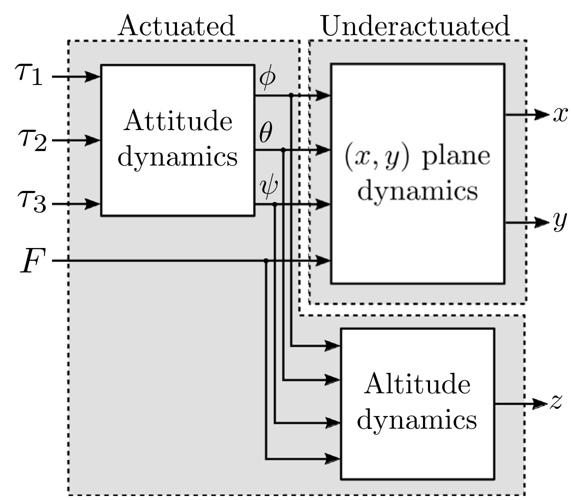

Fig. 2. Block diagram of the quadrotor dynamics illustrating the actuated and underactuated subsystems.

2. System model and control goals

The representation of the quadrotor has been the reason for many research and discussions. Two main representations of the quadrotor can be given: the earth coordinate representation and the body coordinate representation. Besides, orientation can be given in terms of the Euler angles, a geometric representation, and quaternions. See the manuscripts (Chovancová et al., 2014; Zhang et al., 2014a) for more details on different model representations.

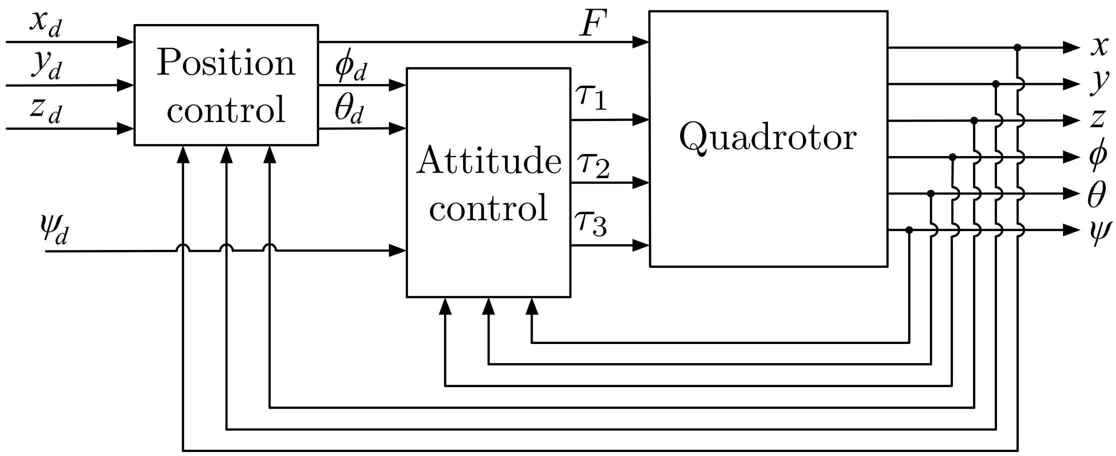

Fig. 3. Block diagram of the quadrotor dynamics in closed-loop with position and attitude controllers.

2.1. Quadrotor UAV model

Although the main aim of this survey is to review research on different PID control structures, a brief description of the quadrotor model is given. In consideration of Fig. 1 and under the assumption that the vehicle's center of mass coincides with the body frame reference, the dynamic model of the quadrotor represented concerning the inertial reference frame can be written as (García Carrillo et al., 2013; Lopez-Sanchez et al., 2023; Pérez-Alcocer et al., 2016),

$$m\ddot{\boldsymbol{p}} + m\boldsymbol{g}_z = \boldsymbol{f}_p + \boldsymbol{\delta}_p(t), \tag{1}$$

$$M(\boldsymbol{\eta})\ddot{\boldsymbol{\eta}} + C(\boldsymbol{\eta},\dot{\boldsymbol{\eta}})\dot{\boldsymbol{\eta}} = \boldsymbol{\tau}_\eta + \boldsymbol{\delta}_\eta(t), \tag{2}$$

where m is the mass of the vehicle, $\boldsymbol{p} = [x\ y\ z]^\top \in \mathbb{R}^3$ is the position vector, $\boldsymbol{\eta} = [\phi\ \theta\ \psi]^\top \in \mathbb{R}^3$ is the attitude vector, $M(\boldsymbol{\eta}) \in \mathbb{R}^{3\times3}$ and $C(\boldsymbol{\eta},\dot{\boldsymbol{\eta}}) \in \mathbb{R}^{3\times3}$ are the inertia and Coriolis matrices, respectively, $\boldsymbol{g}_z = [0\ 0\ g]^\top \in \mathbb{R}^3$, g is the gravitational acceleration constant, $\boldsymbol{\delta}_p(t) \in \mathbb{R}^3$ and $\boldsymbol{\delta}_\eta(t) \in \mathbb{R}^3$ are the external disturbances vector, and $\boldsymbol{f}_p \in \mathbb{R}^3$ and $\boldsymbol{\tau}_\eta \in \mathbb{R}^3$ are the forces and torques in the inertial reference frame, respectively. The forces $\boldsymbol{f}_p$ and torques $\boldsymbol{\tau}_\eta$ are related to the total thrust $F \in \mathbb{R}$ and the torques $\boldsymbol{\tau} = [\tau_1\ \tau_2\ \tau_3]^\top \in \mathbb{R}^3$ in the body reference frame as

$$\boldsymbol{f}_p = [f_x\ f_y\ f_z]^\top = \boldsymbol{r}_3(\boldsymbol{\eta})F,$$
$$\boldsymbol{\tau}_\eta = [\tau_\phi\ \tau_\theta\ \tau_\psi]^\top = W(\boldsymbol{\eta})^{-\top}\boldsymbol{\tau},$$

where $\boldsymbol{r}_3(\boldsymbol{\eta}) \in \mathbb{R}^3$ is the third column of the rotation matrix $R(\boldsymbol{\eta}) \in \mathbb{R}^{3\times3}$ and $W(\boldsymbol{\eta})^{-\top} \in \mathbb{R}^{3\times3}$ is a transformation matrix, both matrices are explicitly defined in García Carrillo et al. (2013), Lopez-Sanchez et al. (2023), Pérez-Alcocer et al. (2016). Furthermore, the total thrust is defined as

$$F = \sum_{i=1}^{4} M_i,$$

while the torques in the body reference frame are given by

$$\boldsymbol{\tau} = \begin{bmatrix} l(M_2 - M_4) \\ l(M_3 - M_1) \\ k(M_1 - M_2 + M_3 - M_4) \end{bmatrix},$$
$$k = \frac{k_D}{k_T},$$

being $M_i \in \mathbb{R}$ the thrust force provided by the ith actuator, k_D, $k_T > 0$ the drag and thrust coefficients, respectively, and l the distance of the quadrotor's center of mass to any of the rotor's rotation axis.

In fact, the control input for the quadrotor system (1)–(2) is formed by the signals in the vector $\boldsymbol{u} = [F\ \tau_1\ \tau_2\ \tau_3]^\top \in \mathbb{R}^4$, which has an invertible relation to the actuators' forces

$$[M_1\ M_2\ M_3\ M_4]^\top = B^{-1}\boldsymbol{u},$$

with

$$B = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & l & 0 & -l \\ -l & 0 & l & l \\ k & -k & k & -k \end{bmatrix}.$$

Since there are more degrees of freedom than control inputs, the quadrotor is considered an underactuated system (Moreno-Valenzuela & Aguilar-Avelar, 2018). In Fig. 2, a visual representation of the actuated and underactuated subsystems of a quadrotor is given. Furthermore, it can be observed which control inputs are related to each subsystem.

2.2. Control goals

There is a wide range of applications for quadrotors. Hence, there are different objectives in the field of control to be addressed to achieve each of these applications. We can highlight three as the main control objectives regarding quadrotors.

2.2.1. Hovering

Consists primarily in controlling the attitude of the quadrotor such that the roll and pitch angles remain in a constant value (commonly zero), making it stay static in the horizontal plane. The yaw angle is also kept at a constant value (not necessarily zero), avoiding the rotation of the quadrotor around its vertical axis. Besides, the total thrust, *i.e.*, the summation of the thrust provided by each actuator, compensates for the weight of the quadrotor, making it stay at a fixed altitude.

2.2.2. Position control

Consists of making the quadrotor reach a specified position coordinate in the three-dimensional space and maintain it. Additionally, in a similar manner as for hovering, the yaw angle is kept at an arbitrarily constant value. This objective implies attitude control since a combination of attitude rotations (for pitch and roll angles) makes quadrotor displacement possible over the horizontal plane. It is worth mentioning that regarding the point mentioned above, the attitude trajectory tracking problem may be addressed because the roll and pitch angles vary meanwhile the quadrotor reaches the specified position coordinate.

2.2.3. Trajectory tracking control

Consists of making the quadrotor track a specified path or trajectory in the three-dimensional space such that the path drawn by the quadrotor be the same as the desired trajectory. Similar to the position control case, attitude trajectory tracking is implied. Nevertheless, the yaw angle can also be commanded to track a trajectory in this task.

Hence, different trajectories for each degree of freedom must be tracked in order to accomplish the whole objective. Thus, this is the most challenging among the previously described goals.

Owing to the underactuated nature of the quadrotor dynamics, any of the aforementioned control goals are commonly addressed following a two-loop control structure, as illustrated in Fig. 3.

3. PID-based control of quadrotors

3.1. Linear PID control

Different linear control structures, including the PID control, were addressed (Bouabdallah et al., 2004). However, the study was applied only to the orientation subsystem. The combination of classical PID and more sophisticated LQ controllers to create a hybrid control system was reported in Orsag et al. (2010). The study was supported only by numerical results. Concerning experimental results, in the work (Zhang et al., 2009), four PID controllers are implemented independently for x, y, z positions, and yaw angle. Experimental results for a free-flying quadrotor were given. In Al-Younes et al. (2010), the PID control is used to assess the performance of a nonlinear algorithm with the integral and adaptation extensions. Simulation results supported the comparison, and no performance indexes were given. Similarly, in Shepherd III and Turner (2010), the resulting performance of the linear PID control applied to a quadrotor was used as a comparison method for a neural controller. However, only simulation results were given. In Salih et al. (2010), the development of a PID control method to obtain stability in flying the quadrotor flying object was explained. However, inspired by the inversion of the applied force in the inertial frame, a nonlinear proportional controller was applied to generate the desired angles and to control the position (x, y).

In González-Vázquez and Moreno-Valenzuela (2010), PI actions controlled the quadrotor's horizontal position, while PID algorithms controlled the quadrotor's orientation and vertical position. The theory of singularly perturbed systems justified closed-loop stability.

The linear PID control and the integral backstepping scheme were experimentally compared in Hoffmann et al. (2010). Both controllers were analyzed concerning robustness and disturbance rejection. Experimental results on PID control were reported (Yang et al., 2010) in a quadrotor orientation subsystem. The P, PI, and PID controllers were tested by numerical simulation in Hossain et al. (2010). The PID controller stabilized the system faster and more accurately than the other two schemes. In Azfar and Hazry (2011), the linear PID controller was proven to achieve good accuracy in an experimental quadrotor project. Again Chan et al. (2011), with PID controllers for attitude control, the quadrotor system was able to hover stable.

Based on the classic scheme of PID control, the paper (Li & Li, 2011) aimed to regulate the posture of a 6-degrees-of-freedom quadrotor. An experimental quadrotor was developed in Yoon and Goo (2011) and was controlled by means of linear PID control. In Ghadiok et al. (2011), an experimental system was developed by using linear PID controllers. In particular, the authors implemented autonomous indoor aerial gripping using a low-cost custom-built quadrotor. The work in Zeng et al. (2012) reported a numerical comparison between the PID control and the MRAC scheme, highlighting each scheme's advantages and disadvantages. A PID based on affine parametrization was discussed in Garcia et al. (2012). Interestingly, the robustness was discussed using the $H-\infty$ norm of the weighted complementary sensitivity function. In Lee et al. (2012), the first stability analysis of a PID-based controller for a quadrotor through Lyapunov's theory was reported. Here, a PID control for the attitude and a dynamic surface control method for the altitude was used. From the Lyapunov stability theory, all signals of a quadrotor system were proven uniformly and ultimately bounded. However, the control approach has no priority or intention to influence the position (x, y) since no auxiliary commands for roll and pitch were given. In Cetinsoy (2012), a simulation study with four PD controllers for roll, pitch, yaw, and altitude controls and two PID controllers for lateral position controls was developed. In Zhan et al. (2012) through flight experiments, a PID control the system was tested, and its efficiency was validated in an experimental quadrotor. Simulation and experimental test in a laboratory-built quadrotor were reported in Cavalcante Sá et al. (2013).

A quadrotor helicopter powered through a cable was studied in Yibo et al. (2013). The PID controller is implemented to keep the tethered unmanned quadrotor hovering at a specific position. Numerical simulations of linear PID control to stabilize a quadrotor were reported in Joyo et al. (2013).

The work in Benzaid et al. (2013) reported a study on the stability of a control strategy conformed by integral backstepping and PID linear control. This was the second work in the literature on the topic reporting a stability analysis using Lyapunov's theory.

Simulation results of quadrotor attitude control with different PID controller architectures were presented in Czyba and Szafranski (2013). Simulations of PID control were achieved in Bai et al. (2013). In Kim et al. (2013), experiments with a PID controller implemented in a quadrotor were reported. The linear PID controller has been applied in the stabilization of the quadrotor in Abas et al. (2013).

In Liu et al. (2015), a linear robust PID controller was developed to stabilize a quadrotor, and in Issam and Qingbo (2015), Kalantari et al. (2015), Qi et al. (2015) linear PID controllers with a technique for compensating the battery discharging were developed. The works (Bo et al., 2016; Chen & Thein, 2016; Denuelle et al., 2015; Dharmawan et al., 2016; Fang et al., 2016; Fernandes et al., 2015; Gao et al., 2016; García et al., 2015; Gharib & Moavenian, 2016; Gomes & Thé, 2015; Haddadi et al., 2015; Hsu & Shih, 2016; Kafi et al., 2015; Katigbak et al., 2016; Khan & Kadri, 2015a, 2015b; Lyu et al., 2015; Nguyen Duc et al., 2015; Pai et al., 2016; Pan et al., 2016; Praveen & Pillai, 2016; Rambabu et al., 2015; Thu & Igorevich, 2015; Torres et al., 2015; Wang & Chen, 2016; Wang et al., 2016a; Wei et al., 2015; Xie & Lynch, 2016; Yan et al., 2016) provided gain-tuning guidelines for the proposed linear PID controllers.

In Abdelmoeti and Carloni (2016), Lozano and Gutiérrez (2016), Wei (2016), a cascade structure was employed to develop linear PID controllers for quadrotor position and attitude control using the parameter space approach. In Guardeño et al. (2019), an optimum-based method for tuning a MIMO PID controller for a quadrotor was presented. Experiments were reported to validate the approach. A modified relay feedback test was proposed in Chehadeh and Boiko (2019) for tuning a linear PID controller. Experimental tests were provided. In Ma et al. (2019), nested PID controllers were employed for the navigation of a quadrotor. Low level PID controllers in addition to an interaction control technique were developed in Hongpeng and Weibo (2019), Kocer et al. (2019), Lee (2019), Shehzad et al. (2019) to address the contact problem. The works reported in Maithripala and Berg (2014, 2015) introduced a formal stability analysis for the stabilization of the attitude of a quadrotor by means of a linear PID controller. However, the position dynamics was neglected, whereby this was only a partial analysis of a more complex problem. To solve the path tracking problem for a quadrotor, a PID cascade control taking into account the dynamics of the actuators by using a transfer function was presented in Paiva et al. (2015). A cascade linear PID feedback control algorithm to stabilize the attitude of a quadcopter so that the balancing state can be ensured despite disturbances was presented in Wang et al. (2016b). In Zhang (2020), a self-designed quadrotor with an STM32-based ARM flight control board was controlled using a linear PID scheme, and its functionality was demonstrated through experimental tests. The stabilization and trajectory tracking problem of a quadrotor was addressed in Koruba and Krzysztofik (2020) by using a linear PID scheme. In Lopez-Sanchez et al. (2020), a PID scheme was implemented to track an optimized trajectory for parameter identification purposes. A particularization of the Ziegler–Nichols theory for PID control tuning was developed in Canal et al. (2020) to tune a PID controller applied on a quadrotor. The modification of the tuning procedure provided an improvement over the classic methodology. In Shi et al. (2021), a linear PID scheme was implemented to control a quadrotor and perform surveillance tasks and pedestrian detection.

3.2. Nonlinear PID

This section describes schemes combining different nonlinear control philosophies, such as backstepping, sliding mode control, and feedback linearization, along with linear or nonlinear PID control so that the resulting overall control inputs are nonlinear. Implying, then, that the total thrust, the rolling, pitching, and yawing torques, and the desired roll and pitch angles are computed through nonlinear expressions.

In Mian and Wang (2008), a backstepping-based PID nonlinear controller for the rotational subsystem of the quadrotor was proposed. However, the resulting control scheme was highly complex. A PID-based sliding mode controller was proposed in Luong Tuan and Won (2013). The algorithm was able to provide robustness characteristics to disturbances. In Goodarzi et al. (2013), a nonlinear PID control system for a quadrotor UAV was proposed to follow an attitude tracking command and a position tracking command. Real-time implementations and numerical simulations of the linear PID control in a quadrotor have been reported in Bi and Duan (2013), Bokan et al. (2013), Boudjit and Larbes (2013), Bourgeois et al. (2014), Cetinsoy (2013), Cheng et al. (2013), Cole and Wickenheiser (2013), Danjun et al. (2015), He and Zhao (2014), Hernandez et al. (2013), Hong et al. (2015), Jiang et al. (2013), Khairuddin et al. (2014), Lu et al. (2014), Predoi et al. (2014), Singh and Anvar (2014), Singh et al. (2014), Tran et al. (2015), Trirattanawananon et al. (2014), Wang et al. (2014), Wu et al. (2013) and Vempati et al. (2014). Some of them just conducting a partial linearization of the altitude dynamics. In Tan and Wang (2014), the nonlinear PID controller that partially linearizes the system is optimized using the invariant ellipsoid method based on the invariant set theory. The block feedback linearization and PID approach successfully controlled a small-scale quadrotor in Duong et al. (2014). In Zhang et al. (2014b), the feedback linearization method was given in combination with inner loops conformed by PID control actions. The closed-loop system was not analyzed in the previous two works, and stability was left just to intuitive arguments.

An improved backstepping control strategy was investigated in Lin et al. (2015) by introducing an integral term for each channel. The resulting scheme is a feedback linearization type with inner linear PID loops. A sufficient condition was provided for the parameter selection of the PID controller to guarantee the stability of the closed system. The stability of the closed-loop system was studied by means of the Lyapunov theory. In Yu et al. (2015), a nonlinear PID controller was designed using the Lie group theory. The nonlinear scheme requires the logarithmic map of the rotations. Only rotation was considered, and Lyapunov stability was justified. A nonlinear PID controller based on nested saturation to regulate the position of a quadrotor was applied in Rubio et al. (2015). Although experiments validated the given approach, closed-loop stability was not discussed. In Cao and Lynch (2016), Liu et al. (2016a), a combination of linear and nonlinear PID control schemes was developed, where the linear schemes were used for attitude control and the nonlinear ones for position control. The work Somasiri et al. (2016) proposed a nonlinear geometric PID controller for attitude stabilization of a quadrotor. The scheme was successfully implemented in a quadrotor. However, closed-loop stability was accurately discussed.

A design of a nonlinear robust H-infinity PID controller to regulate the rotational moments of a quadrotor was given in Ortiz et al. (2016). A nonlinear PID control design was proposed in Bouzid et al. (2017a, 2017b). The main idea consisted of combining the classical sliding modes approach with the PID structure. The closed-loop Stability was adequately discussed. A combined integral backstepping-PID controller was used in Benzaid et al. (2016) to control a quadrotor performing a 3D trajectory tracking. The controller was successfully tested in numerical simulations. This document constructively presents the development of the controller. Stability was discussed but not its robustness.

In Fan et al. (2017b), a nonlinear trajectory tracking controller based on sliding mode and the PID control method was designed. A fractional order PID scheme was given in Wang et al. (2018) for attitude control, and an integral backstepping method with mass estimation was used for position control. The method does not follow a single philosophy but a combination of known ones. In Yavuz and Ikizoglu (2018), PID and LQR controllers were designed, and then, a hyperbolic tangent weight function was applied to increase the overall performance by selecting the proper controller at the proper time.

A nonlinear PID-type motion controller for a quadrotor was introduced in Moreno-Valenzuela et al. (2018). A rigorous analysis of the closed-loop system trajectories was provided, and experimental results were reported. A combination between a linear PID controller and sliding mode PID algorithm was presented in Deveerasetty and Zhou (2018). In Najm and Ibraheem (2019), a nonlinear PID controller was proposed to stabilize a quadrotor system's translational and rotational motion and the stability was studied accurately. The authors of Cai et al. (2019) used the PID method to control the fully-actuated subsystem, and a sliding mode-observer-based equivalent-input-disturbance approach to control the under-actuated subsystem of a quadrotor. A stability analysis was given. Similarly, in Yu et al. (2019), a controller was designed using the PID and the backstepping approaches. Experiments were reported. A combination of PID controllers and three continuous sliding modes schemes was proposed in Rios et al. (2019). Stability and experimental results were discussed.

A non-linear PID control was used in Salamat and Tonello (2019) to adjust the integral action automatically. The strategy is combined with a particle swarm estimator. In Jurado et al. (2017), simulations were employed to validate a model reference adaptive control for the attitude dynamics, along with a linear PID controller for the position dynamics considering noise in the measurements and external disturbances. In Mohammadi et al. (2019), a nonlinear control method was designed using a combination of PID control, backstepping, and sliding mode controls to stabilize the quadrotor attitude and carry out the trajectory tracking task. Aiming to reduce power consumption, a combination of a robust PID and model-based control was introduced in Miranda-Colorado and Aguilar (2020) to control a quadrotor.

The work Najm et al. (2022) proposed a nonlinear PID controller with an improved active disturbance rejection controller to address the stabilization and trajectory tracking problem under exogenous disturbances. Nevertheless, stability analysis nor experiments were provided. On the other hand, in Kartal et al. (2020), a guaranteed performance nonlinear PID controller was developed through backstepping and second-order sliding modes techniques. Rigorous experimental studies were carried out in addition to a stability analysis to validate and demonstrate the proposed scheme's functionality. An hybrid control system comprised by a nonlinear PID scheme and an improved active disturbance rejection control under presence of exogenous disturbances and parametric uncertainties was introduced in Najm et al. (2022). In Wang et al. (2022), the stabilization of a quadrotor under state and time constraints by means of an implicit PID scheme where the feedback gains were obtained from linear matrix inequalities was introduced.

3.3. Adaptive PID control

This section addresses works where controllers formed by a combination of linear or nonlinear PID controllers with adaptive schemes were developed. In such schemes, the adaptive capabilities can be classified into two sets: adaptive gains and robustifying adaptive terms. The adaptive gains class comprises the algorithms on which the gains of the PID controller are tuned online. The robustifying adaptive terms class is formed by those algorithms on which the PID gains remain static during operations, and some other terms estimate parts of the quadrotor dynamics or parameters of the model.

An application of a self-tuning PID controller based on adaptive pole placement was developed in Yang et al. (2013). The controller can tune the PID parameters online according to the system change. Tuning guidelines were provided, but stability and robustness were not discussed. A combination of a single neural network with traditional PID control was introduced in Xu and Zhou (2013). The algorithm adjusts the weight coefficients corresponding to the PID gains by an adaptation procedure. An iterative feedback tuning was adopted in Prucksakorn et al. (2013) to provide a more flexible and optimized way for tuning PID controllers used for the quadrotor. In Moonumca et al. (2013), a PID controller with an adaptive proportional gain was introduced. Numerical results were presented. An integral backstepping control combined with an adaptive terminal sliding mode was given in Modirrousta and Khodabandeh (2015) to control the attitude of the quadrotor. Additionally, an adaptive robust PID controller was designed to control the quadrotor's position. The stability and robustness of the proposed controller were proved using the classic Lyapunov criterion.

To compensate for the in-ground effect, an adaptive nonlinear disturbance observer was designed in He et al. (2017) to enhance closed-loop PID control. The observer and controller were implemented in a simulation framework. By using the theory of adaptive interaction, self-tuning PID controllers were designed in An et al. (2017) to control a quadrotor. Simulation results illustrated that the controller appropriately adjusts PID gains under the self-tuning algorithm. The method was based on the theory of fuzzy mathematics and control system modeling. One of the advantages is that key control parameters are self-adapted to the PID controller designed.

In Rosales et al. (2018) a novel trajectory tracking algorithm for quadrotor was proposed. The PID controller was developed following an adaptive neuronal technique, and the discrete theory of Lyapunov verified its stability. Based on the dynamic model of the control system, a fuzzy adaptive PID control for the outer-loop angle and PID control for the inner-loop angular speed were built in Yu et al. (2018). In Sierra and Santos (2019), an adaptive neuromass estimator and an adaptive neural disturbance estimator complement the action of a set of PID controllers, stabilizing the UAV and improving the system performance. The work reported in Kourani et al. (2019) used an adaptive robust control system architecture based on a PID controller to generate the position inputs and a nonlinear robust attitude control system. Closed-loop stability was studied. A decentralized model reference adaptive control with adaptive gains and the PID control were proposed in Jurado and Hernandez (2019) to achieve the attitude control task for a quadrotor. In Mofid et al. (2020), the control of a quadrotor under sensor failure is addressed by using an adaptive PID-SMC scheme. The closed-loop stability is guaranteed by means of Lyapunov's theory.

A combination of active force control and the PID scheme was used in Abdelmaksoud et al. (2020) to control a quadrotor and provide rejection to external disturbances. A combination of a fuzzy-PID scheme, H_∞ control, and a modified disturbance observer was developed in Ghasemi and Azimi (2022) to control the position and attitude of a quadrotor. The fuzzy logic scheme handles the gains of the PID controller while the H_∞ scheme attenuates the fuzzy approximation errors. In Noordin et al. (2021), an adaptive PID scheme was proposed for the position and attitude stabilization of a quadrotor. The adaptive mechanism is based on sliding mode control and the gradient descent algorithm. Besides, a fuzzy compensator is included to eliminate the chattering issue of the sliding mode control. In Noordin et al. (2022), an adaptive PID scheme based on second order sliding modes control along with a fuzzy compensation system was introduced to control a quadrotor. The self-tuning properties of the proposed controller were based on Lyapunov's stability theory and the gradient descent approach.

A comparative study on the performance of linear PID, linear quadratic regulator, fuzzy logic, and model reference adaptive PID schemes for the position and attitude stabilization of a quadrotor was presented in Shakeel et al. (2022). Based on simulation results, the authors concluded that the linear quadratic regulator was the most suited one since the small overshoot and short settling time obtained with it. However, the authors pointed out that real-time experiments are required to provide more conclusive results.

3.4. Event-based PID control

This section addresses the development of controllers using the PID scheme with the event-based control philosophy. Event-based control arises as an alternative to time-triggered control. In this philosophy, the control commands are computed once a specified event occurs. The event-based control paradigm is based on the theory of discrete event systems (Zeigler, 1989). Frequently this event is related to the magnitude of the error of the desired signal, i.e., once the error leaves a specified region or boundary.

In Wang et al. (2011) an event-based scheme for intelligent PID was proposed. The event-triggered scheme eliminates small vibrations in the system while diminishing the number of actuation steps. Event-based PID controllers were proposed in Durand et al. (2018) and tested for controlling the position of a real-time mini quadrotor. Stability was ensured upon the base that the quadrotor model is linear and decentralized. An event-driven PID control mechanism for autonomous quadrotor helicopters that reduces the usage of communication channels was proposed in Ye (2018). The event-driven PID controller can maintain the satisfactory stabilization effect with the ability of reducing the number of transmissions significantly. A high-level event-based controller based on time-window scope approach was presented in Kim et al. (2022) for detecting emergencies during the operation of quadrotors. The algorithm cooperates with existing low-level control methods, such as PID control, to ensure safety during waypoint navigation.

3.5. Gain-scheduling control

The gain scheduling technique mainly consists of obtaining a linear parameter-varying model of the system to develop a linear controller with a structure that allows the controller gains to be varied based on some system variables. Commonly the system variables are tightly related to the desired performance of the plant. The main objective of varying the gains is to allow the controller to be effective among different operating points and scenarios. For a further and comprehensive description of this control philosophy, please see Rugh and Shamma (2000), Shamma and Athans (1991).

A gain-scheduling algorithm was proposed for a PID controller in Fang et al. (2011). Numerical simulations were used to validate the controller. More recently, simple linear PI and PID control schemes were used in Chee and Zhong (2013) in order to achieve navigation and collision avoidance of a quadrotor. A gain scheduling algorithm was also incorporated. In Bouzid et al. (2021), a gain-scheduling PID scheme was developed to stabilize a quadrotor with rotating and extendable arms. The developed scheme allows adaptation of the PID gains based on the current morphology of the quadrotor. A comparative study on the performance of a linear PID, a gain-scheduling PID, and a backstepping scheme to control a quadrotor was developed in Imane et al. (2022). Based on simulations, the authors concluded that the most suitable scheme among the tested was the backstepping scheme. Nevertheless, its mathematical derivation is the most complex in contrast with the linear PID and the gain-scheduling PID. A method to schedule the PID control frequencies for time-optimal quadrotor waypoint navigation was introduced in Kang et al. (2022). The introduced method consists of a control frequency agent and a future state predictor. Simulations showed the functionality of the proposed scheme since reduces the travel time of a quadrotor for waypoint navigation.

3.6. Fault-tolerant control

This section describes controllers combining the linear or nonlinear PID scheme with different philosophies addressing the control of quadrotors providing particular robustness to any kind of actuator fault. In Sadeghzadeh et al. (2012, 2011a, 2011b) studies on a gain-scheduled PID control were given in order to deal with faults in the propellers. Although the results were justified with experiments, stability was intuitively discussed only. An adaptive PID controller for fault-tolerant control of a quadrotor helicopter system in the presence of actuator faults was proposed in Amoozgar et al. (2012). The authors of the manuscript (Yu et al., 2014) proposed and implemented a PID structured fault tolerant controller. A fault-tolerant Lyapunov-gain-scheduled PID control for a quadrotor in presence of actuator fault was presented in the work (Bouguerra et al., 2015).

A passive fault tolerant controller based on nonlinear PID backstepping was proposed in Benrezki et al. (2015). Interestingly, the Lyapunov stability was discussed accurately and experimental results were given. In He et al. (2016), a fault-tolerant control method which includes a fault detection and diagnosis approach for the rotor fault of quadrotor was proposed. In addition, a reconfigurable PID controller was developed. An active fault-tolerant control scheme for a quadrotor was presented in Qin et al. (2017) by using PID controller as the main part. The chaos particle swarm was used in Jun et al. (2018) to optimize the PID gains off-line. A fault handling mechanism was added.

3.7. Fractional-order PID control

Fractional order control is an interesting topic; its study has been increasing in recent years. However, the main problem is realizing the fractional operator either in continuous or discrete time. Several numerical techniques have been proposed as a remedy to this complication.

With application to quadrotor control, artificial neural networks for emulating the analog fractional order $\mathrm{PI}^{\lambda}\mathrm{D}^{\mu}$ controller as a whole were introduced in Efe (2011). Automatic flight controller by combining the fractional PID as the inner loop for attitude control and backstepping as the outer loop achieving trajectory tracking was proposed in Fu and Li (2015) Stability by means of Lyapunov's stability theory was given. The stabilization of a quadrotor was addressed in Liu et al. (2020) by using a combination of fuzzy-logic and fractional order PID control. The parameters of the adaptive fuzzy fractional order PID scheme were tuned using the particle swarm optimization algorithm. In Saribas and Kahvecioglu (2021), a comparison of the performance of conventional PID and fractional order PID controllers for a quadrotor was presented. The gains of both schemes were tuned by means of genetic and particle swarm optimization algorithms, and four different criteria for the comparison were considered.

3.8. Intelligent PID control

Intelligent control takes its name and attributes based on artificial intelligence techniques with learning capabilities, such as fuzzy logic and neural networks. These intelligent schemes mainly exploit two properties of this kind of technique: association and function approximation. Besides, two approaches are used most to combine intelligent algorithms with PID control structures. The first and most widely used is to tune the PID gains by intelligent methods, either by a training stage or by providing online self-tuning. The second one consists of adding to the PID structure an intelligent-based term in order to estimate and compensate for unknown or unmodeled dynamics. Prior to 2012, some intelligent PID algorithms were surveyed in Li and Song (2012). Thus, we will focus on algorithms reported after that date.

In Fatan et al. (2013), an adaptive neuro PID controller was used for controlling the altitude of a quadrotor in which the controller could obtain proper coefficients adaptively and based on existing conditions for controlling the desired system. The design of fuzzy-PID hybrid control systems was proposed in Zareb et al. (2013) to control the Arducopter mini quadrotor. The modeling of a quadrotor and a control strategy using a self-tuning fuzzy PID algorithm and path planning using Dijkstra's algorithm were presented in Gautam and Ha (2013). In Mehranpour et al. (2013), a new fuzzy PID adaptive controller was designed for the flight control of a quadrotor, the fuzzy PID controller was implemented on the quadrotor through hardware-in-the-loop simulation in LabVIEW software. Online optimization to allow self-tuning of a PID scheme in a quadrotor was used in Ghiglino et al. (2013). This was done using an ABC colony technique which, compared to genetic algorithms, offers greater simplicity and excellent optimization performance.

In Yu and Zhang (2013), a fuzzy PID control algorithm was proposed to comply with the requirements of flight control. Matlab simulations indicated that the fuzzy PID control algorithm was effective in flight control. A hybrid control method based on backstepping and fuzzy adaptive PID controller was introduced in Gao et al. (2014). A PID controller for attitude and altitude control of a quadrotor and a performance criterion to tune its gains using genetic algorithms were proposed in Noshahri and Kharrati (2014). A parameter tuning approach based on gradient optimization was introduced to tune a PID controller gains under an optimization cost function in Zhu et al. (2015). In Zhao et al. (2015), a back propagation neural network-based PID control strategy for the attitude of quadrotor was introduced. The control of the quadrotor position was ignored. A neural network was taught in Lower and Tarnawski (2015) by control system with standard PID controller. This approach was used to check how neural networks cope with stabilizing the quadrotor under flight tasks. A decentralized PID neural network control scheme was proposed in Chen et al. (2015a) for the stabilization of a quadrotor helicopter subjected to wind disturbance.

In the paper Julkananusar et al. (2015), the gains of linear PID controllers for a quadrotor were tuned by using the fictitious reference iterative tuning for attitude control. Simulations supported the results. The same technique was later applied in Julkananusart and Nilkhamhang (2015) for tuning linear PID attitude controllers with a double-loop structure in a quadrotor.

In Gao and Yue (2015), an inner-loop attitude controller and an outer-loop position controller for a quadrotor were designed. The inner-loop attitude controller is designed with backstepping algorithm. The outer-loop position controller is realized with fuzzy adaptive PID algorithm. Stability was not considered. The control of a quadrotor was obtained through PID controllers tuned by particle swarm optimization in Estevez and Graña (2015). In Wang et al. (2015), the control parameters of a PID controller were adaptively adjusted by fuzzy RBF neural network. The control parameters of system were optimized by the hybrid learning methods integrating the offline particle swarm optimization algorithm with the online gradient descent algorithm of local searching ability. No stability was discussed. Similarly, in Hashemi and Pasdar (2015) a hybrid fuzzy-PID controller to control a quadrotor MAV landing was introduced. In Tao et al. (2016), a control method based on the combination of PID and a fuzzy system was given. The control parameters were adjusted online with the given algorithm. A robust adaptive control was developed in Belhadri et al. (2016) by using a neural network algorithm based on a PID controller with the aim of adjusting its gain parameters. A comparison among a type-2 fuzzy controller, type-1 fuzzy controller, and fuzzy-PID to control the altitude of a quadrotor was presented in Wicaksono et al. (2016). From that three control methods that have applied, and overall tested, type-2 fuzzy showed better result than others. Similarly, in Priyambodo et al. (2016) the gains of a PID controller were optimized by means of fuzzy logic and then applied to a quadrotor. In Liu et al. (2016b), a simple particle swarm optimization method was proposed to adjust the PID gains to stabilize a quadrotor. A particle swarm optimization called multi-objective particle swarm optimization with an accelerated update methodology was employed in Mac et al. (2016) to tune a PID controller for the AR.Drone quadrotor.

In Fan et al. (2016), the self-adaptive fuzzy parameter tuning rules for a PID attitude controller were given. Simulation were presented. A PID controller for the position and attitude stabilization of a quadrotor using the differential-evolution optimization algorithm was proposed in Pedro et al. (2016). A fuzzy PID with ability of self-tuning according to the current environment was given in Ma and Ji (2016). A PID scheme plus adaptive neural network compensation was developed in Xiang et al. (2017). Although the scheme achieved the motion task efficiently in simulation, the stability and robustness were theoretically studied. In Noordin et al. (2017), gains of a linear PID controller for quadrotor hovering were fine-tuned using particle swarm optimization algorithms. A similar work was given in Khodja et al. (2017). The model of an H-shaped racing quadrotor and the genetic algorithm based-PID scheme were discussed in Alkamachi and Erçelebi (2017). In particular, PID gain tuning was achieved by using genetic algorithm optimization. The design of a robust self-tuning PID controller for trajectory tracking based on fuzzy logic was developed in Doukhi et al. (2017). Such a controller offered several advantages over certain types of conventional control methods. In Yu et al. (2017), linear PID control is combined with an online fuzzy logic velocity planner in order to improve the hovering of a quadrotor. Differential evolution optimization algorithm to tune the parameters of a PID controller was compared in Reyad et al. (2017) concerning other PID approaches.

Comparison between a regular PID controller and a fuzzy PID scheme was presented in Bodrumlu et al. (2017). However, the study was limited and clear differences were not established. A two-stage automatic PID tuning scheme based on the differential evolution algorithm was developed in Wang et al. (2016c). For a cascade PID control system, an auto-tuner was designed in Chen and Wang (2017) with aim of achieving control of a quadrotor. The auto-tuner consisted of four components: relay feedback control, recursive estimation of the frequency response, estimation of the integrating plus delay model, and PID controller design.

The parameters of PID controller used for quad-copter control were tuned by using an improved genetic algorithm in Gaur et al. (2017). A gradient descent based methodology was employed in Babu et al. (2017) to tune a PID controller parameters for the AR.Drone quadrotor. The PID parameters were tuned automatically using particle swarm optimization in Adriansyah et al. (2017). By using simulation tools, a self-tuning fuzzy PID controller was proposed in Fahmizal et al. (2017) to adjust the gains of the PID controller. The type-2 fuzzy tuning having three-dimensional membership functions of a PID controller was found suitable for outdoor applications of a quadrotor in Wicaksono et al. (2017). A neural network supervisory control technique for the classical PID controller using fast online sequential learning method called online sequential extreme learning machine was introduced in Doukhi et al. (2018). In Li et al. (2018), a hierarchical approach that combines a model-free policy gradient method (a convolutional neural network) with a PID controller was given. Based on back propagation neural networks, an adaptive PID controller was proposed in Teng et al. (2018) for quadrotor UAV with unknown variable payloads. The work in Nazaruddin et al. (2018) proposed a novel technique to design a PID control using virtual sensing system, consisting of diagonal recurrent neural network and extended Kalman filter. In Cherrat et al. (2018), an adaptive fuzzy PID control law for attitude and altitude stabilization of a quadrotor was given. In particular, PID control with adaptive gains was used in order to approximate an ideal virtual controller. The attitude and altitude stability was discussed with rigorous arguments, but the stability in the (x, y) coordinates was not studied. The work in Fu et al. (2018) proposed a fuzzy PID method for quadrotors. In Hasseni and Abdou (2018), optimization of PID gains was achieved in order to get efficient motion control of a quadrotor. In Giernacki et al. (2018), the off-line optimal PID gain tuning in the context of auto-tuning of controllers was used in UAVs based on an optimization algorithm via the cuttlefish algorithm. The use of particle swarm optimization was proposed in Connor et al. (2018) to improve a PID controller on a quadrotor.

Considering the difficulty of gains tuning of the PID controller, in Lu et al. (2018), a method of combining inheritance operation of genetic algorithm and particle swarm optimization was used to tune the PID scheme gains. A fuzzy PID control scheme was applied in Parivash and Ghasemi (2018) including a feedback linearization term in the control law to compensate model nonlinearities. In Mohammadi et al. (2018), a fuzzy-logic PID controller was designed and applied to handle full control of a quadrotor. In Huang et al. (2018), another fuzzy PID was given where gains were tuned on-line. A novel fuzzy PID-type iterative learning control was designed in Dong and He (2019) for quadrotors. Gains were updated on-line. A nonlinear intelligent PID controller based on an adaptive neural network was introduced in Khosravian and Maghsoudi (2019). The gains of the controller were continuously updated using the neural network. In Gomez-Avila et al. (2019), a PID controller for a quadrotor based on neural networks was proposed. The neural network can overcome the limitations of the PID when controlling complex nonlinear systems. Gains were adapted online by using the neural network. A linear PID controller was combined with a fuzzy logic approach to stabilize the quadrotor in Alsafadi et al. (2019). In Pai et al. (2019), a fuzzy-PID controller provided position error compensation in a quadrotor vehicle having a person-tracking and observation system. The work in Housny et al. (2019) presented an adapted multidimensional particle swarm optimization algorithm in order to improve the performances of a fuzzy-PID controller for stabilizing a quadrotor for trajectory tracking tasks. In El Gmili et al. (2019) PID controllers were optimally tuned using the heuristics particle swarm optimization and Cuckoo search. In Siti et al. (2019), PID controllers were synthesized using genetic algorithm methods. In Carvalho et al. (2021), a fuzzy-PID scheme was introduced to stabilize and control the height of a quadrotor providing self-adjustment of the controller parameters. An improved particle swarm algorithm aiming to optimize the parameters of a fuzzy-PID controller was developed in Li et al. (2021). The algorithm used the adaptive inertia weight method in order to avoid the local optimality issue of the classical method. The work Kucherov et al. (2021) introduced an auto-tuning machine learning-based method for a PID scheme in order to control a quadrotor. Simulations were provided to validate the proposed auto-tuning method. A comparative study of a decentralized PID controller for a quadrotor was presented in Hasseni et al. (2021) where the gains of the PID scheme were tuned using different bio-inspired algorithms. In Rao et al. (2022), a cascaded intelligent controller comprised of a fuzzy neural network and a fuzzy neural network-based PID scheme for a quadrotor was developed. The fuzzy neural network scheme was trained offline and handles the attitude dynamics, while, the fuzzy neural network-based PID scheme performs online learning and handles the position dynamics. Experiments were provided to show the functionality of the proposed controller. The trajectory tracking problem was addressed in Hassani et al. (2021) using a PID scheme by tuning its gains by means of the ant colony algorithm. The functionality of the controller and the tuning method was validated in simulations. An intelligent controller formed by a combination of active force control, PID control, and fuzzy logic was developed in Abdelmaksoud et al. (2023). The gains of the active force PID scheme were tuned using fuzzy logic. The functionality of the proposed controller was shown through simulations by testing the performance under various types of external disturbances.

3.9. MPC and PID control

The model predictive control is a model-based approach in which proper control inputs are commanded to the plant in order to achieve a specific task. The computation of the control inputs is based on the knowledge of the system model and its parameters and limitations. By having this information about the plant, the controller can compute the most appropriate inputs for the plant to achieve the task within a time window. This section presents some works addressing the integration of the model predictive control method with the PID controller.

A combination between model predictive control and PID control is presented in Cheng and Yang (2018). MPC is used for position control and PID for attitude control. In Liang et al. (2018) a PID controller was designed under networked predictive scheme and verified on a quadrotor experiment platform.

3.10. Formation, cooperative systems and consensus and PID controllers

The linear PID control was used for the formation of lead and wing quadrotor UAVs in Tang et al. (2011). By using techniques of motion planning, in Chen et al. (2015b) the multi-quadrotor formation control was solved. The planned trajectory was implemented in by using linear PID controllers. The authors of Srigarom et al. (2015) implemented a linear PID scheme in order to control a quadrotor and enable it to operate in a swarm configuration. In Estevez et al. (2016), PID controllers for both quadrotor attitude and trajectory control were tuned by particle swarm optimization. Tests of the particle swarm optimization algorithm minimizing an energy function to achieve the PID controller tuning for the horizontal motion of quadrotor teams transporting hoses under different stress conditions were given.

The authors of Aguilera-Ruiz et al. (2017) implemented behaviors observed in social animals in a swarm of 10 simulated quadrotors. The simulations were carried out considering the dynamic model of the quadrotor, and PID controllers were used for a stable flight of the quadrotors swarm. In Wu et al. (2017), a linear PID controller was used to control each single quadrotor and a sliding mode controller was adopted to solve the formation flying problem. The leader–follower control problem was addressed in Pebrianti et al. (2018) by using linear PID controllers. In Dhiman et al. (2018) proposed a cooperative control law to control the motion of quadrotor and load. The proposed approach uses a combination of two PID controllers.

A decentralized control law was suggested in Shirani et al. (2019) to maintain the formation of the quadrotor without direct communication. The proposed controller was a sub-optimal LQR-PID law whose coefficients are obtained by solving linear matrix inequalities. To achieve a desired quadrotor formation, a PID-based control scheme was used in Lv et al. (2018). By using a combination of consensus protocol with PID controller, in Abbasi et al. (2018), formation flight and path tracking of a group of quadrotor was performed. In Thien and Kim (2018) a PID control was proposed for constant disturbance rejection in order to solve the formation control of a group of quadrotors. The consensus problem for a multi-agent system comprised of three quadrotors was addressed in Najm et al. (2020) by using genetic algorithms to tune the consensus law, while the PID scheme was used to control the position of the quadrotors. In Dhiman et al. (2020), a combination of a PID and PD scheme was employed to develop a position control and collaborative transportation of a suspended load by using multiple quadrotors. The formation control problem was addressed in Biantoro et al. (2021) by combining the virtual structure and artificial potential field approaches. Besides, the PID scheme was implemented to control the altitude and attitude of a quadrotor.

4. Simulations

In order to picture better the behavior of the quadrotor under different control schemes, numerical simulations were carried out employing schemes such as: model-free linear PID, nonlinear PID-type, PID with adaptive neural networks, and a model-based PID. In addition, a nonlinear PID regulator controller was included in the comparison. It is worth mentioning that all the schemes were tested for the trajectory tracking task.

Model-free linear PID controller (MF)

This controller was implemented in Lopez-Sanchez et al. (2020). Nevertheless, the structure of the controller contains some terms that can be considered as a model compensation action. Thus, those terms were not included in the presented simulation, resulting in

$$
\begin{aligned}
F &= \frac{f_z}{\cos(\phi)\cos(\theta)},\\
\theta_d &= \tan^{-1}\left[\frac{f_x\cos(\psi_d)+f_y\sin(\psi_d)}{f_z}\right],\\
\phi_d &= \tan^{-1}\left[\frac{\cos(\theta_d)\left(f_x\sin(\psi_d)-f_y\cos(\psi_d)\right)}{f_z}\right],\\
\boldsymbol{f}_p &= K_{pp}\boldsymbol{e}_p + K_{ip}\int_0^t \boldsymbol{e}_p\mathrm{d}t + K_{dp}\dot{\boldsymbol{e}}_p,\\
\boldsymbol{\tau} &= K_{po}\boldsymbol{e}_\eta + K_{io}\int_0^t \boldsymbol{e}_\eta\mathrm{d}t + K_{do}\dot{\boldsymbol{e}}_\eta,
\end{aligned}
$$

where $\boldsymbol{f}_p = [f_x\ f_y\ f_z]^\top$, K_{pp}, K_{ip}, and $K_{dp} \in \mathbb{R}^{3\times 3}$ are positive definite diagonal matrices containing the proportional, integral, and derivative gains for the position dynamics and similarly, K_{po}, K_{io}, and $K_{do} \in \mathbb{R}^{3\times 3}$ are positive definite diagonal matrices containing the proportional, integral, and derivative gains for the attitude dynamics. This controller will be denoted as MF (model-free linear PID) in the remainder of the document.

The gains used for the MF controller in simulations were the following

$$
\begin{aligned}
K_{pp} &= \mathrm{diag}\{12\ 12\ 95\}, & K_{po} &= \mathrm{diag}\{4.5\ 4.5\ 6.5\},\\
K_{dp} &= \mathrm{diag}\{5\ 5\ 35\}, & K_{do} &= \mathrm{diag}\{1.75\ 1.75\ 3.75\},\\
K_{ip} &= \mathrm{diag}\{5\ 5\ 25\}, & K_{io} &= \mathrm{diag}\{0.5\ 0.5\ 0.5\}.
\end{aligned}
$$

Nonlinear PID-type controller (NL)

This controller was introduced in Moreno-Valenzuela et al. (2018). It is comprised of a position and an attitude motion controller where the position control loop computes desired roll and pitch angles for the attitude control loop. Both, position and attitude controllers contain model compensation terms along with PID terms. Additionally, the integral part of the attitude controller have a hyperbolic tangent function which can improve the performance of the controller increasing its robustness against unmodeled dynamics. This controller will be denoted as NL (nonlinear PID-Type) from now on.

The gains used for the NL controller in simulations were defined as

$$
\begin{aligned}
K_{pp} &= \mathrm{diag}\{9\ 9\ 11\}, & K_{po} &= \mathrm{diag}\{0.375\ 0.375\ 0.651\},\\
K_{dp} &= \mathrm{diag}\{6\ 6\ 6\}, & K_{do} &= \mathrm{diag}\{0.9\ 0.9\ 1.5\},\\
K_{ip} &= \mathrm{diag}\{0.01\ 0.01\ 2.3\}, & K_{io} &= \mathrm{diag}\{0.02\ 0.02\ 0.02\},\\
\alpha &= 0.5, & K_o &= \mathrm{diag}\{0.45\ 0.45\ 0.45\},\\
\beta &= 1, & \sigma &= 20.
\end{aligned}
$$

Adaptive neural network-based PID-type controller (ANN)

This controller was presented in Lopez-Sanchez et al. (2023). As in most of the controllers for quadrotors, it is comprised by a position and an attitude control loops. But in this case, each loop presents an architecture that can be expressed as a PID-type controller along with an adaptive neural network that provides special robustness against parameter uncertainties and unmodeled dynamics. This scheme will be referred to as ANN (adaptive neural network PID-Type) hereafter.

The gains used for the ANN controller in simulations were selected as

$$
\begin{aligned}
K_{U_p} &= \mathrm{diag}\{4.0\ 4.0\ 9.0\}, & N_p &= \mathrm{diag}_{10}\{0.8\},\\
K_{ip} &= \mathrm{diag}\{0.5\ 0.5\ 0.8\}, & N_\eta &= \mathrm{diag}_{10}\{1.15\},
\end{aligned}
$$

Table 1
Parameters of the QBall 2 (Lopez-Sanchez et al., 2020) used for the simulations of the PID control schemes.

	Description	Value	Units
m	Quadrotor mass	1.82245	kg
I_{xx}	Inertia moment about x-axis	0.00749	kg m^2
I_{xy}	Inertia product	−0.00051	kg m^2
I_{xz}	Inertia product	−0.00003	kg m^2
I_{yy}	Inertia moment about y-axis	0.00976	kg m^2
I_{yz}	Inertia product	−0.00098	kg m^2
I_{zz}	Inertia moment about z-axis	0.05130	kg m^2

$$K_p = \text{diag}\{1.8\ 1.8\ 1.8\}, \qquad \kappa_p = 0.4,$$
$$K_{U\eta} = \text{diag}\{0.5\ 0.5\ 1.0\}, \qquad \kappa_\eta = 0.15,$$
$$K_{i\eta} = \text{diag}\{0.05\ 0.05\ 0.05\}, \qquad \alpha_p = 0.001,$$
$$K_\eta = \text{diag}\{4.8\ 4.8\ 8.5\}, \qquad \alpha_\eta = 0.001.$$

Model-based PID controller (MB)

This controller was implemented and used as a reference in Lopez-Sanchez et al. (2023) to assess the benefits of other controllers. The model-based PID controller contains model compensation terms for both, the position and the attitude dynamics. In the remainder of the document this algorithm will be denoted as MB (model-based PID).

The gains used for the MB controller in simulations were the following:

$$K_{1p} = \text{diag}\{4.5\ 4.5\ 9.0\}, \qquad K_{1\eta} = \text{diag}\{0.5\ 0.5\ 1.0\},$$
$$K_{2p} = \text{diag}\{0.5\ 0.5\ 0.8\}, \qquad K_{2\eta} = \text{diag}\{0.05\ 0.05\ 0.05\},$$
$$K_{3p} = \text{diag}\{1.8\ 1.8\ 1.8\}, \qquad K_{3\eta} = \text{diag}\{4.8\ 4.8\ 8.5\}.$$

Nonlinear PID regulator controller (NLR)

This controller was presented in González-Vázquez and Moreno-Valenzuela (2010) and has an uncommon structure. The derivation of the controller is carried out decomposing the quadrotor dynamics in the actuated and underactuated dynamics. In this scheme, the actuated dynamics are governed by means of a nonlinear PID controller meanwhile the underactuated dynamics are stabilized by a PI controller. In our simulations, a derivative action term was added to the PI controller related to the underactuated dynamics in order to improve its performance for trajectory tracking tasks. This controller will be denoted as NLR (nonlinear PID regulator) from now on.

The gains used for the NLR controller in simulations were selected as

$$K_{pa} = \text{diag}\{15\ 5\ 5\ 5\}, \qquad K_{pu} = \text{diag}\{0.85\ 0.85\},$$
$$K_{ia} = \text{diag}\{0.2\ 0.5\ 0.5\ 0.5\}, \qquad K_{du} = \text{diag}\{0.5\ 0.5\},$$
$$K_{da} = \text{diag}\{9\ 3.5\ 3.5\ 3.5\} \qquad K_{iu} = \text{diag}\{0.05\ 0.05\}.$$

Quadrotor model used in simulations

The benchmark platform used in the simulation was Quanser's QBall 2 quadrotor which has been used in several works related to quadrotor control (Chen et al., 2019; Fan et al., 2017a; Hua et al., 2019; Jurado & Lopez, 2018; Kourani & Daher, 2021; Lopez-Sanchez et al., 2020, 2022, 2023, 2021). The parameters of the QBall 2 used in the simulations were taken from Lopez-Sanchez et al. (2020) and are given in Table 1.

Desired trajectory and disturbances

To compare the performance of each controller, the trajectory tracking task of an eight-shaped path described by the following equations was carried out in simulation:

$$\begin{aligned}
x_d(t) &= 0.5\sin\left(\frac{2\pi}{5}t\right)\ [\text{m}],\\
y_d(t) &= \cos\left(\frac{2\pi}{10}t\right)\ [\text{m}],\\
z_d(t) &= \begin{cases} 1-0.7e^{-0.1t^3}\ [\text{m}], & t \le 5,\\ 1\ [\text{m}], & t > 5,\end{cases}\\
\psi_d(t) &= 0.0\ [^\circ].
\end{aligned} \tag{3}$$

In addition, disturbances were added to the position and attitude dynamics in (1)–(2) during the trajectory tracking task at $t \geq 40$ [s]. The disturbance vector for the position dynamics is given by

$$\delta_p(t) = \begin{cases} [0\ 0\ 0]^\top & [\text{N}],\ \forall\ 0 \le t < 40[\text{s}],\\ \begin{bmatrix} 0.5\sin(\frac{4\pi}{5}t)\\ 0.5\cos(\frac{4\pi}{10}t)\\ 0.5\sin(\frac{4\pi}{5}t)\end{bmatrix} & [\text{N}],\ \forall\ t \ge 40[\text{s}],\end{cases}$$

while for the attitude dynamics the disturbance vector is given by Xi et al. (2021)

$$\begin{aligned}
d_\eta(t) = {} & 0.045\sin(2.5\pi t-3) + 0.09\sin(2\pi t+7)\\
& + 0.135\sin(0.5\pi t-9.5) + 0.09\sin(0.3\pi t)\\
& + 0.054\sin(0.15\pi t+4.5) + 0.045\sin(0.05\pi t+2)\\
& + 0.135\sin(0.01\pi t+3) + 0.225,
\end{aligned}$$

$$\delta_\eta(t) = \begin{cases} [0\ 0\ 0]^\top & [\text{Nm}],\ \forall\ 0 \le t < 40[\text{s}],\\ \begin{bmatrix} d_\eta(t)\\ d_\eta(t)\\ d_\eta(t)\end{bmatrix} & [\text{Nm}],\ \forall\ t \ge 40[\text{s}].\end{cases}$$

Results

Fig. 4 depicts a three-dimensional view of the path drawn by the quadrotor under each of the tested controllers tracking the desired position trajectories in (3). Please notice that all the schemes were able to achieve the trajectory tracking task, even the MF and the NLR algorithms, which are the simplest ones, maintain the quadrotor stable in the presence of external disturbances. As can be observed, every path traces an eight-shaped figure close to the desired one. Thus, it can be said in general words that all the controllers accomplished the control objective and performed well.

The tracking of each of the desired trajectories with the tested controllers are shown in Fig. 5. Notice that all the schemes provided very small tracking errors after some transients. In particular, the MF controller took almost 20 s to reach the desired height. This performance is a result of the lack of model parameters in its structure, especially the lack of the vehicle's weight, which directly affects its performance on the z coordinate. Nevertheless, once disturbances arose, the MF algorithm becomes the closest to the desired height, while the others presents oscillations with different amplitudes being the NL the one with the highest tracking error.

In Fig. 6, the desired roll $\phi_d(t)$ and pitch $\theta_d(t)$ angles computed by each scheme and the tracking of them are presented. Since each controller is responsible for computing its own desired roll and pitch angles in order to ensure stability and the tracking of the trajectory on the x and y coordinates, these angles are presented separately. Please notice that although all the schemes are different, the desired roll and pitch angles computed by each scheme are very similar to each other. Nonetheless, under external disturbances, the desired roll and pitch angle profiles changed regarding the undisturbed period.

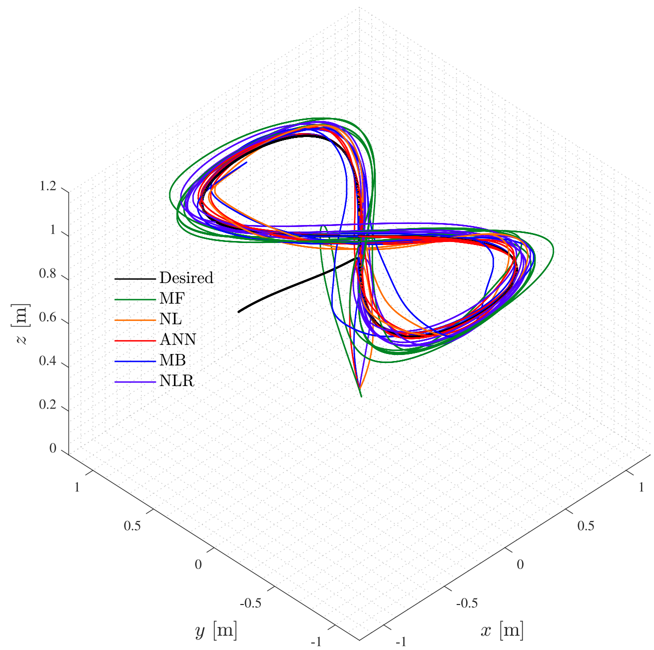

Fig. 4. Three-dimensional view of the paths drawn by the quadrotor while tracking the desired trajectory in simulation by implementing the MF (Model-free PID), NL (Nonlinear PID-Type), ANN (Adaptive neural networks PID-Type), MB (Model-based PID), and NLR (Nonlinear PID regulator) controllers.

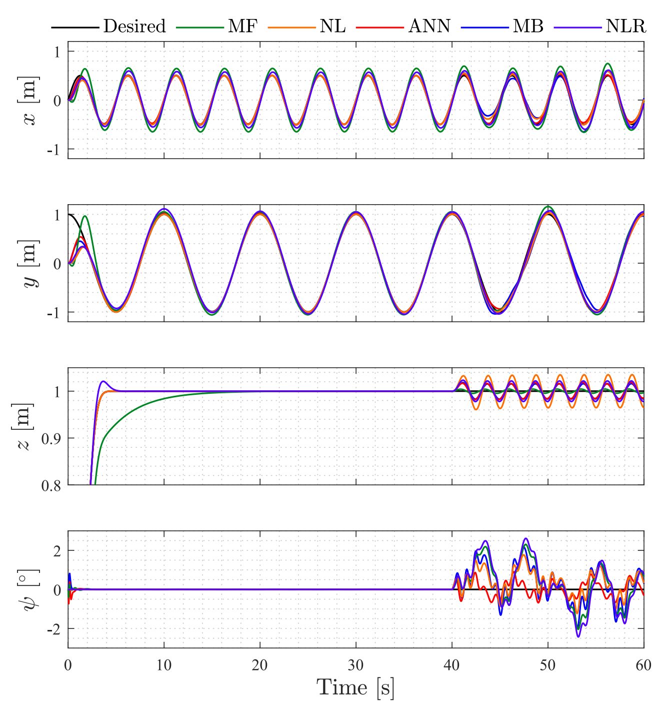

Fig. 5. Tracking of the desired position trajectories $x_d(t)$, $y_d(t)$, and $z_d(t)$ and the desired yaw angle $\psi_d(t)$ in simulation by implementing the MF (Model-free PID), NL (Nonlinear PID-Type), ANN (Adaptive neural networks PID-Type), MB (Model-based PID), and NLR (Nonlinear PID regulator) controllers.

Figs. 4–6 help to picture the behavior of the quadrotor under each of the controllers, but Figs. 7 and 8 provide an insightful view of their performance since depict the position and attitude errors obtained with each controller, respectively.

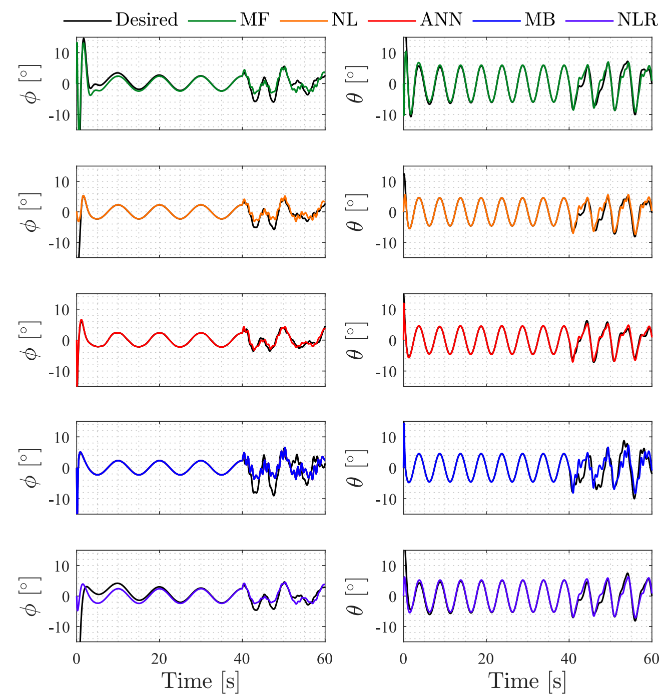

Fig. 6. Desired roll $\phi_d(t)$ and pitch $\theta_d(t)$ angles and actual roll $\phi(t)$ and pitch $\theta(t)$ angles by implementing the MF (Model-free PID), NL (Nonlinear PID-Type), ANN (Adaptive neural networks PID-Type), MB (Model-based PID), and NLR (Nonlinear PID regulator) controllers.

The position error was defined as

$$e_p = \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} = \begin{bmatrix} x_d - x \\ y_d - y \\ z_d - z \end{bmatrix}$$

and the attitude error was defined as

$$e_\eta = \begin{bmatrix} e_\phi \\ e_\theta \\ e_\psi \end{bmatrix} = \begin{bmatrix} \phi_d - \phi \\ \theta_d - \theta \\ \psi_d - \psi \end{bmatrix}.$$

Notice that all the schemes were able to effectively track the trajectory in the z coordinate, even those schemes lacking either of robustifying terms or adaptive compensation. Besides, all of them manage to stabilize the quadrotor, *i.e.*, the control algorithms guarantee that the attitude errors are relatively close to zero during the undisturbed period, but in the presence of external disturbances the ANN scheme remained the closest to zero. Please notice that the height error and attitude angle errors for all the controllers tend smoothly to zero during the undisturbed period, while, the position errors in the x and y coordinates remained oscillating during the same period. Precisely, the height z and the attitude angles: roll ϕ, pitch θ, and yaw ψ, are the actuated states and are directly controlled by the total thrust F and the torques τ_1, τ_2, and τ_3, respectively. On the other hand, the position in the (x, y) plane is underactuated and must be controlled by a combination of all the actuated states. Based on these observations, we can comment that a key feature of a trajectory tracking controller is the computation of the desired roll and pitch angles. This feature governs how the actuated states interact and are combined to control the underactuated ones. In addition, it can be observed that a simple controller such as the MF or even the NLR, which is not suited for the trajectory tracking task, can stabilize the quadrotor under external disturbances. However, schemes with adaptive properties as the ANN, robustifying terms as the NL, or with prior and accurate information of the model as the MB presented a superior performance. But in the case of using the ANN and NL schemes, the design, and error convergence

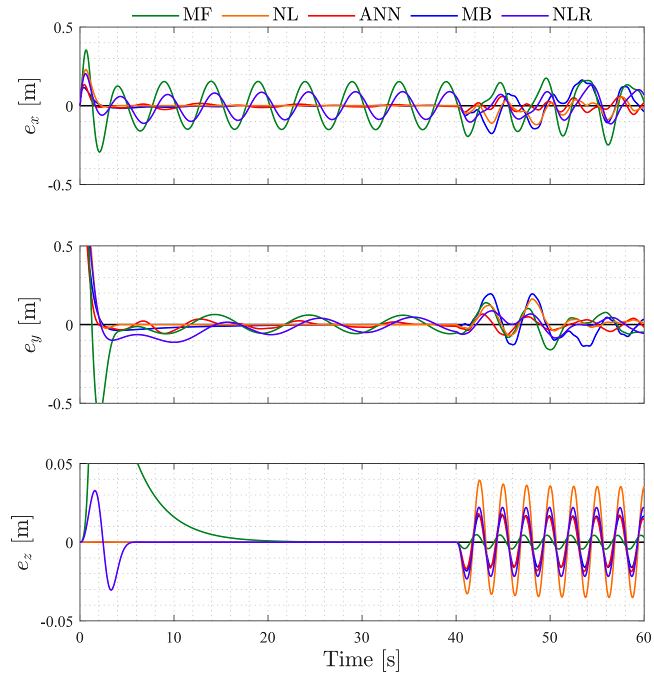

Fig. 7. Trajectory tracking position errors $\boldsymbol{e}_p = [e_x \ e_y \ e_z]^\top$ obtained in simulation by implementing the MF (Model-free PID), NL (Nonlinear PID-Type), ANN (Adaptive neural networks PID-Type), MB (Model-based PID), and NLR (Nonlinear PID regulator) controllers.

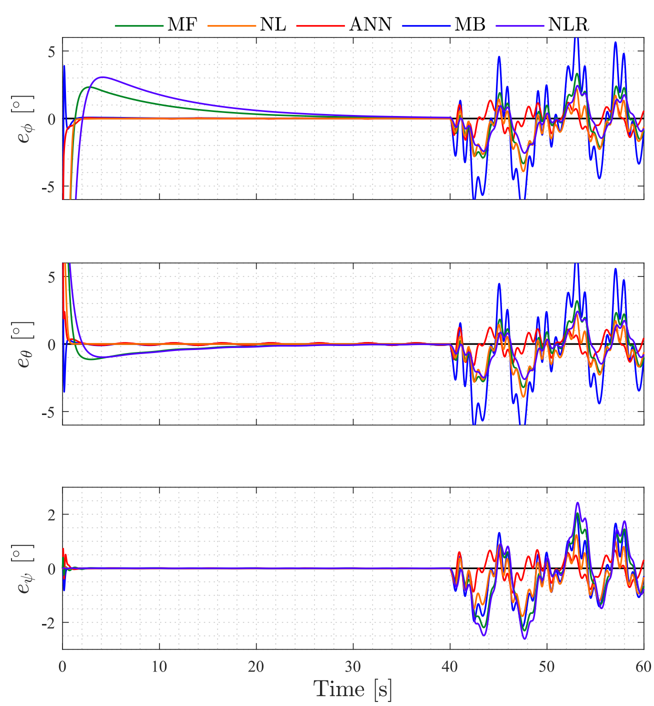

Fig. 8. Trajectory tracking attitude errors $\boldsymbol{e}_\eta = [e_\phi \ e_\theta \ e_\psi]^\top$ obtained in simulation by implementing the MF (Model-free PID), NL (Nonlinear PID-Type), ANN (Adaptive neural networks PID-Type), MB (Model-based PID), and NLR (Nonlinear PID regulator) controllers.

analysis are more difficult. In the MB case, a parameter identification procedure must be carried out.

The control actions provided by each controller are shown in Fig. 9. Notice that all torques commanded by each scheme are relatively similar, even during the period with disturbances. Nevertheless, the

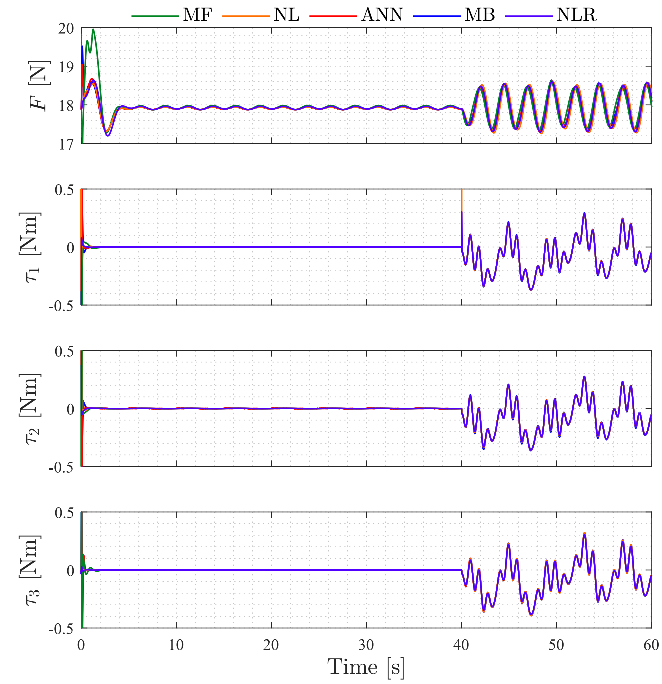

Fig. 9. Control inputs F and $\boldsymbol{\tau} = [\tau_1 \ \tau_2 \ \tau_3]^\top$ computed by the MF (Model-free PID), NL (Nonlinear PID-Type), ANN (Adaptive neural networks PID-Type), MB (Model-based PID), and NLR (Nonlinear PID regulator) controllers in simulation.

total thrust computed by the MF scheme differs from the other ones considerably at the beginning of the simulation. This is owed to the fact that has no information on the vehicle's weight; leading to exceeding the actual force necessary to compensate for it.

Quantitative results

The root mean square (RMS) value of the tracking errors and the control actions obtained with each controller were computed. The RMS values were computed in two time periods, the first one is 20 [s] $\le t <$ 40 [s], which is disturbance-free and considers that the quadrotor has achieved the desired altitude. The second one is 40 [s] $\le t \le$ 60 [s], corresponding to the period where the disturbances appeared and remain. The results are presented in Table 2, the smallest RMS value of the errors are in blue color and the highest ones are in red color. In a similar fashion, the smallest RMS values of the control inputs are in blue color and the highest ones in red color.

Based on Table 2, it turns out that the NL scheme performed the best during the undisturbed period; nonetheless, it was not the best in the presence of external disturbances, and provided the worst result for the height error. In contrast, the ANN scheme did not excel in the undisturbed period but was outstanding under external disturbances on almost all the coordinates. Besides, it can be observed that the MF scheme obtained only three of the worst results regarding the tracking errors during the undisturbed period, and even though it can be cataloged as the worst given its performance, it performed similarly to the NL scheme during the disturbances. What can be highlighted from these results, it is that even though the MF scheme is the simplest among all, it can operate adequately in the presence of disturbances. Besides, it obtained the smallest RMS value for the height tracking error under external disturbances; which is owed to the integral action.

The benefits of the adaptive features that an adaptive neural network PID controller offers can be appreciated by the results of the ANN scheme since provided the smallest tracking errors on the (x, y) plane and the attitude errors during the period with disturbances. Recalling that the x and y coordinates are underactuated, it suggests that schemes such as this could improve the performance of position controllers under adverse conditions.

Table 2
RMS values of the trajectory tracking errors and computed control actions.

Signal	Undisturbed 20 [s] $\leq t < 40$ [s]					Disturbed 40 [s] $\leq t \leq 60$ [s]				
	MF	NL	ANN	MB	NLR	MF	NL	ANN	MB	NLR
e_x [m]	0.1077	0.0003	0.0050	0.0018	0.0626	0.1211	0.0489	0.0284	0.0882	0.0686
e_y [m]	0.0415	0.0012	0.0119	0.0024	0.0353	0.0714	0.0574	0.0327	0.0942	0.0449
e_z [m]	0.0002	0.0	0.0	0.0	0.0	0.0031	0.0247	0.0119	0.0115	0.0155
e_ϕ [°]	0.1487	0.0005	0.0121	0.0088	0.2851	1.5739	1.4128	0.7598	3.1676	1.2287
e_θ [°]	0.0735	0.0023	0.0564	0.0554	0.0898	1.5377	1.4145	0.7420	3.1667	1.2459
e_ψ [°]	0.0015	0.0004	0.0029	0.0019	0.0015	1.0612	0.7339	0.4014	0.9693	1.2497
F [N]	17.9349	17.9144	17.9142	17.9143	17.9237	17.9559	17.9311	17.9304	17.9376	17.9392
τ_1 [N m]	0.0001	0.0001	0.0005	0.0001	0.0001	0.1640	0.1644	0.1639	0.1657	0.1638
τ_2 [N m]	0.0011	0.0006	0.0010	0.0009	0.0010	0.1614	0.1626	0.1616	0.1647	0.1617
τ_3 [N m]	0.0002	0.0001	0.0005	0.0002	0.0002	0.1689	0.1712	0.1694	0.1711	0.1678

Table 3
PID-based control schemes: Advantages and disadvantages.

Scheme		Advantages	Disadvantages
Linear	Non-optimum	The controller is easy to design and implement. Accurate knowledge of the system model is not needed.	Linearization of the quadrotor's dynamic model is needed. The tuning procedure is not straightforward, and it is time-consuming. Only valid for a specific operation point under certain conditions. It needs to be updated if the task changes. It is not robust to external disturbances.
	Optimum	The controller is easy to design and implement, and the obtained gains guarantee the scheme's functionality. It can reduce energy consumption.	Linearization of the quadrotor's dynamic model is needed. The gains need to be recalculated for different flight tasks. The optimum performance is only guaranteed for the phenomena and effects considered during the scheme's development.
Nonlinear		Different nonlinear control methodologies can be coupled to it. It is valid for a wide range of operation points. Nonlinearities of the quadrotor model are considered. A rigorous analysis of the closed-loop system stability can be provided.	The tuning procedure is time-consuming. Several experimental tests should be realized until an acceptable performance is achieved. It needs to be updated if the task changes.
Adaptive		High robustness under parameter uncertainty. Can operate in the presence of unmodeled dynamics.	An appropriate representation of the system dynamics is needed. Convergence or at least boundedness of the adapting parameters must be guaranteed.
Event-based		Low computational power and complexity. Easy implementation. Null or inaccurate knowledge of the system's dynamic model is required. It can operate under relatively low update rates. It can reduce energy consumption.	Several simulations and experimental tests are needed to find appropriate gains. Time-consuming approach. Explicit discretization of the closed-loop system must be obtained.
Gain-scheduling		Allows operating in different situations and environmental scenarios. Relatively simple control structures can be implemented. It is not computationally expensive or complex to implement.	Several simulations and experimental tests are needed to find appropriate gains. Time-consuming approach. Expertise is needed to define the objective function to switch among each gains set.
Fault-tolerant		High robustness to actuator partially or total faults. Robustness to unmodeled dynamics, parameter uncertainties, or significant variations on them. Guaranteed operation under adverse conditions.	Measurement of many system states is required. Fault detection or identification mechanisms must be implemented. Apriori knowledge of the system's behavior under specific faults is required.
Fractional order		Allows a broader set of parameters that can stabilize the closed-loop system. Offers an improvement in robustness regarding the integer order PID scheme. It can be more efficient than an integer order PID scheme.	The implementation is complicated due to the fractional terms. Requires more computational resources. The stability analysis is much more complex than an integer order PID scheme.
Intelligent	Fuzzy	Accurate knowledge of the system model is not needed. Practical when dealing with hard-to-model phenomena or complex dynamics. Several operation points and conditions can be considered and addressed.	An expert must define the fuzzy rules, and the performance will be strongly related to his expertise and experience. It is harder to prove stability through analytical ways. The complexity of the implementation is related to the number of fuzzy rules used.
	Neural networks	Accurate knowledge of the system model is not needed. High robustness to parameter uncertainty and unmodeled dynamics. Robust to external disturbances. Learning capabilities.	The speed of convergence is slow since fast convergence rates unstabilize the vehicle. High computational power and complexity. For non-adaptive NN, a training stage is needed.
Model predictive control		Optimal control input commands. Operational constraints can be incorporated.	Accurate parameter identification is required. High computational power. Susceptible to parameter uncertainty and variations.

Table 4
PID-based control schemes: Flight task feasibility, robustness and complexity.

Scheme		Flight task feasibility						Robustness				Complexity	
		Hovering	Way point navigation	Trajectory tracking		Payload transport		Parameter uncertainty	Unmodeled dynamics	External disturbances	Actuator fault	Computational	Implementation
				High velocity	Low velocity	Static	Dynamic						
Linear	Non-optimum	3	2	1	2	1	0	1	1	1	0	0	0
	Optimum	3	3	2	3	3	1	1	1	1	0	1	0
Nonlinear		3	3	3	3	3	3	3	2	2	1	1	2
Adaptive		3	3	3	3	3	3	3	2	3	1	2	2
Event-based		3	3	1	3	2	0	1	1	1	0	1	2
Gain-scheduling		3	3	2	3	3	2	2	1	2	0	1	1
Fault-tolerant		3	3	2	3	3	3	3	2	2	3	2	3
Fractional order		3	3	3	3	3	2	2	2	2	1	2	3
Intelligent	Fuzzy	3	3	2	3	3	2	2	3	2	1	2	2
	Neural networks	3	3	3	3	3	3	3	3	2	2	3	3
MPC		3	3	3	3	3	3	0	0	1	0	3	3

Flight task feasibility: numbers from 0 to 3 were used to indicate how feasible each scheme is to perform specific tasks; the higher the number, the greater the performance at the task. **Robustness:** numbers from 0 to 3 were used to indicate the robustness of each scheme under certain kinds of disturbances; the higher the number, the greater its robustness. **Complexity:** numbers from 0 to 3 were used to indicate each scheme's complexity to be executed and implemented; the higher the number, the greater its complexity.

5. Open problems and future directions

Many of the solutions given in terms of the PID control have been created ad hoc, that is, prioritizing the solution of the task rather than providing an analysis to deduce the limitations and advantages of the control strategy. It is in the latter on which we believe that the main research opportunities are found. We discuss in the next some problems that can be addressed in future research:

- Control via PID/PI nested loops: Most commercial quadrotors are equipped with brushless DC motors. Usually, the velocity of these motors, and in consequence the force delivered by the propellers, is controlled by a PI current-based loop. To the best of our knowledge, there is no formal study even with a linearized model of the two-loop control of quadrotors: a PI loop for the current and a PID loop for the motion control. The problem of analyzing nested PI and PID loops either with Lyapunov's theory or practical stability tools remains open.
- Control PID equipped with integrator anti-windup: The most common nonlinearity found in physical nonlinear systems is the input saturation, which in combination with the integral term of the controller can lead to long settling time, overshoot, and even instability. This phenomenon is known as windup. To the best of our knowledge, there are no control solutions relying on integrator anti-windup ideas.
- Nonlinear PID control: This control structure consists of a nonlinear proportional, a nonlinear integral, and a nonlinear derivative terms. Usually, each nonlinear term is multiplied times a gain. As is pointed out in this survey, some solutions have been in terms of nonlinear PID control structures. We believe that nonlinear PID controllers in terms of the unit quaternion can be developed in order to improve the performance avoiding the problem of singularities of the system arising from the Euler–Lagrange formalism.
- PID control with deep neural networks: Neural networks and PID control have been used to control quadrotors. However, the literature indicates that good results have been obtained when using deep neural networks in the control of other nonlinear systems, but a few works have been reported with applications to quadrotors. We have noticed that the application of deep neural networks together with a PID algorithm either to solve the problem of regulation or trajectory tracking in quadrotors has not been carried out.
- Saturated PID control: As discussed earlier in this paper, the motion in the horizontal plane of a quadrotor is achieved by computing roll and pitch angles. But high roll and pitch angles can destabilize the vehicle. Thus, with high position error values, high desired roll and pitch angles are obtained, which is more common in position regulation problems and waypoint navigation. A common practice in real-time implementations is to limit the maximum desired roll and pitch angles to avoid instability. Nevertheless, based on the reviewed works, most of them do not take this issue into account. We believe that with a control theory treatment of this issue, more efficient controllers can be obtained.
- Less studied PID control combinations: Derived from the analysis presented in this paper, we have realized that the less studied combinations of the PID control are with gain scheduling, fault-tolerant, and fractional order control methods. In consequence, opportunities to develop novel solutions by using PID control with the mentioned techniques are now present. The key points are the robustness improvements that can be achieved with the incorporation of extra compensation terms.

Inspired by Emran and Najjaran (2018), Tables 3–5 are provided in order to summarize and highlight the findings of this review. In Table 3, the advantages and disadvantages of the reviewed PID-based schemes are depicted. Notice that this Table can also be useful to look for research opportunities. For example, improvements to some PID-based controllers can be achieved by looking for removing the disadvantages discussed there. In addition, Table 4 shows the rate of the task feasibility, robustness, and complexity for the reviewed PID-based schemes. In addition, the reviewed PID-based schemes' feasibility of performing some of the most common tasks for quadrotors, their robustness, and their complexity are rated in Table 4. Table 5 lists a sample of the reviewed works regarding their classification to provide the reader information on the validation method employed and if theoretical support was provided to guarantee the scheme's functionality. Furthermore, a classification of works regarding the control objective and application that addresses is provided in Table 6.

The future of the application of PID control is simple: it will continue to apply for a very long time. However, as was discussed above, there are still many questions and problems concerning new theories and practical validation to be solved.

6. Conclusion

The importance of PID control relies upon its simplicity, efficiency, and in the first place, how easy it is to implement it. For a long time, it has been applied in many types of electro-mechanical and aerial systems. Based on our exhaustive literature review, we have realized that quadrotors' most common control technique is PID control.

The literature revealed that linear PID control is the natural choice for controlling the quadrotor position and orientation. A significant trend in quadrotor control research is the design of PID-type controllers, including nonlinear, combination with other techniques, adaptive control, and off-line and online gain tuning.

Table 5
A sample of reviewed works reporting PID control structures for the quadrotor position and orientation as the main topic.

Scheme		Work	Uncertainties and disturbances	Closed-loop trajectory analysis	Validation method
Linear		Campos et al. (2005)	No	No	Experiment
		González-Vázquez and Moreno-Valenzuela (2010)	Yes	Yes	Simulation
		Lee et al. (2012)	Yes	Yes	Experiment
		Canal et al. (2020)	Yes	No	Simulation
		Shi et al. (2021)	Yes	No	Experiment
Nonlinear		Bokan et al. (2013)	No	No	Experiment
		Yu et al. (2015)	Yes	Yes	Experiment
		Pérez-Alcocer et al. (2016)	Yes	Yes	Experiment
		Kartal et al. (2020)	Yes	Yes	Experiment
		Wang et al. (2022)	Yes	Yes	Simulation
Adaptive		Modirrousta and Khodabandeh (2015)	Yes	Yes	Simulation
		He et al. (2017)	Yes	No	Simulation
		Kourani et al. (2019)	Yes	No	Experiment
		Mofid et al. (2020)	Yes	Yes	Simulation
		Ghasemi and Azimi (2022)	Yes	No	Experiment
Event-based		Wang et al. (2011)	Yes	No	Simulation
		Durand et al. (2018)	Yes	No	Experiment
		Ye (2018)	No	No	Simulation
		Kim et al. (2022)	Yes	No	Simulation
Gain-scheduling		Fang et al. (2011)	Yes	No	Experiment
		Chee and Zhong (2013)	Yes	No	Experiment
		Bouzid et al. (2021)	Yes	No	Simulation
		Imane et al. (2022)	Yes	No	Simulation
		Kang et al. (2022)	Yes	No	Simulation
Fault-tolerant		Sadeghzadeh et al. (2011a)	Yes	No	Experiment
		Amoozgar et al. (2012)	Yes	No	Experiment
		Yu et al. (2014)	Yes	No	Experiment
		Bouguerra et al. (2015)	Yes	No	Simulation
		Qin et al. (2017)	Yes	Yes	Experiment
Fractional order		Efe (2011)	Yes	No	Experiment
		Fu and Li (2015)	Yes	No	Simulation
		Liu et al. (2020)	Yes	No	Simulation
		Saribas and Kahvecioglu (2021)	Yes	No	Simulation
Intelligent	Fuzzy	Gao et al. (2014)	Yes	No	Experiment
		Huang et al. (2018)	Yes	No	Experiment
		Dong and He (2019)	Yes	Yes	Simulation
		Pai et al. (2019)	Yes	No	Experiment
		Abdelmaksoud et al. (2023)	Yes	No	Simulation
	Neural networks	Chen et al. (2015a)	Yes	Yes	Simulation
		Wang et al. (2015)	No	No	Experiment
		Belhadri et al. (2016)	Yes	No	Simulation
		Xiang et al. (2017)	Yes	No	Simulation
		Nazaruddin et al. (2018)	Yes	No	Simulation
Model Predictive		Cheng and Yang (2018)	Yes	No	Simulation
		Liang et al. (2018)	Yes	No	Experiment
Cooperative		Srigrarom et al. (2015)	No	No	Experiment
		Thien and Kim (2018)	Yes	Yes	Experiment
		Najm et al. (2020)	Yes	No	Simulation
		Dhiman et al. (2020)	Yes	No	Experiment
		Biantoro et al. (2021)	Yes	No	Simulation

Based on the analysis of the results of the presented simulations, we can comment that simpler PID schemes can be employed to successfully achieve the trajectory-tracking task. Nonetheless, providing the controller with some information on the model parameters such as the mass, improves its response and helps to reach faster the desired signal. In addition, an exhaustive design based on the closed-loop system's stability based on the nonlinear model of the quadrotor provides good results. Finally, adding adaptive capabilities to the PID scheme improves its performance under external disturbances and certainly provides robustness against parameter uncertainty. A critical feature of a controller for a quadrotor is computing the desired roll and pitch angles; since considerably impacts the performance in the horizontal plane. While simple control algorithms may be used to control the actuated states, more elaborated ones should be employed to control the position in the horizontal plane.

Opportunities in open problems for control research are observed. In particular, many PID-based control schemes have been given without a Lyapunov stability analysis. These studies would provide insight into the gain tuning and disturbance rejection either when disturbances come from unmodeled dynamics or arise from external sources.

Table 6
Classification by control objective of some works that use the PID control scheme.

<table>
<tr><th>Hovering</th><th>Position control</th><th>Trajectory tracking</th><th>Payload Transport</th><th>Multiagent Systems</th></tr>
<tr><td>Zhang et al. (2009)</td><td>Shepherd III and Turner (2010)</td><td>Sadeghzadeh et al. (2011a)</td><td>Estevez and Graña (2015)</td><td>Cheng et al. (2013)</td></tr>
<tr><td>Yoon and Goo (2011)</td><td>Gautam and Ha (2013)</td><td>Hernandez et al. (2013)</td><td>Kourani et al. (2019)</td><td>Pebrianti et al. (2018)</td></tr>
<tr><td>Lee et al. (2012)</td><td>Duong et al. (2014)</td><td>Modirrousta and Khodabandeh (2015)</td><td>Sierra and Santos (2019)</td><td>Abbasi et al. (2018)</td></tr>
<tr><td>Zhan et al. (2012)</td><td>Gao and Yue (2015)</td><td>Wang and Chen (2016)</td><td>Canal et al. (2020)</td><td>Lv et al. (2018)</td></tr>
<tr><td>Abas et al. (2013)</td><td>Hong et al. (2015)</td><td>Cao and Lynch (2016)</td><td></td><td>Shirani et al. (2019)</td></tr>
<tr><td>Khairuddin et al. (2014)</td><td>Khan and Kadri (2015b)</td><td>Wang et al. (2018)</td><td></td><td>Biantoro et al. (2021)</td></tr>
<tr><td>Zhu et al. (2015)</td><td>Fang et al. (2016)</td><td>Doukhi et al. (2018)</td><td colspan="2">Estevez et al. (2016)</td></tr>
<tr><td>Chen et al. (2015a)</td><td>Ma and Ji (2016)</td><td>Rosales et al. (2018)</td><td colspan="2">Dhiman et al. (2018)</td></tr>
<tr><td>Priyambodo et al. (2016)</td><td>Teng et al. (2018)</td><td>Gomez-Avila et al. (2019)</td><td colspan="2">Dhiman et al. (2020)</td></tr>
<tr><td>Pedro et al. (2016)</td><td>Nazaruddin et al. (2018)</td><td>Siti et al. (2019)</td><td></td><td></td></tr>
<tr><td>Noordin et al. (2017)</td><td>Rao et al. (2022)</td><td>Yu et al. (2019)</td><td></td><td></td></tr>
<tr><td>Yu et al. (2017)</td><td>Kang et al. (2022)</td><td>Mohammadi et al. (2019)</td><td></td><td></td></tr>
<tr><td>Lu et al. (2018)</td><td></td><td>Kartal et al. (2020)</td><td></td><td></td></tr>
<tr><td>Ye (2018)</td><td></td><td>Shakeel et al. (2022)</td><td></td><td></td></tr>
<tr><td>Alsafadi et al. (2019)</td><td></td><td></td><td></td><td></td></tr>
</table>

We consider that the history of its application is at its first stages, and critical developments are just about to come.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article

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