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A Survey on Fractional Order Control Techniques for Unmanned Aerial and Ground Vehicles

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ABSTRACT In recent years, numerous applications of science and engineering for modeling and control of unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) systems based on fractional calculus have been realized. The extra fractional order derivative terms allow to optimizing the performance of the systems. The review presented in this paper focuses on the control problems of the UAVs and UGVs that have been addressed by the fractional order techniques over the last decade.

INDEX TERMS Fractional calculus, fractional order control techniques, unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs).

I. INTRODUCTION

Nowadays, the research interests of UAVs and UGVs is growing rapidly due to their potential in usage for a countless number of applications. UAVs are suitable to perform important tasks, among which are surveillance, reconnaissance, agricultural imaging, search and rescue, etc [1], [2]. There are many types of UAVs used in mentioned applications such as single rotor helicopters, multi rotor-crafts, fixed wing planes and hybrid combinations [3]. Each platform has its particular advantages and disadvantages. Similarly, UGVs also have arisen the interests of many researchers and organizations, especially the military, since the 1960s [4]. This has conducted to the development of different models of UGVs, which can be distinguished in wheeled mobile robots (WMRs) and legged mobile robots (LMRs) depending on the locomotion mechanism. Currently, UAVs and UGVs are used in many applications both individually and collectively including reconnaissance, surveillance, combat, rescue, agriculture, etc [5]. Because various applications in which UAVs and UGVs are involved, the need of solving various problems in their control has occurred. In recent years, the research community has addressed several control problems in UAVs using integer order control (IOC) techniques, e.g trajectory tracking [6]–[11], attitude control [12]–[16], path planning [17]–[22], state estimation [23]–[27], formation control [28]–[32], fault tolerant control (FTC) [33]–[37], fault detection and diagnosis (FDD) [38]–[42], and collision avoidance [43]–[47]. Similarly, the control issues which have been studied in UGVs are: trajectory tracking [48]–[52], path planning [53]–[57], state estimation [58]–[62], formation control [63]–[67], fault tolerant control (FTC) [68]–[72], fault detection and diagnosis (FDD) [73]–[75], and collision avoidance [76]–[78].

Many scientists are widely using fractional controllers to achieve more robust performance in many control systems some of which are servo-mechanisms, water tank system and other industrial applications [79]–[84]. Compared with the traditional integer order controllers, fractional order control (FOC) techniques have achieved more impressive results of UAVs and UGVs system in term of improving the robustness during wind gusts, payload variations, and friction, and modeling uncertainties [85]–[88]. Because of the FOC techniques permit to consider more efficient constraints such as phase

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margin, gain crossover frequency, complementary sensitivity, energy efficiency and isodamping behavior for tuning the controllers. Additionally, it is indicated that fractional calculus has the capacity to configure the phase and gain of the frequency response in a system independently and get the Bode ideal transfer function [89]. Therefore, this paper reviews and highlights the existing work using the fractional order control (FOC) techniques as the best solutions for the control problems of UAVs and UGVs.

This review is structured as follows. In section II, the mathematical fundamental of fractional calculus used in control theory is introduced. FOC techniques of UAVs and UGVs are respectively described in the section III and section IV. Finally, concluding remarks are presented in section V.

II. BASICS OF THE FRACTIONAL CALCULUS

Fractional calculus corresponds to the generalization of the classical operation of derivation and integration to orders other than integer. Since the last decades, several applications in the science and engineering areas have been developed (modeling, control theory, mechanical and dynamic systems, signal and image processing, etc.) based on fractional calculus theory [90]–[94].

A. FRACTIONAL ORDER DERIVATE DEFINITIONS

Three important approaches of fractional derivatives used extensively in the field of control theory are introduced by Grünwald-Letnikov, Riemann-Liouville and Caputo [95], [96].

1) GRÜNWALD-LETNIKOV DEFINITION

The Grünwald-Letnikov (G-L) definition of fractional derivate is defined as:

$$ {}_aD_t^\alpha = \lim_{h\to 0} \frac{1}{h^\alpha} \sum_{j=0}^{[\frac{t-a}{h}]} (-1)^j \binom{\alpha}{j} f(t-jh) \tag{1}$$

where $[\frac{t-a}{h}]$ is an integer amount, a and t are the limits of the operator, $\alpha > 0$. The binomial coefficient $\binom{\alpha}{j}$ is defined as:

$$\binom{\alpha}{j} = \frac{\Gamma(\alpha+1)}{\Gamma(j+1)\Gamma(\alpha-j+1)} \tag{2}$$

$\Gamma(.)$ is the gamma function defined as:

$$\Gamma(n) = \int_0^\infty t^{n-1} e^{-t} dt \tag{3}$$

The G-L definition is a discrete form of the fractional derivative and it is primarily used in numerical solutions of fractional-order differential equations [79], [97].

2) RIEMANN-LIOUVILLE DEFINITION

The Riemann-Liouville (R-L) definition of fractional derivate is defined as:

$$ {}_aD_t^\alpha = \frac{1}{\Gamma(n-\alpha)} \left(\frac{d}{dt}\right)^n \int_a^t \frac{f(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau \tag{4}$$

where α is a real value, n is an integer value with the condition $n-1<\alpha<n$, t and a are the limits of integration.

The R-L definition is an integral form of the fractional derivative and it is appropriate for finding the analytical solution of simple functions (e^t, t^b, $cos(t)$, etc.) [98].

3) CAPUTO DEFINITION

The Caputo definition of fractional derivate is defined as:

$$ {}_a^CD_t^\alpha = \frac{1}{\Gamma(n-\alpha)} \int_a^t \frac{f^{(n)}(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau \tag{5}$$

where α is a real value, n is integer value with the condition $n-1<\alpha<n$, t and a are the limits of integration.

The Caputo derivate has advantages over R-L definition, due to the consideration of initial conditions of integer order such as $y(0)$, $\dot{y}(0)$, which are interpretable with real physical phenomena [98].

The three definitions presented, G-L and Caputo definitions are the most used for their aforementioned characteristics. Caputo derivate is used because of practical application and G-L definition for its representation discrete suitable to numerical solutions. However, the analytical methods are very complicated and should be limited the number of coefficients because of the limited available memory of the microcontrollers [79]. Because of this difficulty, the existing literature prefers continuous or discrete approximation methods by ease implementation. Nevertheless, when accuracy is increased in these methods, high-order transfer functions are obtained. The approximation methods purpose is expressing the fractional term s^α, obtained by the Laplace transform taking to the G-L or Caputo definitions, in a rational approximation function in the s, z or δ domain. The digital implementations are achieved by the discrete approximation methods (z, δ) and can be implemented directly to any microprocessor based devices like as PIC, PLC, FPGA, etc. One of the methods of discrete approximation is based on G-L definition aforementioned. More details about the study of rational approximation functions of s^α can be found in [89].

III. FRACTIONAL ORDER CONTROL TECHNIQUES APPLIED TO THE CONTROL PROBLEMS IN UAVs

In this section, FOC approaches of UAVs are introduced.The UAVs applications such as trajectory tracking control, path planning, collision avoidance, attitude control, state estimation, formation control and fault tolerant control are investigated.

A. TRAJECTORY TRACKING CONTROL

A fractional order derivative (FOD) controller which is also called the first generation of the CRONE (Commande Robuste d'Ordre Non Entier) strategy for the trajectory tracking control of a rotary-wing aircraft is proposed [99]. Its structure is given by:

$$C(s) = ks^\alpha, \quad \alpha \in (0,1), \quad k \in \Re. \tag{6}$$

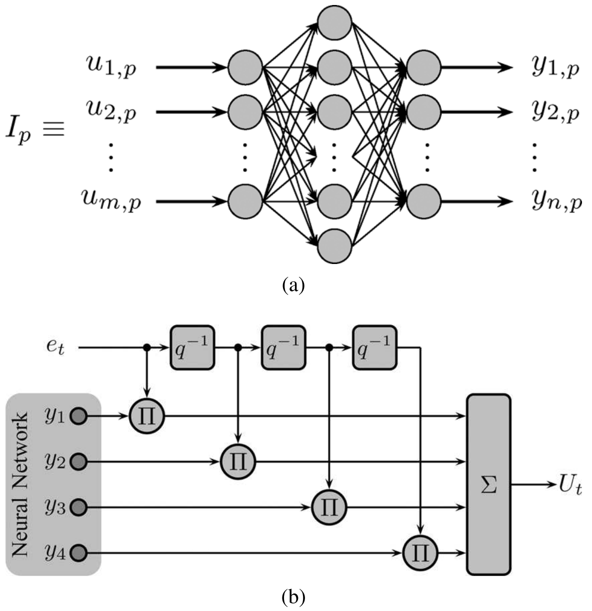

FIGURE 1. **Neural network based approximator. (a) neural network structure. (b) neural network assisted FIR approximator [100].**

The controller of the UAV is designed, by assuming a constant phase margin around the gain-crossover frequency. The effectiveness of the controller without considering the external disturbances is shown by simulation. In addition, the Bode plots of the closed-loop control system with a constant phase margin around the gain-crossover frequencies are presented. It demonstrates that the FOC controller eliminates the nonlinear effects and parameter uncertainties. However, there is no comparison with any type of IOC controller. An application of an analogical fractional order proportional-integral-derivative (FOPID) controller emulated by a neural network based approximator is proposed in [100]. The analogical FOPID controller is given in (7).

$$C(s) = k_p + \frac{k_i}{s^{\lambda}} + k_d s^{\mu} \tag{7}$$

where, k_p, k_i and k_d are the proportional, integral and derivative terms, respectively. λ and μ are the fractional orders integral and derivative terms. It consists of two sections: a neural network and a Finite Impulse Response (FIR) filter, which permits to approximate the response obtained by the analogical FOPID controller sampled to 1ms (see Fig. 1(a) and Fig. 1(b) respectively).

The neural network structure contains 20 neurons with hyperbolic tangent type neuronal activation function, which is trained to provide the coefficients to the FIR approximator ($A_0 = \{a_0, a_1, a_2, a_3\}$), varying the action coefficients and differintegration orders ($A_i = \{k_p, k_d, k_i, \lambda, \mu\}$) of the fractional controller. In this work, the range of the controller parameters are $k_p \in (0, 3)$, $k_d \in (0, 0.5)$, $k_i \in (0, 1)$ and $\lambda, \mu \in (0, 1)$. The simulation results show that the presented structure successfully emulates the analogical FOPID controller under the wind disturbances, powering uncertainties and measurement noises. Moreover, the proposed scheme has a very low computational complexity, which allows to use for real-time applications based on microprocessor or FPGA.

A novel FOPID controller based on modified Black-Nichols method is proposed in [101], whose transfer function is defined as:

$$C(s) = k_p \left(\frac{1 + T_i s^{\lambda}}{T_i s^{\lambda}} \frac{1 + T_d s^{\mu}}{1 + T_f s} \right), \quad \lambda, \mu \in (0, 2). \tag{8}$$

where k_p is the proportional term, T_i is the integration time, T_d is the derivative time, T_f is filter time term, λ and μ are the fractional orders integral and derivative terms respectively. The results are compared with an integer order PID (IOPID) control, Fuzzy-PID hybrid control and a backstepping approach (BS) under two realistic scenarios considering the parameters uncertainties, extra payload and sensor noise. The Integral Square Error (ISE) and Integral Squared Control Input (ISCI) indexes are used for the quantification of the results. According to the performance indexes, the FOPID has the best performance in terms of precision and energy consumption in comparison to the other nonlinear techniques. This clearly demonstrates that linear controllers based on FOC techniques can achieve similar or better results than the other traditional nonlinear techniques for UAVs.

An optimal FOPID controller tuned with a genetic algorithm (GA) approach under certain design specifications is presented in [102]. The fitness function used to optimize the parameters k_p, k_i, k_d, λ and μ of the FOPID controller is:

$$f = \beta e_{ss} + \delta e_{st} + \gamma e_{os} \tag{9}$$

where e_{ss} is steady-state error, e_{st} is settling time error, e_{os} is overshoot error, β, δ and γ are weight factors. The proposed strategy is evaluated with MATLAB simulations using a variable set-point and circular trajectory without considering external disturbances, obtaining a good trajectory tracking with both references. Nevertheless, it is necessary to compare the proposed controller against some IOC technique.

In other work, a FOPD controller is designed and applied to AR.Drone 2.0 [103]. The controller parameters are obtained based on the specifications of phase margin, gain crossover frequency and robustness.

$$\begin{aligned} \angle C(j\omega_{gc})P(j\omega_{gc}) &= -\pi + \phi_m \\ \left|C(j\omega_{gc})P(j\omega_{gc})\right| &= 1 \\ \left.\frac{d(\angle C(j\omega)P(j\omega))}{d\omega}\right|_{\omega=\omega_{gc}} &= 0 \end{aligned} \tag{10}$$

where, $C(s)$ is the controller, $P(s)$ is the process, ϕ_m, is the phase margin desired in closed-loop and ω_{gc} is the gain crossover frequency. Additionally, the absolute integral error (IAE) and integral squared error (ISE) indexes are used for choosing the best FOPD controller. The performance of FOPD controller considering wind disturbances is compared against the controllers based on extended prediction self-adaptive control (EPSAC) approach and integer order PD (IOPD) control. The results show that the FOPD controller has a similar response to the EPSAC method, which is an advanced technique of process control.

A novel fractional-order backstepping sliding mode control (FOBSMC) approach for an UAV is proposed in [104]. The globally asymptotically stability of the proposed controller is achieved using Lyapunov stability theory. Subsequently, the effectiveness and robustness of the controller have been tested by flight trajectories with external disturbances.

Finally, fractional order sliding mode control (FOSMC) strategies are presented in [105] and [106]. The trajectory tracking problems are resolved using FOSMC and IOPD controllers [105]. The FOSMC uses a switching function ($S(t)$) and a double power reaching law ($\dot{S}(t)$) to avoid the chattering problem, which are described as:

$$\begin{aligned} S(t) &= \dot{e}(t) + k_p e(t) + D^{\alpha} e(t) \\ \dot{S}(t) &= -k_1 \|S(t)\|^{\gamma} sign(S(t)) - k_2 \|S(t)\|^{\gamma+1} sign(S(t)) \end{aligned} \tag{11}$$

where $e(t) = \{e_{\varphi}, e_{\theta}, e_{\psi}\}$, are the errors of attitude tracking, $k_p = \{k_{p\varphi}, k_{p\theta}, k_{p\psi}\}$, k_1, k_2 are real constants, $sign(.)$ is the signum function and γ the fractional order derivative. For comparison purpose, an integer SMC is developed. The proposed strategy with FOSMC presents a faster response and higher tracking accuracy. Similarly, a FOSMC for a second-order non-linear model of a quadrotor with an unknown additive perturbation term is presented in [106]. Theirs switching function ($S(t)$) and reaching control law ($\dot{S}(t)$) are chosen as:

$$\begin{aligned} S(t) &= \dot{e}(t) + \lambda e(t) \\ \dot{S}(t) &= -\sigma D^{-\beta} sign(S(t)) - \mu S(t) \end{aligned} \tag{12}$$

where $e(t)$ is the tracking error, λ, μ and σ are real constants, $sign(.)$ is the signum function and β is the fractional order derivative. The performance of the FOSMC is compared against an integer order SMC (IOSMC). The MATLAB simulations demonstrate the robustness of the FOSMC controller under additive perturbations. In addition, the chattering in some of the control signals of the FOSMC is less than the SMC controller.

B. PATH PLANNING/ COLLISION AVOIDANCE

A fractional order potential field (FOPF) method is applied for path planning and collision avoidance in two cooperative source seeking applications [107], [108]. The method can be used in path planning when UAVs are attracted to the source (attractive potential field) and collision avoidance as each UAV or obstacle are repelled (repulsive potential field). The FOPF is obtained based on the definition of Coulomb electric field as:

$$V_n(r) = \frac{q}{4\pi\epsilon_0}\frac{\Gamma(2-n)}{r^{2-n}}, \quad \forall n \in (0,2)(2,+\infty) \tag{13}$$

where q is the source point charge, ϵ_0 is the permittivity vacuum, r is the distance to the charge, n can be an integer or non-integer greater than zero and $\Gamma(.)$ is the gamma function. In order to implement the FOPF, the function $V_n(r)$ can be

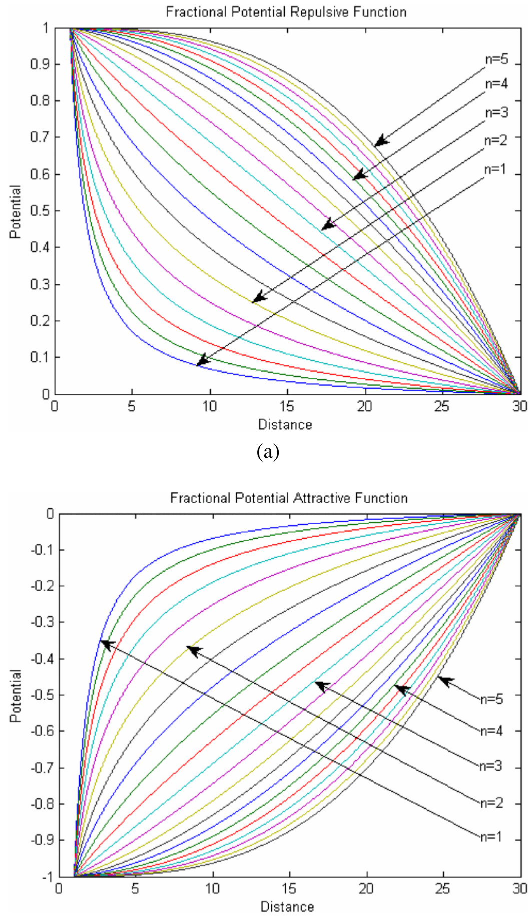

FIGURE 2. FOPF. (a) repulsive field. (b) attractive field [107].

normalized to a value between (0, 1), using the maximum distance (r_{max}) and minimum distance (r_{min}). The repulsive FOPF is given as:

$$U_{rep}(r) = \begin{cases} \dfrac{r^{n-2} - r_{max}^{n-2}}{r_{min}^{n-2} - r_{max}^{n-2}}, & \forall n \in (0,2)(2,+\infty) \\ \dfrac{\ln r - \ln r_{max}}{\ln r_{min} - \ln r_{max}}, & n = 2 \end{cases} \tag{14}$$

while, the attractive FOPF is $U_{att}(r) = -U_{rep}(r)$. FOPF evaluation with $1 \leq n \leq 5$ for repulsive and attractive potential fields are shown in Fig. 2.

Contrarily, the FOPF method allows to use different level of potential fields, which can be useful in dangerous cases. This is an advantage of the FOPF with regard to the integer order potential field (IOPF). From Fig. 2(a), it can be seen that more force can be applied with the greater n than a FOPF with the smaller n. It shows that FOPF and extended Kalman filter (EKF) achieved suitable results.

C. ATTITUDE CONTROL

An application of FOSMC and neural networks to attitude control of a quadrotor is proposed [109]. The switching function ($S(t)$) and a reaching law ($\dot{S}(t)$) in FOSMC method are defined as:

$$S(t) = e(t)^{(1+\beta)} + \lambda e(t)$$
$$\dot{S}(t) = -QD^{\beta} sign(S(t)) \quad (15)$$

where $e(t)$ is the tracking error, $\beta \in (0, 1)$ is the fractional order derivate and λ, Q are real constants. The neural networks approach is applied to compensate the power loss in the battery of the quadrotor. Two neural networks create the maps to provide the relation at the pulse-width modulation (PWM) signal level between the controller and UAV dynamics. The scheme is given in Fig.3.

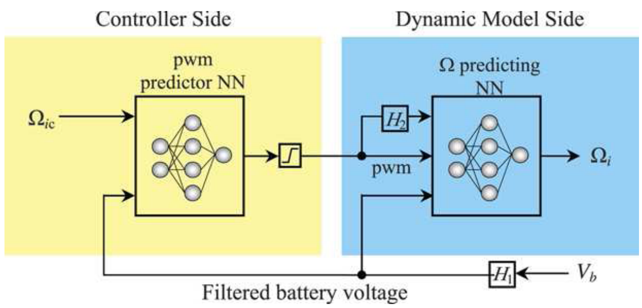

FIGURE 3. **Neural network components for the relation in PWM level [109].**

where V_b is the battery voltage, Ω_{ic} is the angular speed at ith motor specified by the controller, Ω_i is the angular speed at ith motor, H_1 and H_2 are low pass filters. The strategy is evaluated by simulation, where FOSMC and neural networks present the feasibility under the effect of wind disturbances, measurement noise and during the voltage loss in the battery, when it discharges from 11.1V to 9.9V in 130s. A fractional-order control structure that enforces finite-time convergence of the sliding surface is proposed [111]. The model-free fractional-order control law is given by:

$$\tau_i(t) = -k_{t_{ni}} I_t^{\nu} sign(S_{qi}(t)) + \tau_i(t_{ni}) \quad (16)$$

where $k > 0$ is the feedback gain, τ_i is the ith component of the control torque vector $\tau = [\tau_\phi, \tau_\theta, \tau_\psi]^T$, S_{qi} is the sliding error manifold, ν is the fractional order integral term and t_{ni} is the sequence of instants at which $S_{qi}(t_{ni}) = 0$. The performance of the scheme proposed is evaluated experimentally by using the AR.Drone 2.0 quad-rotor. Two trajectories (a circle and a sine function) for attitude tracking control are chosen to validate. The results show that the quad-rotor effectively achieves the angular positions with a minimum tracking error without chattering. This work is extended in [112], where the problem of underactuation to control the translational coordinates (x, y) is addressed and a solution based on a virtual position control approach is proposed. In the similar approach, the performance of AR.Drone 2.0 is validated through both simulations and real-experiments. Two order of integration values are implemented, with which the classical integer SMC and FOSMC for attitude control are considered. For both cases the same position is obtained based on the virtual control. However, adjusting the value of integration obtains more precise results. A novel robust FOSMC combined with a state constrained controller is presented in [113]. The inner-loop controllers are based on FOSMC for the attitude control, while outer-loop controllers use the state constrained control for the translational movements (x, y, z). The fractional order slide mode surface is defined as:

$$S(t) = D^{\alpha+1}e(t) + m_1 e(t) + n_1\beta(e(t)) \quad (17)$$

where $e(t)$ is the respective orientation error (ϕ, θ, ψ), m_1, n_1 are positive constants, $\alpha \in (0, 1)$ is the fractional order derivative term. The function $\beta(e(t))$ is defined as:

$$\beta(e(t)) = \begin{cases} e(t)^{\frac{p_1}{q_1}}, & \text{if } \bar{S}(t) = 0 \text{ or } \bar{S}(t) \neq 0, |e(t)| > u \\ e(t), & \text{if } \bar{S}(t) \neq 0, |e(t)| \leq u \end{cases} \quad (18)$$

where u is the small positive threshold, p_1, q_1 are positive odd integers with condition $1 < q_1/p_1 < 2$ and $\bar{S}(t) = D^{\alpha+1}e(t) + m_1 e(t) + n_1 e(t)^{\frac{p_1}{q_1}}$. For the comparison purpose, two additional integer SMC controllers are designed. The simulations and experiments are implemented by using the Quanser QBall 2 quadrotor driven by MATLAB. In addition, lumped disturbances approximated by a sum of sinusoidal functions are considered. Finally, the results demonstrate that FOSMC has lower values of overshoot and convergence time in comparison to the other controllers.

A FOSMC via disturbance observer for attitude control of a quadrotor is presented [114]. Firstly, the estimation of the fractional order derivative of the external disturbance is realized by using a new fractional order disturbance observer (FODOB), whose representation is given by:

$$\begin{aligned} D^{1+\alpha-\beta}p(t) &= -LB_d(D^{\alpha-\beta}p(t) + LD^{\alpha}\dot{x}(t)) \\ &\quad - L(AD^{\alpha-\beta}x(t) + BD^{\alpha-\beta}u(t)) \\ D^{1+\alpha-\beta}\hat{d}(t) &= D^{1+\alpha-\beta}p(t) + LD^{\alpha}x(t) \end{aligned} \quad (19)$$

where $\beta \in (0, 1]$ is the system order, $x(t) \in \Re^n$ is the state variable, $u(t) \in \Re^m$ is the control signal, $A \in \Re^{n\times n}$ is the state matrix, $B \in \Re^{n\times m}$ is the control matrix, $B_d \in \Re^{n\times 1}$ is the disturbance matrix, $C \in \Re^{p\times n}$ is the output matrix, $\hat{d}(t)$ is the estimated disturbance of $d(t)$, $p(t)$ is an auxiliary vector, $\alpha \in (0, \lambda)$ depends on the order of FOSMC and L is the observer gain matrix. Subsequently, a FOSMC for the attitude control is designed, whose switching function $(S(t))$ and reaching law $(\dot{S}(t))$ are defined as:

$$\begin{aligned} S(t) &= a_1 e_y(t) + a_2 D^{\alpha} e_y(t) \\ \dot{S}(t) &= -a_1\dot{e}_y(t) + a_2 D^{1+\alpha-\beta} C(Ax(t) + Bu(t) + B_d d(t)) \\ &\quad - a_2 D^{\alpha}\dot{y}_d(t) \end{aligned} \quad (20)$$

where a_1, a_2 are real constants, α is the fractional order of the sliding surface and $e_y(t) = y(t) - y_d(t)$ is the tracking error of the output. The FOSMC with FODOB is compared with a SMC-DOB. The numerical simulations show that the proposed method decreases the tracking error to high speed and suppresses the chattering problem.

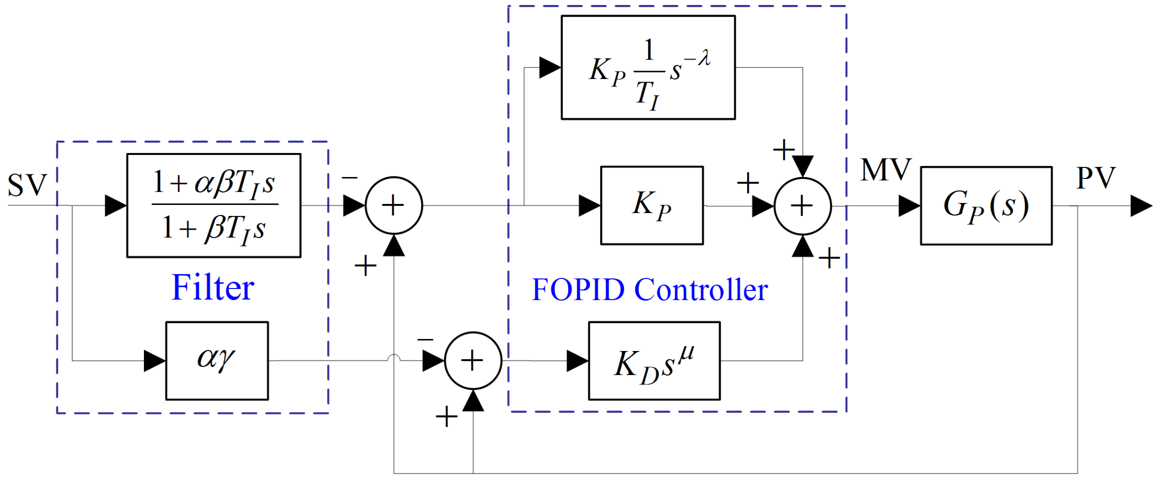

FIGURE 4. **Filter type 2DOF-FOPID control structure [110].**

In contrast to the work presented in [111], a novel FOSMC with a nonlinear PI nonlinear structure is proposed in [115]. The proportional term acts as a nonlinear dissipater, while the fractional integral part removes the chattering effect out of the control signal. The fractional-order control law is given by:

$$\tau_i(t) = -k_1\, |S_i(t)|^{\alpha}\, sign(S_i(t)) - k_2\; t_{ni} I_t^{\beta}\, sign(S_i(t)) + \tau_i(t_{ni}) \tag{21}$$

where $k_1 > 0, k_2 > 0$ are the feedback gains, τ_i is the ith component of the control torque vector $\tau = [\tau_\phi, \tau_\theta, \tau_\psi]^T$, S_i is the sliding error manifold, α, β are the fractional order terms and t_{ni} is the sequence of instants at which $S_i(t_{ni}) = 0$. The simulations and real-experiments are executed by using MATLAB and the AR.Drone 2.0 quad-rotor. Four different controllers are used for the comparison purpose: fractional sliding mode PI nonlinear controller, first-order sliding mode controller, sliding mode PI-like controller and a second-order sliding mode super-twisting controller. All the angle references are considered as sinusoidal functions. The results show a similar attitude tracking with all the controllers. However, when the quaternion error vector and the control signals are compared between the controllers, it is easy seen that the fractional controller has less tracking error and smaller control effort signal than the other methods. Likewise, the chattering phenomenon is lesser than in the conventional controllers.

A fractional order filter with two-degrees-of-freedom PID controller for the pitch control of a UAV is presented [110]. The structure is given in Fig. 4 and it consists of a filter and a FOPID controller, which can be independently tuned to ensure the disturbance rejection and trajectory tracking performance. Firstly, the FOPID controller is tuned by using the follow specifications: phase and gain margins, robustness to variations in the gain of the system, robustness to high-frequency noise and disturbance rejection. The controller parameters (K_P, K_D, T_I, λ and μ) are obtained by resolving the set of five nonlinear equations generated with the specifications aforementioned using the optimization toolbox of MATLAB. Finally, the filter parameters $\alpha \in [0, 1]$, $\beta \in [1, 2]$, $\gamma \in [0, 2]$ are computed by using a particle swarm optimization (PSO) method to satisfy some performance criteria such as rise time (t_r), settling time (t_s), steady-state error (E_{ss}), overshoot (M_p) and integral absolute error (IAE). The fitness function used to optimize is:

$$J(k) = w_1 M_p + w_2 t_r + w_3 t_s + w_4 E_{ss} + w_5 IAE \tag{22}$$

where $k = [\alpha \quad \beta \quad \gamma]$ are the parameters to be optimized and $w = [w_1.w_2, w_3, w_4, w_5]$ are the inertia weights. The proposed controller presents a good disturbance rejection and command tracking according to the MATLAB simulations.

Subsequently, a robust FOPID controller for the pitch angle control of a Fixed-Wing UAV based on multi-objective bat algorithm (MOBA) and multi-objective genetic algorithm (MOGA) are presented in [116] and [117], respectively. The objective functions used to optimize in both works are:

$$\begin{aligned} J_1 &= \|S(j\omega)\|_\infty \\ J_2 &= \|T(j\omega)\|_\infty \end{aligned} \tag{23}$$

where $\|S(j\omega)\|_\infty$ is the infinity norm of the sensitivity function and $\|T(j\omega)\|_\infty$ is the complementary sensitivity function. In MOBA approach, a combined objective function $J(k)$ is obtained by summing the objective functions given in (23), using weighted-sum method.

$$J(k) = \sum_{k=1}^{2} J_k w_k, \quad w_1, w_2 > 0,\; w_1 + w_2 = 1 \tag{24}$$

The MOGA approach uses each objective function individually to find a set of solutions with a different trade-off (the so-called Pareto front). Then a solution is selected with the desired balance between conflicting design objectives. The results show that the FOPID controllers track the trajectory and satisfy the designed conditions of the objective function. At the same time, they have a better performance than the IOPID controllers.

A new method to obtain a flat phase margin with FOPID controller is proposed [118]. This method is applied for the roll control of a UAV using the specifications: gain margin, phase margin and robustness to gain variations of the system with two different approaches. The first approach consists in a limited number of frequency samples of $G(s)$ around of its crossover frequency for the controller design. This approach allows greater computational efficiency than the classical method, which uses a first order plus time delay (FOPTD) model. In the second approach, an approximated open loop system ($G'(s)$) with the same amplitude of $G(s)$ and different phase curve is used. Moreover, two additional controllers are used: an IOPID controller and a classical FOPID. For the performance evaluation of the controllers, uncertainties in the aerodynamic parameters of the UAV are added. The simulation results in MATLAB demonstrate that the new FOPID controller is more robust than the other controllers in closed loop.

A fractional order proportional-integral (FOPI) controller design for the roll-channel or lateral direction control of a fixed-wing UAV is presented [85]. The transfer function of the controller is:

$$C(s) = k_p \left(1 + \frac{k_i}{s^\lambda}\right) \tag{25}$$

where, k_p and k_i are the proportional and integral terms respectively, $\lambda \in (0, 2)$ is the fractional order integral term. Firstly, the roll-channel model of the UAV is obtained using closed-loop system identification, which requires a rough PID tuning to determine $C_0(s)$. Once the roll-channel model is obtained, it is necessary to approximate a FOPTD system. The outer loop FOPI controller is tuned based on the performance specifications described in (10). The proposed FOPI controller is compared with an integer order PI (IOPI) controller through simulation and real flight experiments, by considering the effect of wind gust disturbances and payload variation, which demonstrate the robustness of the FOPI controller with respect to IOPI controller.

A variant of fractional order proportional-integral FO[PI] controller for the roll-channel or lateral direction control of a fixed-wing UAV is presented in [86], whose representation in transfer function is:

$$C(s) = \left(k_p + \frac{k_i}{s}\right)^\lambda \tag{26}$$

where, k_p and k_i are the proportional and integral term respectively, $\lambda \in (0, 2)$ is the fractional order term. For comparison purpose, four controllers are designed: IOPI based on modified Ziegler-Nichols (MZNs) tuning method, IOPID, IOPI and FO[PI] are tuned based on the performance specifications described in (10). These four controllers are evaluated by simulation and real flight experiments under the effect of payload variations. The results show that the designed FO[PI] controller has a better performance than the integer order controllers. The same FO[PI] control structure is used for the pitch control of a vertical takeoff and landing (VTOL) UAV [119] and the lateral longitudinal attitude control of a fixed-wing UAV [120]. The controller parameters are obtained based on the performance specifications given in (10). For the VTOL UAV, three additional controllers MZNs IOPI and IOPID are designed to compare the performance with respect to the proposed FO[PI]. The simulation results under effect of wind gust disturbances and payload variations show that the proposed strategy has better transient response and robustness than the other controllers. Similarly, two additional controllers IOPID, FOPI are designed for the fixed-wing aircraft for comparison purpose. The simulation through MATLAB indicates that the FO[PI] has a better performance with respect to the other controls under wind gust disturbances.

D. STATE ESTIMATION CONTROL

A new fractional order complementary filters (FOCF) approach for the attitude estimation of small low-cost UAVs is presented [121]. The purpose of complementary filters is to combine the outputs of two or more sensors that complement each other over different parts of the system bandwidth. It means that a sensor has reliable data in high frequencies while the other should has reliable data in low frequencies. Two sensors that satisfy this condition are: a gyroscope and an inclinometer. Fig. 5 shows the idea of the complementary filter in frequency domain and its equivalent representation in a closed-loop system.

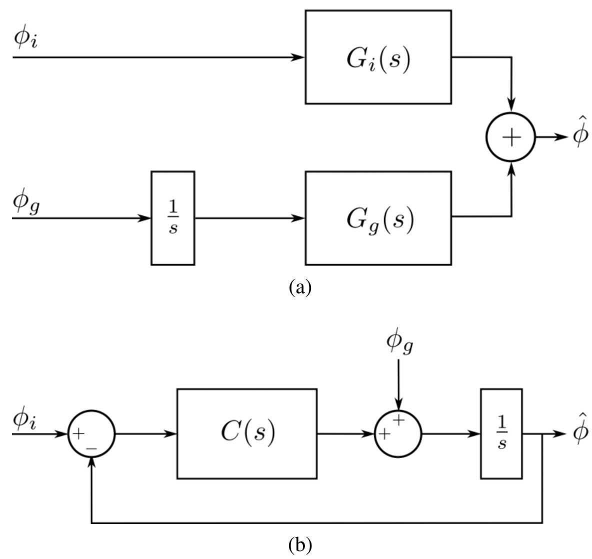

FIGURE 5. Complementary Filter. (a) frequency domain. (b) closed-loop [121].

where ϕ_i, ϕ_g are the outputs of the inclinometer and gyroscope respectively. $G_i(s)$, $G_g(s)$ are the filters for the inclinometer and gyroscope, $\hat{\phi}$ is the estimation of ϕ. It is important to indicate that the condition for complementary filters is $G_i(s) + G_g(s) = 1$. These filters could be chosen as following:

$$G_i(s) = \frac{C(s)}{C(s)+s} \qquad G_g(s) = \frac{s}{C(s)+s} \tag{27}$$

According to the Fig. 5(a) and (27), $\hat{\phi}$ is defined as:

$$\hat{\phi} = \phi_i \frac{C(s)}{C(s)+s} + \frac{\phi_g}{s}\frac{s}{C(s)+s}$$
$$\hat{\phi} = \left(s\phi_i C(s) + \phi_g - \hat{\phi}C(s)\right)\frac{1}{s}$$
$$s\hat{\phi} = (\phi_i - \hat{\phi})C(s) + \phi_g \quad (28)$$

From (28), an equivalent representation of the complementary filter in closed loop is obtained and represented in Fig. 5(b). It is important to notice that this scheme permits to use control theory for designing the complementary filter. In this way, three complementary filters are designed with several control structures such as proportional (P), IOPI and fractional order integrator (FOI) whose structure is given as:

$$C(s) = \frac{k}{s^{\alpha}}, \quad \alpha \in (0, 1),\ k \in \Re. \quad (29)$$

For validation of the controller performances, Gaussian and non-Gaussian noise are applied. The numerical simulations show that FOCF presents a better performance than the traditional integer order approach.

E. FORMATION CONTROL

A research about formation control based on leader-follower approach so-called distributed fractional order finite-time control (DFOFTC) for a group of UAVs is presented [122]. There are two stages during its operation. Firstly, a distributed sliding-mode observer (DSMO) is designed to approximate the tracking error between the leader UAV and its reference. Secondly, a FOSMC is used to ensure the finite-time convergence of the tracking errors between followers and leader, whose switching function ($S(t)$) is chosen as:

$$S(t) = D^{\alpha+1}e(t) + \sigma_1 e(t) + \sigma_2 e(t)^{q/p} \quad (30)$$

where α is the fractional-order derivative term, σ_1 and σ_2 are positive constants, q and p are positive odd integers. These two strategies are implemented in the follower UAVs. The numerical simulations show the efficacy of the presented approaches.

F. FAULT TOLERANT CONTROL

An adaptive fractional-order fault tolerant control for an UAV under external disturbance and actuator fault is designed [123]. The dynamics of the UAV are separated into two subsystems: velocity and altitude. The actuator fault is considered using the model described as:

$$\delta_e = \rho_f \delta_{e0} + u_f \quad (31)$$

where, $0 < \rho_f < 1$ is the degrade of the control signal, δ_{e0} is the applied control signal and u_f is the bounded bias fault signal. The fractional-order derivative of the external disturbance and actuator fault are estimated using an adaptive technique, while the virtual control signal and its first derivative are estimated with a high gain observer. It permits to eliminate the problem of explosion of complexity in backstepping technique. Moreover, a fractional order terminal sliding mode control (FOTSMC) to pitch dynamics control is used, whose switching function ($S(t)$) is defined the same as the one presented in (30). The simulations show the effectiveness of the designed control strategy, when external disturbances and actuator faults are presented in the system. The control problems in UAVs analyzed with FOC techniques are summarized in Table 1.

IV. FRACTIONAL ORDER CONTROL TECHNIQUES APPLIED TO THE CONTROL PROBLEMS IN UGVs

In this section, the literature of last decade regarding control problems in UGV addressed by fractional order control (FOC) techniques is revised. It was found that trajectory tracking control, path planning and collision avoidance are among the problems treated with different FOC approaches.

A. TRAJECTORY TRACKING CONTROL

The lateral control of a networked UGV based on a fractional order generalized predictive control (FOGPC) is presented in [124]. The cost function of the FOGPC is defined as:

$$J = \int_{N_1}^{N_2} D^{\alpha}[r(t+j|t) - y(t+j|t)]^2 dt + \int_{1}^{N_u} D^{\beta}[\Delta u(t+j-1|t)]^2 dt; \quad \alpha, \beta \in \Re \quad (32)$$

where, N_1 and N_2 are the minimum and maximum prediction horizons, N_u is the control horizon, $y(t)$ is the system output and $r(t)$ is the reference signal. The FOGPC strategy is compared with an integer order GPC (IOGPC) considering two different simulation cases: sensor noise environment and communication network. The results demonstrated that the FOGPC is more robust to sensors noise and communication network, besides it presents lower values of control efforts in the lateral control than the IOGPC. Furthermore, a FOSMC for a four-wheel steering (4WS) vehicle is proposed [125], where a fractional-order sliding surface is used to eliminate the steady-state error produced by the parameter uncertainties of the real vehicle and reference model.

$$S(t) = -\Delta D^{-\alpha}S(t) - \epsilon D^{-\alpha} sign(S(t)) \quad (33)$$

where Δ is a diagonal matrix of positive real values, ϵ is a real constant, $sign(.)$ is the signum function and $\alpha \in (0, 1)$ is the fractional order derivative. A group of simulations to analyze the influence of α and variation of the 4WS parameters on the efficiency and robustness of the system are made. The results indicate that the FOSMC has improved the robustness of the 4WS vehicle.

In [87], FOPID controllers based on PSO algorithm are designed. The trajectory tracking controllers are tuned and applied for driving each wheel of the UGV as shown in Fig. 6. In which, θ_d is the desired orientation, v_r is the desired velocity, θ_a is the actual orientation and v_a is the actual velocity. The fitness function is based on the ISE index:

$$ISE = \left(\int_0^{\infty}[e_{\theta}(t)]^2 dt\right) + \left(\int_0^{\infty}[e_v(t)]^2 dt\right) \quad (34)$$

TABLE 1. Control problems in UAVs addressed by fractional order control techniques.

Problem	Approach	Authors	Dynamic Model	Disturbance	Simulation	Real Test	Year
Trajectory tracking	FOD	A. Monje [99]	Y	N	Y	N	2008
	FOPID	E. Mehmet [100]	Y	Y	Y	N	2011
		R. Ayad [101]	Y	Y	Y	N	2018
		H. Maurya [102]	Y	N	Y	N	2019
	FOPD	R. Cajo [103]	Y	Y	Y	N	2018
	FOBSMC	X. Shi [104]	Y	Y	Y	N	2018
	FOSMC	Y. Guo [105]	Y	N	Y	N	2017
		A G. Vargas [106]	Y	Y	Y	N	2018
Path planning/ Collision avoidance	FOPF	A. Jensen [107]	Y	Y	Y	N	2014
		J. Han [108]	Y	N	Y	N	2018
Attitude control	FOSMC	E. Mehmet [109]	Y	Y	Y	N	2012
		C. Izaguirre [111]	Y	Y	Y	Y	2016
		C. Izaguirre [112]	Y	Y	Y	Y	2018
		C. Hua [113]	Y	Y	Y	Y	2019
		Jing Wang [114]	Y	Y	Y	N	2018
		F. Oliva [115]	Y	Y	Y	Y	2019
	FOPID	F. Geng [110]	Y	Y	Y	N	2012
		N. Katal [116]	Y	N	Y	N	2015
		P. Kumar [117]	Y	N	Y	N	2016
		S.Seyedtabaii [118]	Y	N	Y	N	2017
	FOPI	H. Chao [85]	Y	Y	Y	Y	2010
	FO[PI]	Y. Luo [86]	Y	N	Y	Y	2011
		J. Han [119]	Y	Y	Y	N	2014
		C. Wang [120]	Y	Y	Y	N	2014
State estimation	FOCF	C. Coopmans [121]	Y	Y	Y	N	2014
Formation control	FOSMC	Z. Yu [122]	Y	Y	Y	N	2018
Fault tolerant control	FOTSMC	Z. Yu [123]	Y	Y	Y	N	2017

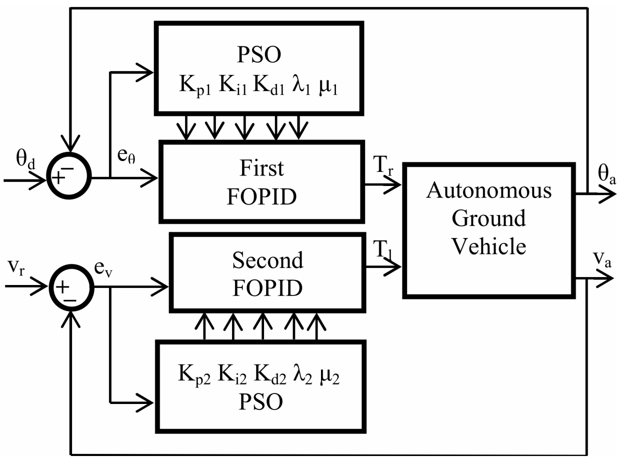

FIGURE 6. Closed-loop structure for tuning FOPID based on PSO algorithm [87].

where $e_\theta = \theta_d - \theta_a$ is the orientation error and $e_v = v_r - v_a$ is the velocity error. For comparison purpose, two IOPID controllers are designed using the same scheme as in FOPD. The tracking performance is implemented through the numerical simulation in MATLAB by using a circular and linear trajectory. A notable improvement over the tracking error is obtained with the FOPD for both trajectories. A longitudinal control for an autonomous Citroën vehicle based on a FOPI controller is proposed in [128]. Firstly, the dynamical longitudinal model is obtained by using an identification process in MATLAB based on the frequency

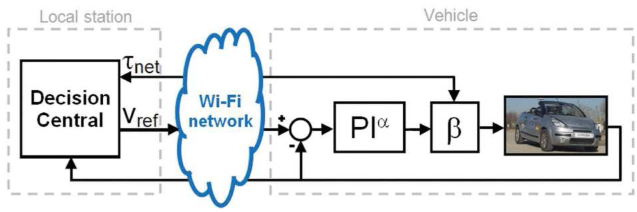

FIGURE 7. Scheme of the FOPI-based gain-scheduled [126].

domain. Secondly, the FOPI controller is tuned based on the specifications of phase margin, gain crossover frequency and disturbance rejection. Its last specification is defined as a value of the sensitivity function for a determine frequencies range. The performance of the FOPI controller is tested in simulation and real vehicle by considering an environment close to reality. The results show the good performance of the fractional controller during changes in the navigation speed, which is important for the comfort of passengers.

An extension of this work for the case of networked control system is presented in [126]. Where a novelty FOPI-based gain-scheduled controller is designed and Its scheme is show in the Fig.7. In which, τ_{net} is the network delay, v_{ref} is the speed reference of the vehicle and β is the external gain in function of network delay. The local station is responsible for detecting traffic risk situations. The adaptive speeds is applied to avoid or reduce possible accidents in its dangerous area. The results demonstrate that when the FOPI-based gain-scheduled controller is implemented, it produces a better performance with respect to using the traditional one.

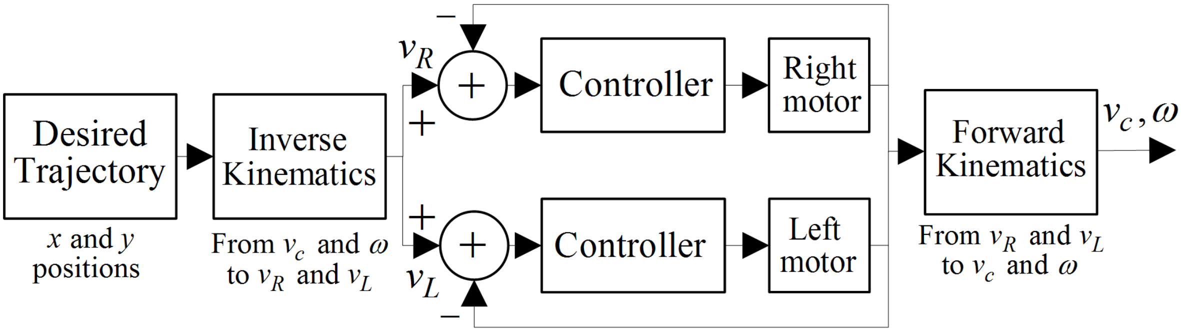

FIGURE 8. Closed-loop structure for the trajectory control of the WMR [127].

In another work, FOPI controllers are designed and applied to the UGV for trajectory tracking [88]. Similarly, IOPI and FOPI controllers for orientation and velocity are designed. The performances of both controllers are evaluated using three different trajectories for the velocity reference and a sinusoidal orientation reference in real experiments. The results indicate that the FOPI has a better performance for control of velocity and orientation of the UGV, considering the trajectory tracking error.

FOPD controllers for a differential drive WMR QBot2 of Quanser Company are designed [127]. The trajectory tracking is based on velocity control of WMR in closed-loop scheme as shown in Fig. 8.

In Fig. 8, v_R is the right wheel velocity, v_L is the left wheel velocity, v_C is the chassis linear velocity and ω is the chassis angular velocity. The inverse and forward kinematics blocks define the relation between the desired linear velocity and angular velocity of the vehicle for a trajectory. Subsequently, an IOPD controller is designed and compared with the FOPD controller on simulation and real application. It shows that the FOPD controller improves the trajectory tracking error with 83% compared to IOPD controller. Nevertheless, this experiment is performed for a straight path without considering a more realistic case of a circular trajectory.

A novel fractional order extremum seeking controller (FOESC) for trajectory tracking of an UGV is presented in [129]. This approach consists in applying fractional order filters instead of integer order filters in a classical extremum seeking controller (ESC). The FOESC scheme is given in Fig. 9. where (x, y) are the coordinates of the center of the vehicle, v is the optimal signal estimate, $\frac{s^q}{(s^q+h)}$ is the fractional order filter, $q \in (0, 1)$ is the fractional order derivative, $sin(\omega t)$ is a periodic perturbation signal, a, c, ω and h are design parameters, $J = f(x, y)$ is the nonlinear map defined as:

$$J = f^* - q_x(x - x_d)^2 - q_y(y - y_d)^2 \tag{35}$$

The extremum seeking algorithm is designed to ensure the output $J = f(x, y)$ converges to its minimal f^*, where $f^* = f(x_d, y_d)$ is the unknown extremum point, q_x and q_y are positive constants. Finally, the simulation based on a vehicle

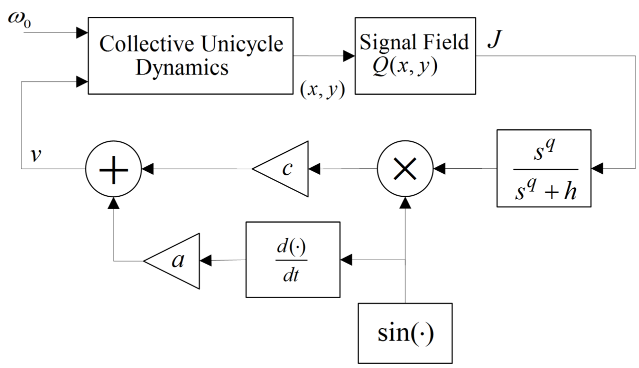

FIGURE 9. Closed-loop FOESC scheme for UGV [129].

model using a FOESC and ESC for performance comparison is presented. The results show that FOESC is more efficient with respect to the rate of convergence and steady-state error than the classical extremum seeking controller.

B. PATH PLANNING/COLLISION AVOIDANCE

A strategic schematic to use fractional order potential field (FOPF) method for path planning and collision avoidance of UGV is developed in [130]. The strategies schematic is shown in Fig.10.

The strategic schematic has three stages but only the tactical stage is addressed in this work. This stage uses the attractive and repulsive forces of the FOPF method to avoid the obstacles and to move toward the target. A simple model permits to calculate the position, velocity and acceleration. The repulsive FOPF is described in (14) and its resultant force is given by:

$$\vec{F}_{rep} = -\nabla(U_{rep}(r)) \tag{36}$$

The attractive FOPF is designed as:

$$\vec{F}_{att} = \alpha_p(\vec{x}_{target} - \vec{x}) + \alpha_v D^n(\vec{v}_{target} - \vec{v}) \tag{37}$$

where $\vec{x}$ and $\vec{x}_{target}$ are the particle and target positions, α_p and α_v are weighting coefficients, $\vec{v}$ and $\vec{v}_{target}$ are the particle and target velocities and n is the fractional order derivative term. For the attractive FOPF, a limitation of vehicle acceleration

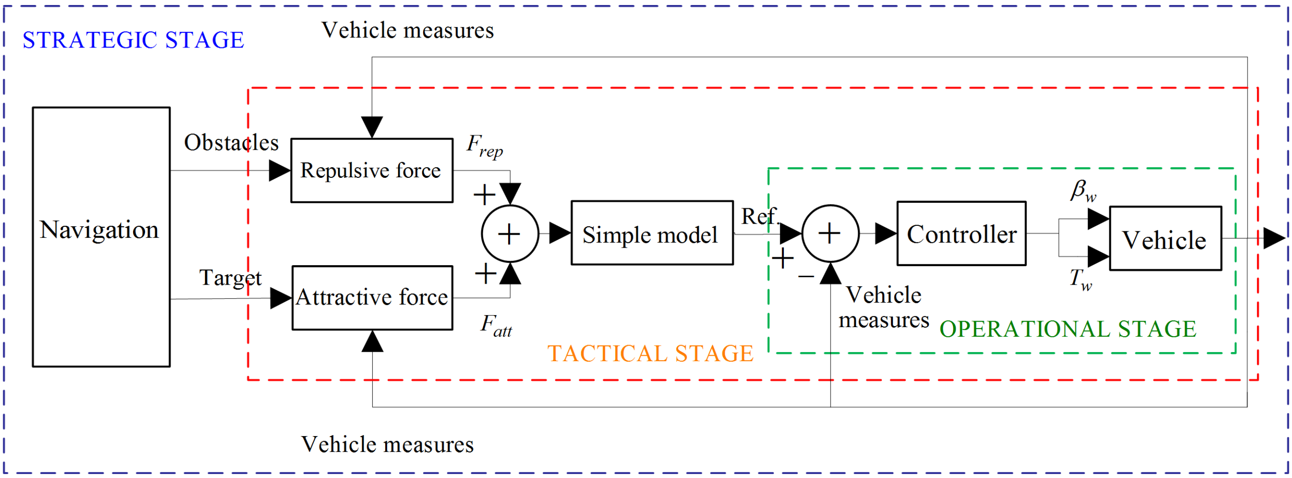

FIGURE 10. Strategic schematic for UGV using FOPF [130].

TABLE 2. Control problems in UGVs addressed by fractional order control techniques.

Problem	Approach	Authors	Kinematic Model	Dynamic obstacle	Static obstacle	Disturbance	Simulation	Real Test	Year
Trajectory tracking	FOGPC	M.Romero [124]	Y	N	N	Y	Y	N	2009
	FOSMC	J.Tian [125]	Y	N	N	N	Y	N	2014
	FOPID	Al-Mayyahi [87]	Y	N	N	Y	Y	N	2016
	FOPI	I.Tejado [128]	Y	N	N	N	Y	Y	2011
		I.Tejado [126]	Y	N	N	N	Y	Y	2013
		K.Orman [88]	Y	N	N	Y	Y	Y	2016
	FOPD	A. Rojas [127]	Y	N	N	N	Y	Y	2017
	FOESC	S.Dadras [129]	Y	N	N	N	Y	N	2017
Path planning/ Collision avoidance	FOPF	J.Moreau [130]	Y	Y	N	Y	Y	N	2017

is imposed to avoid an uncomfortable trip to the passengers. The performance of the FOPF is compared with the classical IOPF. The results show that the FOPF does not present phase variations around the gain cross-over frequency during the mass variations in the vehicle. The control problems in UGVs analized with FOC techniques are summarized in Table 2.

V. DISCUSSION AND CONCLUSIONS

The FOC techniques are analized according to the control problems of trajectory tracking, attitude control, path planning, state estimation, formation control, fault tolerant control, collision avoidance, fault detection and diagnosis present in UAVs and UGVs.The results of the study indicate that FOD, FOPD, FOPI, FO[PI], FOPID, FOBSMC, FOSMC, FOPF, FOGPC, FOESC and FOTSMC are the fundamental control techniques applied to UAVs and UGVs in the last decade.

In addition, the FOC techniques present some advantages. Firstly, FOC techniques are more flexible in tuning the parameters of the controller as order derivative terms are not restricted to integer. Secondly, it has improvement in robustness of closed loop systems under disturbances such as wind gusts, payload variations, friction, manufacturing variations, modeling uncertainties, etc. [85]–[88], [99]–[110], [114], [116]–[125], [127], [129], [130]. Finally, FO controllers can be compensate certain nonlinearities in the systems some of which are hysteresis, dead zone, backlash, etc. [89].

However, very few controllers have been implemented and embedded in the limited control units of the UAVs or UGVs by using continuous or discrete approximation methods. Most of these controllers have been used in trajectory tracking or attitude control, because these problems present in the autonomous vehicles require a robust and fast controller.

Contrarily, a serious drawback in FOC techniques is the approximation of the fractional operator D^{β} in continuous or discrete time form, which requests a high-order approximation [89]. It increases the computational complexity and may generates in a complicate transfer function to implement by numerical issues. Therefore, an adequate and efficient discrete-time approximation or direct method is required for a practical implementation on limited control units.

Recently, an novel discretization method that produces low integer order discrete-time transfer functions and computationally efficient is developed in [131]. Furthermore, a methodology to emulate FOPID using a linear model based on artificial neural network is presented, whose purpose is to reduce the computational complexity for a real-time embedded implementation on commercial microcontrollers [100].

In the last decade, a significant advance in the development of new FOC techniques has been realized. This survey has studied the current state of FOC techniques applied to UAVs and UGVs to address their different control problems. The presented studies for both types of vehicles are given in the table 1 and table 2 respectively.

In the future, the development of efficient methods to implement the FOC techniques with a lower computational complexity will be a necessity with respect to commercial applications.

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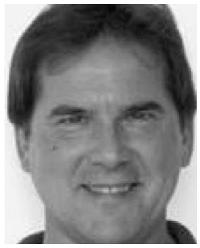

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