

Review Article

Recent Advancements in Autonomous Robots and Their Technical Analysis

Boni Liu 

School of Electronic Engineering, Xi'an Aeronautical University, Xi'an 710077, China

Correspondence should be addressed to Boni Liu; 200607004@xaau.edu.cn

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The purpose of this paper is to discuss and present a technical analysis of the recent advancements in autonomous robots equipped with a manipulator. The autonomous robots include unmanned aerial vehicle (UAV), unmanned underwater vehicle (UUV), and unmanned ground vehicle (UGV). A manipulator can make an autonomous robot more adaptable and robust but it can also affect its performance as well. Several issues can arise because of the installation of a manipulator like the robot becoming unstable due to the extra weight, slow convergence, and errors in the path planning. Therefore, this study presents the numerous recent techniques that are in use to counter the aforementioned problems. The methodology and approach used in this paper are to first present the dynamic model of the autonomous robot. Then, the study offers a performance analysis of the specific robot in question. Finally, the paper formulates the limitations of the recently proposed techniques in the form of a table for each vehicle. The key findings of this study are a comprehensive review of the aforesaid techniques and their technical analysis. The unique contribution of this study is to present some of the limitations that these methods have so the researcher can better select the method according to the mission requirement.

1. Introduction

For the past few years, the researchers are engaged in evaluating the performance of autonomous vehicles with the addition of manipulator design due to the emerging demand in executing the number of flexible tasks in any dull, dirty, difficult, or dangerous environment [1–3]. These manipulators provide easy access to perform several jobs with merely small inertia, high load to weight ratio, and smart flexible structure [4]. For complex dynamic models with time delays in output variables and unmodeled dynamic factors, high-performance tracking has been observed as still one of the challenging tasks.

Acquiring the real and precise dynamics of the system during control design is among the complicated and strenuous activities of the procedure. The researchers in this regard are opting for some hybrid-type control algorithms to improve the tracking performance [5–7]. One may design such control designs, but they require the tuning of several parameters. In short, one researcher has two tough approaches either to

acquire an exact mathematical dynamic model of autonomous vehicles or to estimate the numerous parameters for control design to produce refined input logic for the proposed system. Before going through the literature review, one should understand the types of autonomous unmanned vehicles. These vehicles are autonomous because of their ability to perform any sort of task without any intervention of human beings. Figure 1(a) shows a UUV with a manipulator [8], Figure 1(b) shows a UAV with a manipulator [9], and Figure 1(c) presents a UGV with a manipulator [10].

This entire review paper discusses the four types of unmanned vehicles embedded with gripper, that is, unmanned underwater vehicle (UUV), underactuated quadrotor unmanned aerial vehicle (QUAV), unmanned ground vehicle (UGV), and last but not least unmanned air-cushion vehicle (UACV). In addition to this, the paper addresses the constraints such as the occurrence of time delays and exogenous disturbances in a system.

The idea for embedding the UUV with a manipulator is introduced many times, that is, [11, 12]. This is because of



FIGURE 1: Types of unmanned vehicles embedded with a manipulator.

enabling an ability to grasp the target in water. Most of the UUVs have six degrees of freedom but only four actuators which make them underactuated system. These underactuated systems are very hard to control. Thus, for the stabilization, various hybrid control designs are introduced by researchers. In the catalog of such controllers, one may see model reference adaptive control (MRAC), sliding mode control (SMC), and many other robust control strategies [13–16].

Since the last decade, the extensive use of UAVs has been observed in various fields, either for commercial purposes, that is, surveillance [17, 18], or for military-oriented tasks. This type of unmanned vehicle got a great boom because of its aggressive maneuverability [19–22] over a long field of distance. Researchers have also tried to embed smart manipulator/gripper mechanism [23, 24], with UAV in order to increase the utility of drones in multiple fields. Researchers previously proposed commonly 01 and 02 DOF-based manipulators with unmanned aerial vehicles, that is, quadrotor [25]. Researchers were engaged initially in optimizing the control performance for the control law associated with the above manipulators [26]. The researchers also proposed some advanced mechanical designs and typical construction of quadrotor embedded with grippers of lightweight but with great capability to grasp the object within the working envelop [27].

Researchers also embedded some smart manipulators on such UGVs, that is, [28]. These smart manipulators have increased the manipulating ability to move up to 250 kg mass from one point to another. It is believed that a UGV must have good speed and navigation systems to monitor and manipulate the objects within harsh terrain [29]. Thus, in literature, one may find several types of manipulators as discussed by [30–32]. In most cases, it is recommended to use servo motors for ideal torque and mass ratio. In addition to this, a servo motor can be controlled easily. In today's era, researchers proposed different microcontrollers for experimental design, that is, Raspberry Pi [30], Arduino [33], or any modular programmable logical controller (PLC).

The motivation behind this paper was to collate the research studies about autonomous robots in one place so that new authors and researchers can easily compare the benefits and limitations of each study and pick the one most optimal for their mission requirement.

The main contributions of the paper are to provide one comprehensive review and technical analysis of the old and new studies about the UUVs, UAVs, and UGVs, to shed light on the limitations of the aforementioned studies in the form of an easily accessible table.

The paper is arranged as follows: Section 2 presents some cutting-edge research into autonomous robots. Section 3 discusses the UUV with the manipulator, its dynamic model, and its performance analysis and finally sums up the limitations of the previous techniques in a table. Similarly, Section 4 deals with the UAV, and Section 5 handles the UGV. Then, Section 6 provides technical analysis, and lastly, Section 7 concludes the whole study.

2. State of the Art

The state-of-the-art approach for UUV is discussed in [34] where a nonlinear observer-based model is amalgamated with dual proportional integral derivative (Dual-PID) design. This research provides comparatively effective results for 06 degrees of freedom (DOF) UUV with 02 DOF manipulator.

Researchers in [35] present a state-of-the-art technique for UAVs using 5G networks in a smart city. The researchers use blockchain-based solutions to secure these 5G networks for industrial and defense purposes.

Academics in [36] offer a novel idea of integrating UGV and UAV for construction site data collection. The UGV is autonomous and travels using the help of its sensors and the UAV which alerts it of any danger not visible to UGV on the ground.

3. Unmanned Underwater Vehicle Equipped with Manipulator Design

For repairing the structures, mostly in the offshore oil industry, these UUVs are highly recommended. This is because of their capability to reach in the depth of the sea unlike humans [37]. These UUVs have been blessed with two main abilities, that is, position stalking and dynamic stalking. This means that a UUV can maintain all positions throughout time with respect to the body.

One should not forget about the underwater dynamics that can lead to huge turbulences. These underwater

dynamic factors are hydrodynamic coefficients and the mass flow rate through water inlets [11].

Discussing the previous works related to UUV, in [14], the author addressed the behavior by using SMC. An extended version, that is, higher-order SMC (HOSMC) can also be seen in [16] where the chattering phenomena (high number of oscillations) were reduced using higher order of SMC [13]. In some of the research works, one may see the use of a dual control scheme, that is, using proportional derivative (PD) and proportional integral control (PID) controller to stabilize the underactuated dynamics of UUV. Since this PID and PD, dual scheme produces fine results but in the presence of nonlinearities, this will never hold up the response for so long and shall lead it towards instability.

Researchers [13] proposed multivariable sliding mode control for the stabilization of attitude and position of a UUV equipped with a manipulator. In this case, the proposed UUV is a fully actuated system (number of control inputs are equal to degrees of freedom) that is why it can grasp any object underwater easily but simultaneously the power consumption by the actuators is huge as compared to underactuated UUVs.

3.1. Dynamic Model of UUV. The dynamic model for UUV is achieved after going through the study of both frames of references, that is, Earth frame of reference (inertial frame) and fixed body frame (noninertial frame). The common design is comprised of six actuators that lead to six DOF easily [38]. In this subsection, the main idea related to the state-of-the-art approach is discussed.

Here, the Dual-PID control techniques are fused with the nonlinear model-based observer to stabilize the fully actuated underwater vehicle. This strategy is applied on six DOF-based UUVs embedded with a gripper/manipulator of two DOF; this makes in total eight DOF to control. Figure 2 shows a six DOF UUV physical model embedded with a manipulator [39]. Table 1 presents the orientation, translational, and angular velocities, forces, and moments along with the degrees of freedom for the UUV.

The position and orientation with respect to the inertial frame are given as

$$\begin{aligned} \mu_1(t) &= \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \\ \mu_2(t) &= \begin{bmatrix} \varphi \\ \theta \\ \psi \end{bmatrix}. \end{aligned} \quad (1)$$

In equation (1), $\mu_1(t)$ and $\mu_2(t)$ are the vectors that describe the position and angular velocities of UUVs. The column matrix $\mu_2(t)$ is also known as the attitude of the vehicle.

$$\begin{aligned} T_1(t) &= [u \ v \ w]^T, \\ T_2(t) &= [p \ q \ r]^T, \end{aligned} \quad (2)$$

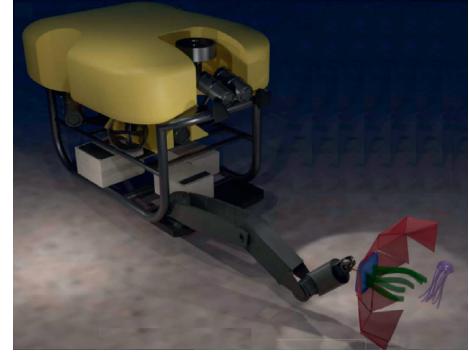


FIGURE 2: UUV with a manipulator.

where $T_1(t)$ represents the translational velocities whereas $T_2(t)$ represents the angular velocities. By combining the translational and angular velocities as in [38], we get

$$v(t) = [T_1(t), T_2(t)]^T \varepsilon \mathcal{R}^6. \quad (3)$$

The rotation matrix can be derived using Newton–Euler methods as

$$R = \begin{bmatrix} c_\theta c_\psi & -c_\theta c_\psi + c_\psi s_\phi s_\theta & s_\phi s_\psi + c_\phi c_\psi s_\theta \\ c_\theta c_\psi & c_\phi c_\psi + s_\phi s_\theta s_\psi & -c_\psi s_\phi + c_\phi s_\theta s_\psi \\ -s_\theta & c_\phi c_\theta & c_\phi c_\theta \end{bmatrix}, \quad (4)$$

where c_x means $\cos(x)$ and s_x means $\sin(x)$. The dynamic model for UUV is shown as follows:

$$\begin{aligned} M(t)\dot{v}(t) &= g(v(t)), \mu(t), U(t) + \tau_{e(g)}, \\ \dot{\mu}(t) &= h(v(t), \mu(t)). \end{aligned} \quad (5)$$

In the above set of equations, $M(t)$ is the inertial matrix that comprised hydrodynamic mass change and functions (e.g., one can see (.)) and $h(. \varepsilon \mathcal{R}^{6 \times 1})$. $M(t)$ is the sum of centripetal mass and Coriolis body mass mentioned as follows [40]:

$$M(t) = M_{CR}(t) + M_{CP}(t). \quad (6)$$

3.2. Kinematics of UUV. As per the conventional study by [41], the kinematic set of equations are given as in equations (7) and (8):

$$\begin{cases} \dot{\varphi} = p + q \sin \varphi \cdot \tan \theta + r \cos \tan \theta, \\ \dot{\theta} = q \cos \varphi - r \sin \varphi, \\ \dot{\psi} = \frac{q(\sin \varphi + r \cos \varphi)}{\cos \theta}, \end{cases} \quad (7)$$

$$\begin{cases} \dot{x} = u(c_\theta c_\psi) + (s\theta s\varphi c_\psi - s\psi c\varphi)v + (s\theta c\varphi s - s\psi s\varphi), \\ \dot{y} = u(c_\theta s_\psi) + (s\theta s\varphi s_\psi + c\psi c\varphi)v + (s\theta c\varphi s_\psi - c\psi s\varphi)w, \\ \dot{z} = -us_\theta + (c\theta s\varphi)v + (c\theta c\varphi)w. \end{cases} \quad (8)$$

TABLE 1: Symbols for the 6 DOF UUV.

Position	Linear and angular velocities	Forces and moments	Degree of freedom
x	u	X	Surge
Y	v	Y	Sway
Z	w	Z	Heave
ϕ	p	K	Roll
θ	q	M	Pitch
ψ	r	N	Yaw

3.3. Modeling of Manipulator Design. For modeling the manipulator design, one should consider the moments of the arm as an external torque. Since the attached manipulators connected with UUV are based on two links and one joint mostly using a simple servo motor. The kinematics for this gripper/manipulator is stated by [42] via opting for direct kinematics. This method helps to compute the orientation by finding the nth number of joints and compute the position of the end effector to grasp the object correctly.

Thus, the nth number of joints can be expressed as $q \in R^n$, whereas the position of the end effector is expressed as $\{n_p \in R^3, n_o \in R^3\}$. One can now develop a relationship between position and orientation easily as provided as follows:

$$n_{p,o} = [n_p, n_o]^T \in R^6. \quad (9)$$

Researchers have used the Denavit–Hartenberg (DH) formulation to find the configuration of an end effector of the gripper. Moreover, the dynamics of UUV stated that the total forces and torque that are acting on the body of UUV in the deep sea can be expressed in generic as

$$\begin{cases} f_i = m_i[a_i + \dot{T}_2(t) \times r_i + T_2(t) \times (T_2(t) \times r_i)], \\ T_m = I \times \dot{T}_2(t) + T_2(t) \times (I \times \dot{T}_2(t)). \end{cases} \quad (10)$$

In equation (10), m_i is an additional mass due to the manipulator and the weight of the object that must be grasped by the manipulator. Moreover, r_i is the vectorial distance from the origin frame I towards the center of gravity of the link. The variable a_i is the translational acceleration from the origin of the frame, whereas $\dot{T}_2(t)$ is the vector denoting the change in angular velocities where $T_2(t)$ is the vector consisting of rotational velocities.

3.4. Performance Analysis of UUV Equipped with Manipulator. There is an effective need for an autonomous unmanned underwater vehicle due to several issues. The important thing at this moment is to save the lives of our divers and get efficient results by using UUVs beneath the sea more than the depth covered by divers. Figure 3 shows a UUV equipped with a manipulator that has multiple links and joints to grasp the object [38].

Researchers also used the bioinspired dolphin algorithm for controlling the locomotion of UUVs like a real dolphin. Figure 4 presents a UUV hardware design based on a bioinspired dolphin algorithm [11].

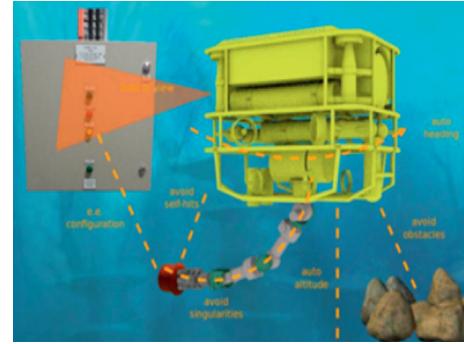


FIGURE 3: UUV equipped with a manipulator.

Using the Newton–Euler dynamic method shown in Figure 5, we can derive the equation of motions [40]. This method is easy but has some limitations such as gimbal lock due to singularity issues.

After going through the latest papers and current state-of-the-art approaches, Table 2 presents the previously proposed techniques for UUVs, the hardware they are applied on, and their limitations.

4. Underactuated Quadrotor UAV Equipped with Manipulator Design

Like underwater vehicles, unmanned aerial vehicle and its dynamic model are also derived from the Newton–Euler method. This method is frequently opted for by various researchers because of less complexity. The only limitation of this approach is the gimbal lock due to the singularity issue which can be reduced, not eliminated completely through hyperbolic tangent function. These equations involve the trigonometric functions; hence, the computation time for these terms is usually huge, and therefore expensive programmable controller is selected which leads to an expensive hardware design [44].

The focus for the UAVs in this paper is set on quadrotor type of UAVs. This is because of a fewer number of actuators that result in less power consumption and long battery time for flight [44–46]. Researchers modified the quadrotor with multirotors as well as the manipulator designs too. There are also some hybrid control schemes too, previously proposed by [47, 48], for the stabilization of the entire behavior of UAV with a gripper mechanism. The same control laws that were proposed before for UAV are proposed here too such as model reference adaptive control, a hybridized version with sliding mode control for quadrotor UAV (QUAV) equipped with 2 DOF manipulator [49].

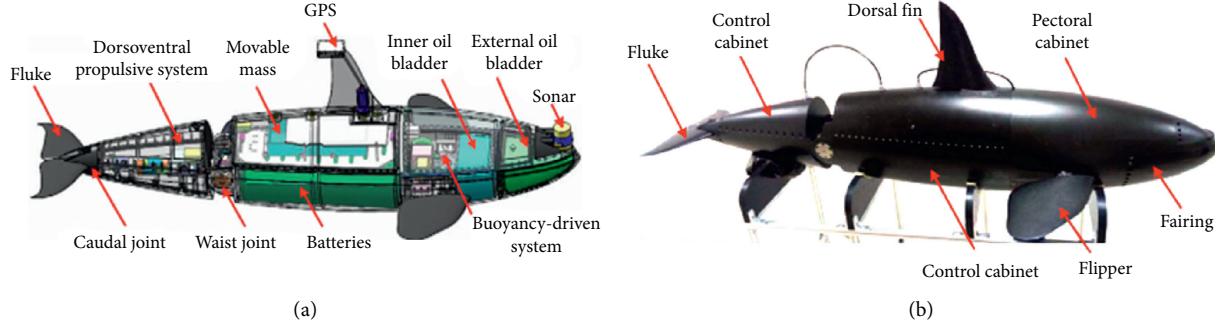


FIGURE 4: UUV hardware design.

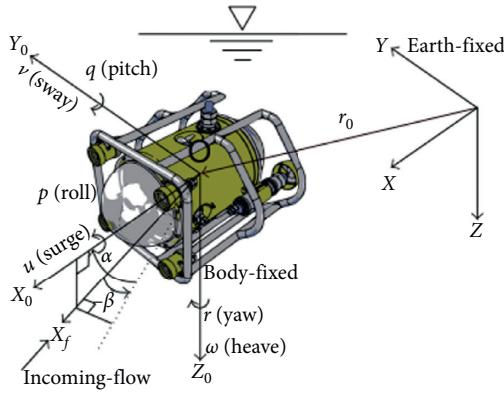


FIGURE 5: Deriving the equations of motion using Newton–Euler method.

4.1. Performance Analysis of UAV Equipped with Manipulator. The paper discusses two categories of unmanned aerial vehicles. One is a cable-driven UAV and the second one is equipped with a manipulator design. The current approaches for the trajectory tracking of UAVs are discussed by [50, 51], in which an adaptive robust control law is proposed. The lumped dynamics are estimated using estimator design and in addition to this, the chattering phenomenon is also eliminated [52]. For unknown modeled factors, one can see several such hybrid techniques. Researchers have also proposed subcontrol blocks, that is, time delay estimator, supertwisting law, and fractional-order SMC technique to minimize the dynamic error in the system. Researchers in this way obtained 20% efficiency for quadrotor equipped with 2 DOF manipulator on a referred path [53]. The hybridized version of the regulation, pole-placement, and tracking (RST) control design with MRAC and the stability for tracking and grabbing the objects both are proved using MIT rules. The work proposed by [53], where quadrotor varies its mass from 0.5 kg to 5.0 kg, and the manipulation related parameters are achieved using the Denavit–Hartenberg principle. Table 3 presents the previously proposed techniques for quadrotor UAVs, the hardware they are applied on, and their limitations.

4.2. Dynamic Model of QUAV with 2 DOF Gripper. Researchers avoided the different parameters, that is, aerodynamic effect, ground effects, and flapping of blades,

and proposed an overall dynamic model. Figure 6 shows the overall model of a dynamic quadrotor with a 2 DOF manipulator [53, 54]. The Newton–Euler method is the most frequent method used and stated by the majority of the people. One can find the separate models as well like in [54] but this will increase the complexity.

The overall mathematical model including the gripper dynamics is derived and stated as

$$\begin{bmatrix} f_q(U) \\ T_q(U, q_A^j) \end{bmatrix} + \begin{bmatrix} f_A(\partial q_A^j) \\ T_A(\partial q_A^j) \end{bmatrix} = \begin{bmatrix} m\bar{I} & 0 \\ 0 & I(q_A^j) \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{\omega} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \times I\omega \end{bmatrix}. \quad (11)$$

In equation (11), the left-hand side is the dynamics of quadrotor and manipulator, respectively, whereas the right-hand side is the vector form of rigid quadrotor body. The term like $f_q(U)$ is the control input force and torque given as $T_q(U, q_A^j)$ for quadrotor whereas the force exerted by manipulator is given as $f_A(\partial q_A^j)$ and torque as $T_A(\partial q_A^j)$. m is the total mass and I is an identity matrix of (3×3) order. $I(q_A^j)$ is the total inertia. Moreover, \dot{v} and $\dot{\omega}$ are angular velocities.

5. Unmanned Ground Vehicle Equipped with Manipulator Design

5.1. Dynamic Model of UGV with Manipulator Designs. As discussed, these unmanned vehicles are deployed in such tasks that are far away from human management. UGVs are among the prominent vehicles that are used for surveillance purposes and can tackle high-risk crises [28]. The part of deploying sensors is the core part that guides the UGV in indoor/outdoor space.

The main motive of proposing the UGV equipped with manipulator design is to navigate it in a space with a specific trajectory tracking and manipulating the objects to mentioned coordinates. Generally, two approaches are commonly adapted with control designs such as mentioned as follows: understanding of failure modes [55].

5.2. Failure Analysis of Acquired Data and Its Usage. The researchers opted for the Newton–Euler method most frequently for UGVs like UUVs and UAVs. Here, the robotic manipulator and the payload duly manipulated are driven using a free diagram as shown in Figure 7 [56]

TABLE 2: Limitations of previously proposed techniques for UUVs.

Techniques	Applied on	Limitations	References
Self-tuning fuzzy proportional integral derivative (PID) nonsingular fast terminal sliding mode control (STF-PID-NFTSM)	PUMA560 robotic manipulator	(1) The average convergence time is 3.5 seconds in the presence of uncertainties (2) The response experiences an undershoot in the presence of unmodeled uncertainties (1) The proposed UUV is a fully actuated system and thus consumes huge power and process time (2) It has a small working envelope and does not consider unmodeled dynamic factors (3) For estimating the sudden hydrodynamic coefficients, the strategy is complex (1) The disturbance taken in the simulation is limited up to $0.01 \sin(t)$	[7]
Nonlinear disturbance observer-based sliding mode control law	UUV with 2 DOF manipulator	(2) It has a small working envelope and does not consider unmodeled dynamic factors (3) For estimating the sudden hydrodynamic coefficients, the strategy is complex (1) The disturbance taken in the simulation is limited up to $0.01 \sin(t)$	[39]
Bioinspired dolphin algorithm embedded with disturbance rejection scheme	UUV with fins like a dolphin	(2) Undersea there are so many other factors, that is, hydrodynamic coefficients which were assumed through ANSYS and computational fluid dynamics (1) Bounded conditions have been defined already (2) Control input somehow experiences the chattering-like noise	[11]
Adaptive iterative approach with boundary layer and hyperbolic tangent function	2nd-order nonlinear system	(1) Either in low or in high pressure, there is an average tracking error of 5.12 percent (2) Each joint experiences an average overshoot of 1.5% and a steady-state error of 0.015 (3) Fuzzy-based PID slows down the maneuverability and increases hardware cost	[6]
Underwater long-arm manipulator (ULAM) with an improved hydraulic driving system (SHDS) with fuzzy-based PID control	UUV with long-arm gripper/manipulator	(1) Chattering effect is available along with some transient and steady-state issues (2) Hardware implementation will be costly as compared to other previously proposed UUVs	[43]
The nonlinear model-based observer design using the linearization of the model to estimate the current state	UUV Visor3	(1) The output response, that is, angular and translational velocities, experiences a chattering effect too with reasonable tracking error because of a long length of gripper and time delays (2) First convergence time but output has a response which has some overshoots too	[40]
DexROV, an EC Horizon 2020-funded project	UUV with TITAN4 from shilling robotics	(2) Chattering is still there due to switching mode b/w terminal SMC and higher-order SMC (1) parameters were assumed for fully loaded and ballasted conditions and did not consider unmodeled dynamic factors	[38]
Hybrid high-order terminal sliding mode (HHOTSM) control approach for (MIMO) uncertain nonlinear systems	Underwater robotic manipulator	(1) The output response, that is, angular and translational velocities, experiences a chattering effect too with reasonable tracking error because of a long length of gripper and time delays (2) First convergence time but output has a response which has some overshoots too	[16]
Sliding mode control-based dynamic positioning system	Applied on ship model in the deep sea	(2) Responses, that is, surge, sway, and yaw, experience 12%-20% overshoots in simulations and experimental work, respectively (1) There is a reasonable error in load and the motor trajectories (2) The convergence rate on the time axis is not suitable for any sensitive pick and drop tasks (3) The technique is based on ANN and a fuzzy set of rules; it will only be implemented on field-programmable gate array (FPGA) or digital signal processing (DSP) kits that lead us to an expensive hardware design	[14]
Supervisory feedforward artificial neural network- (ANN-) based fuzzy control law to address friction and elasticity issues of a manipulator	Flexible joint-based manipulator design	(1) Time delays due to Global Positioning System-(GPS-) based communication. (2) Due to these time delays, the responses have tracking errors	[5]
PID guidance and control laws to perform basic control tasks such as autoheading, autospeed, and straight line	Unmanned surface vehicle	(1) Time delays due to Global Positioning System-(GPS-) based communication. (2) Due to these time delays, the responses have tracking errors	[13]

TABLE 3: Limitations of previously proposed techniques for Quadrotor Unmanned Aerial Vehicles.

Technique	Applied on	Limitations	References
Adaptive control-based regulation, pole-placement, and tracking (RST) control law	QUAV with 2 DOF gripper	(1) Sudden fluctuations are experienced due to variation in altitude (2) Sluggish in grasping the objects (need an improvement for fast grasp) (1) The tuning function for ATDC is a complex procedure	[53]
Adaptive time delay control (ATDC) scheme using a fractional-order nonsingular terminal sliding mode (FONTSMS)	Cable-driven manipulators	(2) The root mean square error for joint 01/02 is 0.3 and 0.32. 5 chattering appears at torque responses in the presences of payload (1) The response experiences chattering in experimental work (2) The software simulations also show some overshoots too	[50]
Continuous nonsingular fast terminal sliding mode (CNFTSM) control scheme using a modified supertwisting algorithm (STA)	QUAV with a cable-driven manipulator	(3) There is also a steady-state error available for manipulator (1) Gimbal lock due to Newton–Euler method (2) Due to cosine and sine terms, the computation time increases; therefore, an expensive DSP kit is proposed for the algorithm (3) The chattering phenomenon appears while real flight takes off and path planning	[52]
A composite controller scheme using 02 subcontrol blocks (one for arm/gripper and second for QUAV), gain tuning method	QUAV with a cable-driven manipulator	(1) In the presence of any disturbance factor, that is, wind disturbance, the robotic manipulator will be diverted from trajectory for some time and refollow the trajectory again (1) There is undershoot and overshoot in yaw angular velocity (2) While performing pitch, the rotors experience oscillations for 10 seconds	[48]
An adaptive terminal sliding mode controller for the trajectory tracking of robotic manipulators using radial basis function neural networks (RBFNNs)	Robotic manipulators	(1) Due to the change of the reference values, too fast several joints and their servos are not able to follow, and the response lags the reference for some time (1) The major shortcoming is the control using the Zigbee module which is sluggish and hence QUAV will never be able to perform aggressive maneuvers	[49]
Combination of gain scheduling and Lyapunov-based model reference adaptive control (MRAC)	UAV for manipulation	(2) At the payload of 250 grams, the QUAV cannot balance itself in a hovering state (1) There is an error in both hovering and path tracking states (i.e., the deviation in between ± 13 cm). At outdoor operations, this error increases up to ± 20 cm. (2) During wind disturbance, the quadrotor deviates from the path for a few seconds and refollows the path again.	[47]
Backstepping control design using an admittance subcontrol block for the manipulator design	Octa-copter UAV with 07 DOF manipulator	(1) There must not be extreme variation in payload mass, and this will lead to bursting or instability because of the previously trained weights (1) After visualizing the pitch and roll response, there are drastic oscillations in the output response due to the ground effect	[26]
Proportional integral derivative- (PID-) based wireless control of quadrotor at hovering state	Quadrotor with a payload of 250 grams	(2) At the payload of 250 grams, the QUAV cannot balance itself in a hovering state (1) There is an error in both hovering and path tracking states (i.e., the deviation in between ± 13 cm). At outdoor operations, this error increases up to ± 20 cm. (2) During wind disturbance, the quadrotor deviates from the path for a few seconds and refollows the path again.	[46]
Nested controller scheme for attitude stabilization, vision-based navigation, and guidance, with the aerial gripping	QUAV with aerial gripping task	(1) There is an error in both hovering and path tracking states (i.e., the deviation in between ± 13 cm). At outdoor operations, this error increases up to ± 20 cm. (2) During wind disturbance, the quadrotor deviates from the path for a few seconds and refollows the path again.	[27]
Direct approximate-adaptive control using cerebellar model arithmetic computer (CMAC) nonlinear approximators	Quadrotor with multiple payload variation	(1) There must not be extreme variation in payload mass, and this will lead to bursting or instability because of the previously trained weights	[45]
Discrete proportional integral derivative control design	QUAV with 4 g weight and 1 kg payload mass	(1) After visualizing the pitch and roll response, there are drastic oscillations in the output response due to the ground effect	[44]

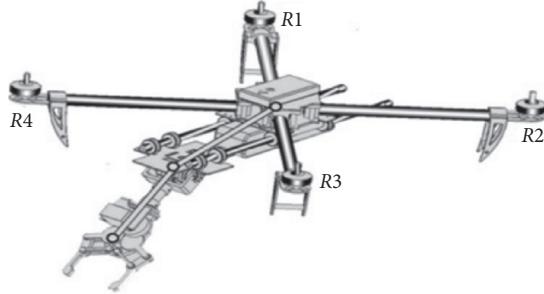


FIGURE 6: UAV with a manipulator.

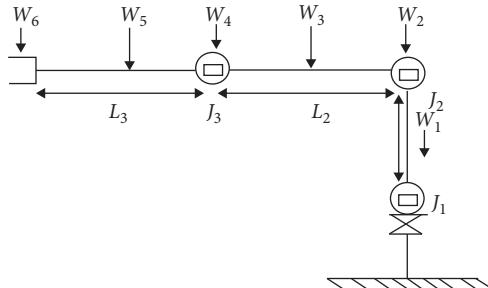


FIGURE 7: Manipulator-free diagram for torque.

$$T = FL, \quad (12)$$

where “ T ” is the torque, “ F ” is the force in Newton, and “ L ” is the perpendicular distance between the point of rotation and applied force.

$$F = W = mg. \quad (13)$$

The term “ m ” is the mass “ g ” which is the gravitation acceleration; hence, with equation (13), equation (12) can be transformed as

$$T = mgL. \quad (14)$$

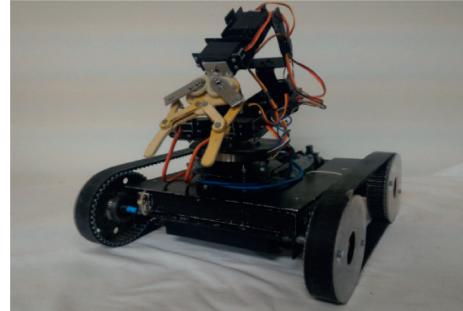
Researchers have proposed various dynamic models for UGV and its manipulators such as in [57]. Figure 8 presents an example of a UGV [31] and a manipulator design [56].

Table 4 presents the previously proposed techniques for UGVs, the hardware they are applied on, and their limitations. Moreover, Table 5 summarizes Tables 2–4 into one easily comprehensible table to further elucidate the shortcomings of all the techniques used for an unmanned vehicle.

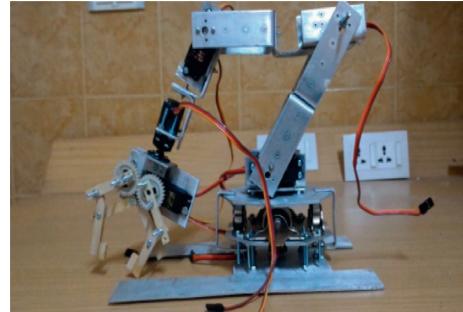
6. Technical Analysis and Discussion

If someone is working on UUV, then one should work on the constraints, that is, chattering effect, producing cost-effective hardware design, minimizing the power consumption, and process time. This manuscript provides an opportunity to evaluate either robust or adaptive control laws with nonlinear observer designs.

Table 2 presents the previously proposed techniques for UUVs, the hardware they are applied on, and their limitations. It is a helpful guide for any future researchers to



(a)



(b)

FIGURE 8: UGV with a manipulator. (a) UGV model. (b) Manipulator design.

choose the best strategy according to their mission requirements.

For quadrotor UAV, one must concern the issues such as the elimination of gimbal lock, chattering noise, and some serious undershoots/overshoots due to unmodeled dynamic factors. The paper suggests a serious need for reviewing the adaptive control law and their amalgamation with state observer design. The emerging bioinspired algorithms such as the pigeon algorithm are recommended while designing the observer design.

Table 3 presents the previously proposed techniques for quadrotor UAVs, the hardware they are applied on, and their limitations. Any future academic researching this field would find this table useful for deciding the best technique for their study.

For UGV, the processing time and hardware designs are emerging issues, and hence paper reviewed some of the fuzzy logic-oriented designs which produce fine response outcomes but are slower due to the fuzzy inference system. Therefore, it is suggested to use a single dimension-based fuzzy logic controller as they minimize the processing time. Once the processing time will be reduced, then a hardware designer may opt for a cheap microcontroller for programming.

Table 4 presents the previously proposed techniques for UGVs, the hardware they are applied on, and their limitations. It delineates the drawbacks of the mentioned strategies and would help in selecting the best method for the UGV.

After going through several research papers, Table 5 has been stated in this paper. This table shows the limitations of

TABLE 4: Limitations of previously proposed techniques for Unmanned Ground Vehicles.

Technique	Applied on	Limitations	References
Computer vision and control approach	UGV with variable payload up to 4 kg and 6 DOF manipulator	(1) NRF module is used to communicate with UGV and hence with the displacement in the antenna's direction may lead to loss of connection. (2) With 06 DOF, still there are certain easy moves that it cannot do and with the UGV prototype, it consumes relatively high power. (3) Without load, its RPMs are between 50 and 70. The approach may not be affordable for heavy payloads. The image processing approach is restricted to only color. It is studied that various approaches recommend tracking object with respect to color, shape, and histogram	[56]
Computer vision and Internet of things (IoT) control approach	UGV with sharp rudder to clear sewerage pipelines	(1) The response and work are fine but the time delay is experienced in the response due to the internet of things and the sensor's resolution factor	[58]
Novel hybrid additive-subtractive manufacturing (HASM)	06 DOF robotic manipulator	(1) Due to fast response, there is a time delay in system response (2) Sudden overshoots are also experienced (1) The simple dual tone multiple frequency-based control is proposed which may face serious distortions in the presence of any external noise.	[29]
DTMF-based control law for robotic arm	Robotic arm for a coconut tree climber	(2) The approach is involved in cutting and climbing on coconut trees to pick and drop the coconuts. Thus, the minor error may destabilize the system and the cutter part may harm any human standing beneath (hazardous in nature).	[59]
European ICARUS project towards the development of unmanned search and rescue (SAR) robots	UGV with large gripper	(1) Focused on only rescue missions but there are some huge tracking errors while performing manipulation of the objects (1) The trajectories are fine with no error but in the absence of unmodeled factors	[28]
An alternative and comprehensive map-generating algorithm	UGV with 2 DOF gripper	2 The output response for gripper experiences the steady-state error of 0.55%	[31]
The design and control of robotic search and rescue system based on an immunocontrol framework	UGV with navigation systems	(1) The communication is performed using a Zigbee module, which is sluggish and thus brings time delay in responses	[30]
CoMoRAT (configurable mobile robot for all-terrain applications) for the installation of variable payloads	Modular UGV	(1) The modular approach is presented that leads to the installation of additional components on UGV to make it affordable for variable load conditions (2) Expensive hardware approach	[33]

TABLE 5: Summary of all previously proposed control laws for all unmanned vehicles.

References	TD	OS/US	SC	Limitations/shortcomings					Vehicle type
				CE/EN	GL	SSE	EHD	PC	
[7]		✓	✓		✓				
[39]							✓	✓	
[11]		✓		✓	✓				
[6]									
[43]					✓	✓	✓	✓	
[40]				✓		✓	✓	✓	UUVs with manipulators
[38]		✓		✓					
[16]			✓				✓	✓	
[14]				✓	✓				
[5]			✓				✓		
[13]	✓				✓	✓			

TABLE 5: Continued.

References	TD	OS/US	SC	Limitations/shortcomings						Vehicle type
				CE/EN	GL	SSE	EHD	PC	T_proc	
[53]		✓		✓						
[50]						✓				
[52]		✓								
[48]				✓	✓		✓	✓	✓	
[49]			✓							
[47]		✓								QUAVs with manipulator design
[26]	✓	✓				✓				
[46]	✓	✓		✓	✓					
[27]			✓		✓	✓				
[45]										✓
[44]			✓	✓						
[56]	✓						✓	✓	✓	
[58]			✓		✓	✓				
[29]		✓								
[59]	✓							✓		
[28]		✓		✓		✓			✓	UGV with manipulator design
[31]					✓					
[30]	✓		✓							
[33]							✓	✓	✓	

TD: time delay. SC: slow convergence rate. GL: gimbal lock. EHD: expensive hardware. T_proc: process time. OS/US: over/undershoots. CE/EN: chattering effect/external noise effect. SSE: steady-state error. PC: power consumption.

all previously proposed control laws over the unmanned vehicles embedded with several manipulator types.

7. Conclusion

This review paper presents a detailed review of the current state-of-the-art approaches and control laws proposed already for three types of unmanned vehicles, that is, UUVs, UAVs (more specifically quadrotors), and UGVs. The manuscript comes up with the limitations in Table 5. By reading Tables 2 to 5, one may see the most frequent problems in such unmanned vehicles, especially when embedded with manipulator design. The control laws so far proposed are fine until the degree of freedom for the manipulator is 02.

If the DOF value increases, the tracking performance also degrades and one may experience the chattering noise and deviation from tracking for some time and refollow the path. In addition to this, there is also degradation in transient and steady-state performances, that is, steady-state error and slow convergence. These vehicles are designed for fast maneuvers and aggressive operations with greater reliability but with these constraints, these unmanned vehicles compromise on their overall performance.

For future research ideas, one could revisit the robust and adaptive control laws with an amalgamation of bio-inspired algorithms and smart observer designs to manage these problems. Also, the current team is planning to evaluate the bioinspired algorithms for individual unmanned vehicle types and may come up with another review.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The author declares no conflicts of interest.

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