

# Survey of Simulators for Aerial Robots

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**Abstract**—Uncrewed Aerial Vehicle (UAV) research faces challenges with safety, scalability, costs, and ecological impact when conducting hardware testing. High-fidelity simulators offer a vital solution by replicating real-world conditions to enable the development and evaluation of novel perception and control algorithms. However, the large number of available simulators poses a significant challenge for researchers to determine which simulator best suits their specific use-case, based on each simulator’s limitations and customization readiness. This paper analyzes existing UAV simulators and decision factors for their selection, aiming to enhance the efficiency and safety of research endeavors.

## I. INTRODUCTION

Uncrewed Aerial Vehicles (UAVs) are being widely adopted for a variety of use cases and industries, such as agriculture, inspection, mapping, and search and rescue [1]. In particular, aerial manipulation and human-robot interaction applications have been on the rise, including tasks such as parcel delivery, warehouse management, sample collection, and collaborative robot operations [2], [3].

Testing experimental algorithms directly on hardware can pose significant risks, as unexpected behaviors may emerge. Moreover, crashes can incur substantial costs, disrupt development schedules, and contribute to environmental harm due to the frequent replacement of damaged vehicle components. Additionally, in the context of the increasing adoption of machine learning-based techniques, collecting data from hardware can prove highly inefficient and often impracticable. Hence, a dependable, fast, precise, and realistic UAV simulator is essential to facilitate rapid advancements in this field.

In this work, we analyze some of the prominent UAV simulators and key selection criteria and decision factors to consider when selecting a simulator. This research builds upon discussions and contributions made during the workshop titled “*The Role of Robotics Simulators for Unmanned Aerial Vehicles*” at the 2023 International Conference on Robotics and Automation (ICRA) in London, UK<sup>1</sup>. Specifically, our work addresses the following non-trivial question:

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This work was partially funded by the National Science Foundation grant no. 1925189, by the EU’s MSCA FLYFLIC grant no. 101059875, by the EU’s H2020 AERIAL-CORE grant no. 871479, and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - 448549715.

<sup>1</sup><https://imrclab.github.io/workshop-uav-sims-icra2023>

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**Question:** What criteria and considerations should guide the selection and customization of a simulator to optimize its suitability for a specific application, while also understanding its limitations?

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There are a few existing survey papers focusing on simulators and their role in robotics [4]. For example, a recent survey [5] analyzes a wide range of application areas, including aerial vehicles, and compares features across diverse domains. Regrettably, not every simulator readily supports UAVs. Dynamics considerations for manipulators or ground vehicles can substantially differ from those of aerial vehicles, especially in research that aims to account for aerodynamic effects. In [6], the authors examine various considerations for aerial delivery vehicles, including simulator selection.

We believe that the ensuing discussion and difficulty in selecting a simulator requires a more focused survey paper covering an expanded list of UAV simulators. We provide readers with valuable insights based on our experiences in international robotics competitions, innovative research projects, and real-world applications, contemplate the future of simulation tools, and provide consolidated information for readers to explore effective solutions for their intended applications.

## II. UAV DYNAMICS BACKGROUND

This section delves into fundamental concepts crucial for a comprehensive understanding of UAV dynamics. The focus here is on UAVs without morphing capabilities. We define key parameters, including UAV mass ( $m$ ), inertia ( $\mathbf{J} \in \mathbb{R}^{3 \times 3}$ ), position ( $\mathbf{p} \in \mathbb{R}^3$ ), global velocity ( $\mathbf{v} \in \mathbb{R}^3$ ), attitude unit quaternion ( $\mathbf{q} \in \mathbb{R}^4$ ), and body angular velocity ( $\boldsymbol{\omega} \in \mathbb{R}^3$ ).

### A. Multirotors

**Basic:** The multirotor’s dynamics are modeled as a 6-Degree-of-Freedom (DoF) floating rigid body using Newton-Euler formalism. This is expressed as  $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u})$ , with state  $\mathbf{x} = (\mathbf{p}, \mathbf{q}, \mathbf{v}, \boldsymbol{\omega})^\top$  and control input  $\mathbf{u}_\Omega = (\Omega_1, \dots, \Omega_n)^\top$ , where  $\Omega_i \in \mathbb{R}_{\geq 0}$ , with  $i = \{1, \dots, n\}$ , denotes the  $i$ -th squared motor speed [1]. The motors exert forces and torques on the multirotor’s Center of Mass (CoM), aggregated as  $\mathbf{f} = \sum_i c_{f_i} \Omega_i \mathbf{z}_{P_i} = \mathbf{F} \mathbf{u}_\Omega$  and  $\boldsymbol{\tau} = \sum_i (c_{f_i} \mathbf{p}_i \times \mathbf{z}_{P_i} + c_{\tau_i} \mathbf{z}_{P_i}) \Omega_i = \mathbf{M} \mathbf{u}_\Omega$ , respectively. Here,  $c_{f_i}$  and  $c_{\tau_i}$  denote constant parameters dependent on the propeller’s shape,  $\mathbf{p}_i \in \mathbb{R}^3$  is the rotor’s position in the body frame,  $\mathbf{z}_{P_i} \in \mathbb{R}^3$  is a unit vector parallel to the rotor’s rotation axis, and  $\mathbf{F} \in \mathbb{R}^{3 \times n}$  and  $\mathbf{M} \in \mathbb{R}^{3 \times n}$  are the force and torque allocation matrices, respectively. The model can be extended for UAVs with tilting propellers by introducing an additional control variable  $\mathbf{u}_w$  for

real-time adjustment of  $\mathbf{F}(\mathbf{u}_w)$  and  $\mathbf{M}(\mathbf{u}_w)$  allocation matrices [2]. Hence, the dynamics are:

$$\begin{aligned} \dot{\mathbf{p}} &= \mathbf{v}, & m\dot{\mathbf{v}} &= m\mathbf{g} + \mathbf{R}(\mathbf{q})\mathbf{F}\mathbf{u}_\Omega + \mathbf{f}_a, \\ \dot{\mathbf{q}} &= \frac{1}{2}\mathbf{q} \circ \begin{bmatrix} 0 \\ \boldsymbol{\omega} \end{bmatrix}, & \mathbf{J}\dot{\boldsymbol{\omega}} &= -\boldsymbol{\omega} \times \mathbf{J}\boldsymbol{\omega} + \mathbf{M}\mathbf{u}_\Omega + \boldsymbol{\tau}_a, \end{aligned} \quad (1)$$

where  $\circ$  and  $\times$  represent quaternion and vector cross products, respectively;  $\mathbf{g} = (0, 0, -g)^\top$ , where  $g$  is the acceleration due to gravity;  $\mathbf{R} \in SO(3)$  is the body-to-global rotation matrix;  $\mathbf{f}_a$  and  $\boldsymbol{\tau}_a$  are external forces and torques acting on the UAV.

**Drag:** Multirotors encounter extra aerodynamic drag forces  $\mathbf{f}_a$  and torques  $\boldsymbol{\tau}_a$  at high speeds (relative to the surrounding airflow), which are generally treated as disturbances proportional to the velocity ( $\mathbf{f}_a \propto \mathbf{v}$  and  $\boldsymbol{\tau}_a \propto \boldsymbol{\omega}$ ) [7].

**Wind:** Wind is typically modeled by a spatio-temporal-varying external force  $\mathbf{f}_a(\mathbf{p}_w, t)$ , where  $\mathbf{p}_w$  and  $t$  represent the global position and time, respectively [1].

**Interactions:** In close-proximity flight, multirotors experience aerodynamic interaction forces, often modeled as a learned function  $\mathbf{f}_a$  based on relative neighbor poses [8].

### B. Fixed-wing

**Basic:** For fixed-wing UAVs, like multirotors, the equations of motion can be derived from the Newton-Euler formalism. Modeling external forces often involves calculating the force  $\mathbf{f}_{s_i}$  contributed by each aerodynamic surface  $s_i$ , with  $i = \{1, \dots, k\}$  and  $k$  representing the total number of surfaces [9], [10]. These forces can then be aggregated to compute the total external aerodynamic force and torque as:

$$\mathbf{f}_a = \sum_i \mathbf{f}_{s_i}, \quad \boldsymbol{\tau}_a = \sum_i (\mathbf{l}_{s_i} \times \mathbf{f}_{s_i}). \quad (2)$$

Here,  $\mathbf{l}_{s_i}$  is the displacement from the CoM to the surface's aerodynamic center (e.g., the center of lift). Hence, we use:

$$\mathbf{f}_{s_i} = \frac{1}{2}\rho|\mathbf{v}_{s_i}|^2 S_i (c_{L_i} \mathbf{e}_{L_i} + c_{D_i} \mathbf{e}_{D_i}), \quad (3)$$

where  $\rho$  is the air density, and for the  $i$ -th surface:  $\mathbf{v}_{s_i}$  is the relative wind at the surface's aerodynamic center in the surface frame,  $S_i$  is the surface area,  $c_{L_i}$  is the lift coefficient,  $c_{D_i}$  is the drag coefficient,  $\mathbf{e}_{D_i} = \mathbf{v}_{s_i}/\|\mathbf{v}_{s_i}\|$  is the unit vector in the drag direction, and  $\mathbf{e}_{L_i}$  is the unit vector in the lift direction, which is perpendicular to  $\mathbf{e}_{D_i}$ . The relative wind is given as:

$$\mathbf{v}_{s_i} = -\mathbf{R}_{s_i}^\top (\mathbf{R}(\mathbf{q})^\top \mathbf{v} + \boldsymbol{\omega} \times \mathbf{l}_{s_i}), \quad (4)$$

where  $\mathbf{R}_{s_i} \in SO(3)$  is the body-to-surface rotation matrix. For control surfaces with a single DoF, both  $\mathbf{R}_{s_i}$  and  $\mathbf{l}_{s_i}$  depend on the control surface deflection,  $\delta_i$ . These deflections are treated as additional control variables  $\mathbf{u}_\delta = (\delta_1, \dots, \delta_c)^\top$  with  $c$  control surfaces. Typical aerodynamic surfaces include wings and vertical or horizontal stabilizers; typical control surfaces are ailerons, rudder, and elevator [9], [10].

**Lift and Drag:** For fixed-wings, lift and drag forces play pivotal roles in vehicle simulation. The coefficients  $c_{L_i}$  and  $c_{D_i}$  can be derived by combining airfoil data at low angle-of-attack with high angle-of-attack approximations obtained from flat-plate theory [11]. Additionally, these coefficients can also

be partly or entirely data-driven (e.g., [12]). For more detailed and high-fidelity models, significant aerodynamic surfaces can be segmented to incorporate additional external forces, such as friction drag and unsteady effects [13]. Furthermore, fixed-wing simulations can account for the influence of propeller backwash, as addressed in [9].

**Wind:** Wind is modeled as a spatio-temporal-varying additive velocity, which contributes directly to the  $\mathbf{v}_{s_i}$  term [14].

**Interactions:** Ground effects can notably affect the behavior of fixed-wing UAVs during landing maneuvers. Like multirotors, data-driven approaches are effective for capturing this effect by relating the coefficient  $c_{L_i}$  to ground proximity [15].

### C. Aerial manipulators

**Basic:** Aerial manipulators are a diverse category of UAVs composed of an aerial base and an end-effector, with common types including rigid tools, articulated arms, and cables. Here, we focus on the most common description, excluding advanced techniques like soft manipulation [16].

**Rigid Tools:** For aerial manipulators with rigid tools, their dynamics align with (1), with adjustments for the tool's inertial properties. The terms  $\mathbf{f}_a$  and  $\boldsymbol{\tau}_a$  account for the wrench applied at the end-effector. If  $\mathbf{f}_e$  and  $\boldsymbol{\tau}_e$  represent the force and torque in the body frame exerted by the environment on the end-effector, assuming these are the sole external forces and torques, then the corresponding wrench at the CoM is:

$$\mathbf{f}_a = \mathbf{R}(\mathbf{q})\mathbf{f}_e, \quad \boldsymbol{\tau}_a = [\mathbf{p}_e]_\times \mathbf{f}_e + \boldsymbol{\tau}_e, \quad (5)$$

where  $[\bullet]_\times$  maps a vector to its skew-symmetric matrix, and  $\mathbf{p}_e$  is the end-effector tip's position in the body frame.

**Articulated Arms:** For manipulators with articulated arms, the system's dynamics become more complex, see [17].

**Cables:** Cables are typically modeled as massless rigid or elastic elements attached via passive spherical joints to the robot's CoM [18]. In this scenario, the dynamic equations in (1) remain valid, with  $\mathbf{f}_a$  accounting for the cable's force. Notably, this formulation does not consider an external torque to be applied to the robot by the cable [17]. Hence, we can write:

$$\mathbf{f}_a = \mathbf{R}(\mathbf{q})\mathbf{f}_e, \quad \boldsymbol{\tau}_a = \mathbf{0}_{3 \times 1}. \quad (6)$$

## III. UAV SIMULATORS

A primary consideration when selecting a simulator often revolves around the specific application domain and whether the available simulators offer the necessary features and sensors tailored to that domain. Additionally, compatibility with common autopilots, like PX4 and ArduPilot, is often a consideration to enable rapid simulation to hardware transfer. Drawing from our own experiences and the referenced literature, we have compiled a set of selection criteria and decision factors that are regularly taken into account when evaluating UAV simulators. These comparative points are outlined in Table I. While, Table II categorizes a range of UAV simulators based on their key elements. Some simulators may belong to multiple categories. What follows offers a concise overview of each simulator featured in Table II.

Table I  
SELECTION CRITERIA FOR UAV SIMULATORS

Criteria	Decision Factors
Physics Fidelity	Required fidelity of physics and dynamics model for the intended use case
Visual Fidelity	Necessity for realistic images, e.g., for computer vision or Machine Learning (ML) applications
Autopilots	Compatibility with common autopilots like PX4 and ArduPilot, useful for Software-In-The-Loop (SITL) and Hardware-In-The-Loop (HITL) testing
Multiple Vehicles	Capability to concurrently simulate vehicles
Heterogeneity	Integration possibilities with other platforms
Sensors	Integration support for common sensors (e.g., cameras, IMU, GPS, LiDAR, optical flow)
UAV Models	Support of common UAV models and ease of integrating new models
Simulation Speed	Real-time speed and ability to run in super real-time, crucial for learning applications
APIs	Compatibility with programming languages, middleware like ROS, and packages such as OpenAI Gym (now Gymnasium)
Integration	Ease of getting started and development as well as whether the software is actively maintained

Table II  
UAV SIMULATORS CATEGORIZATION

Category	Simulators
Universal Simulators	Gazebo Classic (RotorS, CrazyS, PX4 SITL), Gazebo, Isaac Sim/Gym (Pegasus, Aerial Gym), Webots, CoppeliaSim, MuJoCo
Sensor-Focused	Vision: AirSim, Flightmare, FlightGoggles
	LiDAR: MARSIM
Learning-Focused	Isaac Gym (Aerial Gym), MuJoCo, PRL4AirSim, Flightmare, gym-pybullet-drones, safe-control-gym, QuadSwarm, fixed-wing-gym, QPlane
Dynamics-Focused	RotorTM, MATLAB UAV Toolbox, PyFly, ARCAD, HIL-airmanip, RotorPy, Agilicious
Swarming	gym-pybullet-drones, QuadSwarm, Potato
Part of flight stacks	Agilicious, MRS UAV System, CrazyChoir, CrazySwarm2, Aerostack2
Flight Simulators	X-Plane (X-PlaneROS), FlightGear, RealFlight

### A. Universal simulators

*Gazebo Classic* [19] is an open-source, continuously maintained, versatile research simulation platform with a modular design, accommodating different physics engines, sensors, and 3D world creation. Particularly noteworthy is its suitability for aerial manipulator tasks, owing to its ease of creating contact surfaces with customizable frictions [20], [21]. *RotorS* [22], built on top of *Gazebo Classic*, offers a modular framework for designing UAVs and developing control algorithms, particularly focusing on simulating the vehicle dynamics. *CrazyS* [23], an extension of *RotorS*, focuses on modeling the Crazyflie 2.0 quadrotor. However, both *RotorS* and *CrazyS* have limited perception-related capabilities. *PX4 SITL Gazebo* [24], partially originated from *RotorS*, includes the latest support for PX4 SITL, does not depend on ROS, and supports simulating a large number of vehicles. Additionally, PX4 SITL includes an airspeed sensor, which is essential for fixed-wing and Vertical Take-Off and Landing (VTOL) vehicle simula-

tions. The new *Gazebo* [25], formerly known as Ignition, is the successor of *Gazebo Classic* and incorporates quadcopter dynamics and control inspired by the RotorS project. *Gazebo* enables dynamic loading and unloading of environment components, addressing challenges faced by *Gazebo Classic* in replicating large, realistic environments. Moreover, *Gazebo* offers improved interfaces for simulating radio communication between multiple UAVs.

*Isaac Sim* [26], developed by NVIDIA, is a photorealistic high-fidelity simulator for a variety of platforms. *Pegasus Simulator* [27] is an open-source extension to *Isaac Sim* that includes an extended multirotor dynamics model, simulating multiple vehicles in parallel, integration with PX4 and ROS 2, and additional sensors (magnetometer, GPS, and Barometer). *Isaac Gym* [28] is an NVIDIA’s library for GPU-accelerated Reinforcement Learning (RL) simulations and uses more basic rendering than *Isaac Sim*. *Aerial Gym* [29] is an open-source extension to *Isaac Gym Preview Release 4* notable for its capability to parallelize the simulation of thousands of multirotors and includes customizable obstacle randomization.

*Webots* [30] is an open-source, versatile robotics simulator known for its wide range of robotic platforms. While *Webots* primarily focuses on ground-bound robots, it also features two quadrotor models with simplified aerodynamic physics. *Webots* uses ODE for physics simulation, refer to [31] for a comprehensive analysis. Notably, *Webots* has been used for innovative vehicle designs, such as a triphibious robot in [32].

*CoppeliaSim* [33], previously known as V-REP, is a versatile robotics simulator with support for a wide range of programming languages and physics engines. Selecting the appropriate physics engine is crucial to avoid undesirable outcomes, such as velocity or position jumps, unrealistic collision behaviors, and erratic sensor outputs [31]. While it does not natively integrate with ROS, an official plugin enables ROS compatibility. *CoppeliaSim* has been used for applications such as UAV obstacle avoidance [34].

*MuJoCo* [35], or Multi-Joint dynamics with Contact, is a frequently employed physics engine in ML applications. It offers interactive visualization rendered with OpenGL and encompasses various platforms, including a UAV model (i.e. the Skydio X2 quadcopter).

### B. Domain specific simulators

*AirSim* [36] is a Microsoft-led project built on the Unreal Engine, offering various sensors, a weather API, and compatibility with open-source controllers like PX4. *AirSim* primarily serves as a platform for AI research, providing platform-independent APIs for data retrieval and vehicle control. Notably, *AirSim* demands substantial computing power compared to other simulators. *PRL4AirSim* [37] is an extension designed for efficient parallel training in RL applications. The original *AirSim* is open-source, but will no longer be supported by Microsoft. Their focus has shifted to *Project AirSim*, which will be released under a commercial license.

*Flightmare* [38] is a versatile simulator with two main components: a Unity-based rendering engine and a physics

model, both designed for flexibility and independent operation. The rendering engine can generate realistic visual information and simulate sensor noise, environmental dynamics, and lens distortions with minimal computational overhead. Similarly, the physics model allows users to control robot dynamics, ranging from basic noise-free UAVs models to advanced rigid-body dynamics with friction and rotor drag, or even real platform dynamics. Flightmare is extensively used for ML applications, such as for autonomous drone racing [39].

*FlightGoggles* [40], similarly to Flightmare, is an open-source simulator focused on photorealistic simulation. FlightGoggles combines two key elements: (i) photogrammetry for realistic simulation of camera sensors, and (ii) virtual reality to integrate real vehicle motion and human behavior in the simulations. FlightGoggles is built around the Unity engine and includes multirotor physics with motor dynamics, basic vehicle aerodynamics, and IMU bias dynamics. A key feature of FlightGoggles is the “vehicle-in-the-loop simulation,” where the vehicle is flown in a motion capture system, camera images and exteroceptive sensors are simulated in Unity, and collision detection is based on the real-world vehicle’s pose.

*gym-pybullet-drones* [41] is an open-source environment designed for simulating multiple quadrotors with PyBullet [42] physics, tailored for research that combines control theory and ML. This library has interfaces for multi-agent and vision-based RL applications, utilizing the Gymnasium APIs [43]. It supports the definition of various learning tasks on a Crazyflie platform. Notably, *gym-pybullet-drones* includes realistic collisions and aerodynamic effects (e.g., drag, ground effect, and downwash). It includes example RL workflows for single agent and multi-agent scenarios, leveraging Stable-baselines3 [44].

*RotorTM* [45] is an open-source simulator for aerial object manipulation. Notably, this simulator considers cable-suspended loads and passive connection mechanisms between multiple vehicles, a feature lacking in other common simulators. In RotorTM, the cables are considered massless and connected to the robot’s CoM. They can transition from taut to slack during task execution, allowing users to customize the number of robots and the type of payload (e.g., rigid body or point mass). Additionally, the simulator accommodates scenarios where aerial robots are rigidly attached to the load. RotorTM assumes negligible drag on the payload and aerial robot and disregards aerodynamic effects, considering rotor dynamics to be significantly faster than other factors.

*MATLAB UAV Toolbox* [46] is a general purpose toolbox for designing, simulating, testing, and deploying UAVs within MATLAB. It includes tools for algorithm development, flight log analysis, and simulation. The simulation capabilities include a cuboid simulation for quickly constructing new scenarios and a photorealistic 3D simulation environment with synthesized camera and LiDAR readings. The toolbox includes an interface for deploying directly to hardware through PX4-based autopilots. Additionally, the MAVLink protocol is supported. Researchers have explored using the MATLAB UAV Toolbox with flight simulators [47] such as X-Plane, FlightGear, and, in other works (as mentioned in [47]) RealFlight.

*safe-control-gym* [48] is an open-source safety-focused RL environment and benchmark suite, built using the PyBullet physics engine [42], for comparing control and RL approaches. Three dynamics systems (cart-pole, 1D and 2D quadrotor) and two control tasks (stabilization and trajectory tracking) are included. This simulation environment supports model-based and data-based approaches, expresses safety constraints, and captures real-world properties (such as uncertainty in physical properties and state estimation).

*MARSIM* [49] is an open-source C/C++ library primarily focused on accurately simulating LiDAR measurements for UAVs. It constructs depth images from point cloud maps and interpolates them to obtain LiDAR point measurements. The simulator is designed for lightweight computation and offers access to 10 high-resolution environments, including forests, historic building, office, parking garage, and indoor settings.

*QuadSwarm* [50] is an open-source Python library for multi-quadrotor simulation in RL applications, emphasizing fast simulation and the transfer of policies from simulation to the real-world. QuadSwarm provides diverse training scenarios and domain randomization to support RL applications, showcasing zero-shot transfer of RL control policies for single and multi-quadrotor scenarios. The physics model is based on the Crazyflie platform, with OpenGL used for rendering.

*PyFly* [51] is an open-source Python simulator designed for fixed-wing aircraft. It includes a 6-DoF aerodynamic model, wind effects, and stochastic turbulence. *fixed-wing-gym* [51] is an OpenAI Gym wrapper specifically tailored for PyFly, aiming at facilitating RL applications.

*ARCAD* [52], or AirLab Rapid Controller and Aircraft Design, is an open-source MATLAB simulator for fully-actuated multirotors. Its primary goals are to expedite the modeling, design, and analysis of new aircraft and controllers and the visualization of tasks involving physical interactions, including controlled force-based tasks like writing text on a wall.

*HIL-airmanip* [53] offers a distinctive environment for simulating physical interactions between humans and aerial robots, enabling real-time human involvement. In this simulator, the forces exchanged between the human operator and a haptic interface are accurately measured and then transmitted to an aerial manipulator, which is modeled within the RotorS environment. This robotic system consists of a quadrotor combined with a 6-DoF arm mounted beneath it.

*RotorPy* [54] is an open-source Python simulator meant to be lightweight and focused on providing a comprehensive quadrotor model. Its development emphasizes accessibility, transparency, and educational value, initially created as a teaching tool for a robotics course at the University of Pennsylvania. In [54], the simulator’s quadrotor model is extensively detailed, including 6-DoF dynamics, aerodynamic wrenches, actuator dynamics, sensors, and wind models. The model’s validity is verified using a Crazyflie performing agile maneuvers.

*Potato* [55] is a simulator based on data-oriented programming for large-scale swarm simulations. Like Isaac Gym, Potato relies on GPU computation rather than CPU. It includes

basic dynamics for fixed-wing drones, quadrotors, and cars. Potato is not currently open-source, but the authors of [55] expressed the intention to open-source the quadrotor part of the simulator in the future.

### C. Simulators part of flight stacks

*Agilicious* [56] contains a hardware description for a quadrotor with a Jetson TX2 and a software library specifically meant for autonomous and agile quadrotor flight. For simulation, it has a custom modular simulator that incorporates highly accurate aerodynamics based on blade-element momentum theory or with other tools like RotorS, HITL setups, and rendering engines such as Flightmare. The stack uses a custom license, but is free to use for academics after registration.

*MRS UAV System* [57] is a flight stack designed for replicable research through realistic simulations and real-world experiments. Its software stack includes a simulation environment built on Gazebo Classic, CoppeliaSim, or their MRS-multirotor-simulator for quadrotor dynamics, complete with realistic sensors and models. A key feature is its full compatibility with multiple ROS releases, coupled with ongoing active use and maintenance. Moreover, this stack is frequently used for teams of multirotors.

*CrazyChoir* [58] is an open-source modular ROS 2 framework designed for conducting realistic simulations and experiments involving cooperating Crazyflie drones. For simulation, it builds on Webots with a SITL of the Crazyflie firmware.

*CrazySwarm2* [59] is an open-source framework designed for controlling large indoor quadrotor swarms, specifically utilizing Crazyflie drones, similarly to CrazyChoir. For simulation it also relies on SITL of the firmware with a modular simulation framework that currently supports pure visualization or an *ad hoc* Python-based physics simulation.

*Aerostack2* [60] is a versatile open-source flight stack designed to be compatible with various UAV platforms, including PX4, ArduPilot, DJI, and Crazyflie. For simulation purposes, Aerostack2 utilizes Gazebo with custom sensors. However, it does not currently have support for (S/H)ITL simulations.

### D. Flight simulators

*X-Plane* [61] is a commercial cross-platform flight simulator. As with most flight simulators, the primary audience is pilots. X-Plane emphasizes realistic dynamics and includes simulated weather, wind, and lighting conditions. *X-PlaneROS* [62] is a X-Plane ROS wrapper for controlling large-scale fixed-wing vehicles and extracting aircraft data from the simulator. Additionally, this simulator enables human-robot interaction [62]. *QPlane* [63] is a RL toolkit for fixed-wing simulation that can use external flight simulators, such as X-Plane and/or FlightGear.

*FlightGear* [64] is an open-source, user supported, cross-platform flight simulator. Some researchers have explored using this flight simulator for UAV simulation, such as in [65].

*RealFlight* [66] is a commercial Windows Radio Controlled (RC) flight simulator that includes small multirotor and fixed-wing vehicles. Researchers have adopted this flight simulator for UAV simulation, such as in [67].

## IV. UAV SIMULATOR COMPARISON

We provide three tables that compare essential features of aerial simulators, using selection criteria discussed in Table I. These tables encompass extensively utilized simulators for aerial vehicles. For brevity, we have omitted simulators that are less versatile or relatively new, leading to limited adoption.

Table III presents a comparison of notable features within the simulation environments. Notably, OpenGL and OGRE rendering are often regarded as having low visual fidelity, while Vulkan, Unity, and Unreal rendering are considered to offer high visual fidelity. The Operating System (OS) subcategories are Linux, Windows, and Mac, denoted as “L,” “W,” “M,” respectively. “RL” is included as an interface to indicate specialization for RL applications. The category denoted as (S/H)ITL includes interfaces for both SITL and HITL capabilities, with “CF” representing Crazyflie. We include a column indicating the maintenance status at the time of writing this paper. Simulators under active maintenance are marked with ✓. Simulators that have been inactive but show some commits and responses to issues in the past two years are marked with ✨. Finally, simulators that are intentionally no longer maintained or have been inactive for more than two years are marked with ✖. As maintenance statuses may change over time, we advise readers to consider this information as a snapshot and to reevaluate before choosing a simulator.

Table IV compares the vehicle types that can be simulated, referencing the dynamics detailed in Sec. II. In the “Swarms” column, we specify packages designed for swarm purposes with ✓, packages that allow multiple vehicles (though not specifically designed for swarms) with ✨, and packages intended solely for single vehicles with ✖.

Table V provides a comparison of supported sensors for each simulator. Segmentation, magnetometer, and barometer are abbreviated as “Seg,” “Mag,” and “Baro,” respectively.

We indicate features, vehicle types, and sensors supported in the base configurations of these simulators, acknowledging that many of them can be extended for more extensive support.

## V. DISCUSSION

The aerial robotics community has undeniably made significant strides in the development of numerous simulators. However, a significant challenge lies in the fact that the specific requirements of various research groups tend to be platform-dependent and application-dependent, making it challenging to provide to all needs with a single simulator. Moreover, there is a growing consensus that exploring diverse solutions, rather than relying solely on one, can yield more favorable outcomes. Conversely, there is a compelling argument for standardization within this domain, as it would greatly facilitate benchmarking efforts and foster collaboration among researchers. Striking a balance between these two perspectives appears to be the most prudent approach. This entails directing resources and effort towards a select few simulators—more than just one, but not an excessive number—thus harnessing the advantages inherent in both sides of the spectrum mentioned earlier. As a result, several key themes emerge, including the role of

Table III  
COMPARISON OF FEATURES FOR WIDELY USED UAV SIMULATORS: INCLUDED (✓), PARTIALLY INCLUDED (\*), AND NOT INCLUDED (✗)

Simulator	Physics Engine	Rendering	OS			Interfaces	(S/H)ITL	License	Open-Source	Active	Ref.
			L	W	M						
Gazebo Classic (RotorS, CrazyS, PX4 SITL)	ODE, Bullet, DART, Simbody	OGRE	✓	* (✗, ✗, ✗)	✓ (✗, ✗, ✓)	ROS 1/2, C++, RL	PX4, ArduPilot, CF	Apache-2.0	✓	✓ (✗, *, ✓)	[19]–[24]
Gazebo	Bullet, DART, TPE	OGRE	✓	*	✓	ROS 1/2, C++, Python, RL	PX4, ArduPilot, CF	Apache-2.0	✓	✓	[25]
Isaac (Pegasus, Aerial Gym)	NVIDIA® PhysX, Flex	Vulkan	✓	✗	✗	ROS 1/2, Python, RL	Pegasus: PX4	Proprietary (BSD 3)	✗ (✓, ✓)	✓	[26]–[29]
Webots	ODE	OpenGL	✓	✓	✓	ROS 1/2, C/C++, Python, MATLAB, Java	ArduPilot, CF	Apache-2.0	✓	✓	[30]
CoppeliaSim	Bullet, ODE, Vortex, Newton, MuJoCo	OpenGL	✓	✓	✓	ROS 1/2, C/C++, Python, MATLAB, Java, Lua, Octave	—	GNU GPL, Commercial	*	✓	[33]
AirSim	NVIDIA® PhysX	Unreal, Unity	✓	✓	✓	ROS 1, C++, Python, C#, Java, RL	PX4, ArduPilot	MIT	✓	✗	[36]
Flightmare	Ad hoc, Gazebo Classic	Unity	✓	✗	✗	ROS 1, C++, RL	—	MIT	✓	✗	[38]
FlightGoggles	Ad hoc	Unity	✓	*	✗	ROS 1, C++	Motion Capture	MIT	✓	✗	[40]
gym-pybullet-drones	PyBullet	OpenGL	✓	*	✓	Python, RL	Betaflight, CF	MIT	✓	✓	[41]
RotorTM	Ad hoc	OpenGL	✓	✗	✗	ROS 1, Python, MATLAB	—	GNU GPL	✓	✓	[45]
MATLAB UAV Toolbox	MATLAB	Unreal	✓	✓	✓	ROS 2, MATLAB	PX4	Proprietary, Commercial	✗	✓	[46]

Table IV  
COMPARISON OF VEHICLE TYPES FOR WIDELY USED UAV SIMULATORS: INCLUDED (✓), PARTIALLY INCLUDED (\*), AND NOT INCLUDED (✗)

Simulator	Multirotor			Fixed-wings	Aerial Manipulators	Swarms	Cars	Other Vehicles	Ref.
	Basic	Drag	Wind						
Gazebo (Classic & New)	✓	✓	✓	✓	*	*	✓	✓	[19], [25]
Isaac (Pegasus, Aerial Gym)	✓	✗ (✓, ✗)	✗	✗	✗	✓	✓ (✗, ✗)	✓ (✗, ✗)	[26]–[29]
Webots	✓	✗	✗	✗	✗	*	✓	✓	[30]
CoppeliaSim	✓	✓	*	✗	*	*	✓	✓	[33]
AirSim	✓	✓	✓	✗	✗	*	✓	✗	[36]
Flightmare	✓	✓	✗	✗	✗	✓	✗	✗	[38]
FlightGoggles	✓	✓	✗	✗	✗	✗	✓	✗	[40]
gym-pybullet-drones	✓	✓	✗	✗	✗	✓	✗	✗	[41]
RotorTM	✓	✗	✗	✗	✓	✓	✗	✗	[45]
MATLAB UAV Toolbox	✓	✓	✓	✓	✗	*	✗	✗	[46]

aerodynamics in simulation, the need for benchmarking, the relationship between academia and industry, data sharing, and the challenges associated with maintaining these simulators.

**Aerodynamics and Simulation:** One central topic revolves around the role of aerodynamics in UAV simulations. While it is acknowledged that many successful UAV applications do not necessitate intricate aerodynamic modeling, in some scenarios such modeling becomes indispensable. Particular attention is drawn to scenarios involving UAVs navigating in constrained environments, adapting to dynamic environmental conditions, or engaging in interactions with other drones. In these cases,

there is a critical need for incorporating aerodynamics into simulator development, which is even more valid for fixed-wing flight. On the other hand, it is important to note that for most of the applications involving multirotors, even for aerial manipulation tasks, aerodynamics play a less significant role.

**Benchmarking and Standardization:** The large number of simulators in existence necessitates benchmarking and standardization in this field. The absence of a unified benchmarking framework and standardization practices pose substantial challenges for researchers and developers alike. Addressing this issue emerges as a primary objective, as it has become

Table V  
COMPARISON OF INCLUDED SENSORS FOR WIDELY USED AERIAL VEHICLE SIMULATORS: INCLUDED (✓) AND NOT INCLUDED (✗)

Simulator	RGB	Depth	Seg.	Point Cloud	IMU	Mag.	GPS	Baro.	LiDAR	Optical Flow	Ref.
Gazebo (Classic & New)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	[19], [25]
Isaac Sim (Pegasus)	✓	✓	✓	✓	✓	✗ (✓)	✗ (✓)	✗ (✓)	✓	✓	[26], [27]
Isaac Gym (Aerial Gym)	✓	✓	✓	✗	✗	✗	✗	✗	✗	✓	[28], [29]
Webots	✓	✓	✗	✗	✓	✓	✓	✗	✓	✗	[30]
CoppeliaSim	✓	✓	✗	✓	✓	✗	✓	✗	✓	✗	[33]
AirSim	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	[36]
Flightmare	✓	✓	✓	✓	✗	✗	✗	✗	✗	✓	[38]
FlightGoggles	✓	✓	✓	✗	✓	✗	✗	✗	✗	✓	[40]
gym-pybullet-drones	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	[41]
RotorTM	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	[45]
MATLAB UAV Toolbox	✓	✓	✓	✓	✓	✗	✓	✗	✓	✗	[46]

evident that standardized benchmarking is paramount for enhancing the reproducibility and comparability of research within the UAV and more generally, the robotics domain, as many simulators are designed to be general purpose, such as the universal simulators from Sec. III-A.

**Academia versus Industry:** It is evident from the data reported in the tables that there is a distinction between simulators developed in academic and industrial settings. It is universally acknowledged that academic simulators have played a pivotal role in advancing research. However, academic simulators often grapple with sustainability challenges, particularly after the researchers responsible for their development, mainly doctoral students, graduate. In contrast, industry-backed simulators are characterized by robust support, continuous documentation, and sustained evolution. Striking a harmonious balance between academic and industry-driven simulator development emerges as a critical goal for the future.

**Data Sharing and Collaboration:** What also emerges from the above discussion is the need for data sharing within the research community and with industry partners. It is pivotal to emphasize the importance of sharing simulator data and models for making progress in the field. The potential advantage of shared datasets, particularly in the domains of perception and autonomous navigation, are evident. Collaborative endeavors and knowledge sharing among researchers can catalyze forces for simulator improvements and innovation.

**Resource Identification:** The numerous simulators discussed in this paper highlight the challenges newcomers face when selecting the most suitable simulator for their research. The demand for resources to streamline the selection process is clear. This guided the authors' choice to write a survey to assist researchers and developers in navigating the diverse landscape of simulators and making well-informed choices.

**Accessibility and Maintenance:** When selecting a simulator, it is crucial to weigh factors like accessibility and maintainability. The simulator's licensing has a significant impact on its utility and adaptability to specific research requirements. Simulators lacking open-source availability, a free proprietary license, or an academic license can pose obstacles to replicating the work. Moreover, when essential

modifications to the simulator's source code are necessary due to missing features, open-source simulators are preferable, unless the simulator's development team are highly responsive to incorporating these changes. Furthermore, evaluating the long-term sustainability of a simulator is essential. A simulator that is no longer actively maintained may become unstable on newer operating systems and may lack updated integration support for middleware like ROS. In such situations, researchers might find themselves allocating valuable time and effort to maintain the simulator, diverting resources from their actual experiments.

## VI. CONCLUSIONS

Selecting a simulator that is best for a particular application space can be very challenging, but rewarding when it increases safety and reduces testing time and cost. In this paper, we discussed some of the prominent robotic simulators for aerial vehicles. We enumerate possible decision factors to consider when selecting a simulator and we compare features, included vehicle types, and integrated sensors across many widely used simulation packages. We hope that this analysis will be valuable to the community when embarking on aerial vehicle research and selecting a simulation environment.

## ACKNOWLEDGMENT

We gratefully acknowledge feedback from Geoffrey Biggs, Addisu Taddese, Jaeyoung Lim, Jay Patrikar, Marcelo Jacinto, João Pinto, Mihir Kulkarni, Marc Freese, Yunlong Song, Jacopo Panerati, Angela Schoellig, and Guanrui Li.

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