# A Cyber-Physical System's Roadmap to Last-Mile Delivery Drones

Bruno S. Faiçal, Cesar A. C. Marcondes, Denis S. Loubach, *Member, IEEE,* Elton F. Sbruzzi, Filipe A. N. Verri,
Johnny C. Marques, *Member, IEEE,* Lourenço A. Pereira Jr, Marcos R. O. A. Maximo, *Member, IEEE,*
Vitor V. Curtis

***Abstract*—According to recent studies, unmanned aerial vehicles can play a game-changing part in cost reduction and speed increase to address the last-mile delivery problem and attend to emergencies. Last-mile delivery services are getting more and more relevant, especially when in times when social distance is required. However, a systemic view of how to provide a feasible solution to enable this application as a vertical market in the urban context is still inexistent. Given this scenario, our paper contributes by proposing a cyber-physical system roadmap applicable to last-mile delivery drones. The proposed CPS guidelines are based on the system of systems to enable an enhanced operation towards smart cities' governance. This paper also discusses topics from air space control and reservation to communication infrastructure and decentralized control supported on a blockchain.**

***Index Terms*—Unmanned aerial vehicles, Drones, Last-mile delivery, Cyber-physical systems, B5G, Edge Computing, Tradable permit model, Blockchain.**

## I. INTRODUCTION

UNMANNED aerial vehicles (UAVs) can play a game-changing part in terms of cost reduction and speed increase to address the *last-mile delivery* (LMD) problem and also to attend to emergencies [1].

The LMD services are getting more and more important, especially when in times where social distance is required [2]. Studies indicate that the last-mile is one of the most expensive, inefficient, and polluting parts within the supply chain. It can reach from 13 to 75% of the total supply chain cost in given scenarios [3]. Also, last-mile delivery services are a concern for the major e-commerce retailers including Amazon, Walmart, and Alibaba. In this context, UAVs, also known as *drones*, are of special interest [4]. For a recent study on the economic viability of UAVs for LMD and end-user propensity for this technology, see [5].

According to [6], the usage of drones for delivery purposes can have at least four main advantages: (i) autonomy, (ii) avoidance of traditional road network, (iii) cost, and (iv) speed. Despite these advantages, there are lots of open issues, such as airspace utilization, payload capacity planning, auto-pilot, and navigation in shadow areas.

Drones can be remote-controlled or even fully autonomous, depending on local regulations. These regulatory agencies' policies vary from place to place. Generally, drones are classified into high-altitude platforms (HAPs), *e.g.* 17+ km, or low-altitude platforms (LAPs), *e.g.* tens of meters to few kilometers. HAPs are mostly regarded as quasi-stationary and present better endurance to face a few days to months campaign. On the other hand, LAPs are more agile, cost-effective, and can be recharged in a much faster way.

Drones are also categorized depending on their aeronautical frame: they can be fixed- or rotary-wings in this sense. The former, such as small planes, have higher speeds and can carry more load, but they need to keep flying forward with relatively high speeds to stay in the air, making it harder to perform sharp maneuvers. The latter can be represented by a quadrotor drone that can hover at lower speeds or even in place, however, their flight autonomy is limited to less than one hour [7] given the current electronic battery technologies. A hybrid drone is also possible, *i.e.* having fixed- and rotary-wings on the same platform.

As mentioned by Alwateer and Loke [8], drones are on the edge of the delivery service. This can be confirmed as initiatives in the air traffic management (ATM) system, including SESAR and NextGen, indicate ongoing development along with future communication infrastructure preparations. According to [9], unmanned aircraft systems (UASs) traffic management (UTM) is the traffic management operating along with ATM. The UTM's goal is to have a system that safely integrates drones into air traffic considering low-altitude airspace. In this environment, there is also the concept of advanced air mobility (AAM) [10]. The mission of AAM is to leverage the emerging flight market towards an air transportation ecosystem moving people and things by having new and very modern aircraft, such as UAS or drones.

Aerial delivery may impact merchandise, courier, food delivery, humanitarian aid, and passenger transport [11]. The last is considered very ambitious but it is already planned and being scratched. These applications require agents (*e.g.* UAV's or drones) to have a plan and execute delivery routes taking into account cost and time minimization while avoiding collisions with other agents and the environment.

Given this overall picture, our paper introduces a *cyber-*

---

Authors are with the Computer Science Division, Aeronautics Institute of Technology – ITA, São José dos Campos, SP, 12228-900 Brazil

Manuscript received Sep. 5, 2022; revised Oct. 17, 2022.

*physical system's (CPS) roadmap applicable for LMD drones (LMDDs).* The presented CPS guidelines are based on the system of systems (SoS) concept to enable an enhanced operation towards smart cities' governance. We divide it into six main concerns: airspace control and reservation, geofencing service, drone navigation, communication infrastructure, safety mechanisms, and delivery and pick-up facilities. We approach these in dedicated sections or associated with the other concepts. Considering our solution components' orthogonality, we also discuss blockchain and its benefits. The argument proposed in the present paper is also supported by previous experiments, simulations, and results from [12]. There, we addressed the context of last-mile delivery drones by comparing fully cooperative centralized and distributed scenarios. The latter indicates attractive benefits such as fast permit transactions, simple computational infrastructures, and error resilience.

In summary, the main contribution of this paper is the proposal of a layered architecture, exposing decoupled components and their interactions, to enable the innovative and theoretical approach of airspace control based on economic principles, as fair and efficiency, namely the tradable permits for airspace solution presented in [12]. We also conduct a systemic view on how to provide a feasible and scalable solution to enable it as a vertical market in the urban context, still inexistent in the literature. And finally, we discuss how it can be integrated into current regulations.

The remainder of this paper is organized as follows. We present the current state-of-the-art in Section Section II. In Section III, we introduce our proposed CPS for LMD. In the next sections, we detail each aspect of the system: airspace reservation and mobility model (Section IV), communications (Section V), route planning (Section VI), safety and certification (Section VII), and decentralized control (Section VIII). Finally, Section IX provides final remarks and future research directions, followed by a list of acronyms used in this paper (Table II).

## II. RELATED WORKS

[13] presents a view of characteristics, perspectives, and challenges addressing the use of drones for delivery in urban areas. It includes artificial intelligence (AI) on the edge and discusses the regulatory issues that jeopardize the predictions for that application. Nevertheless, a delivery drone system requires a deep integration among physical systems, software, and regulatory instruments to work correctly. In this sense, the City-ATM aims to enable UAVs and air taxis in uncontrolled airspace [14]. However, this approach can face different bottlenecks in a more overloaded system, and scalability can become an impediment. Therefore, a game-theoretic model for assuring airspace reservation and clearance in flight operation could mitigate this issue.

The use of drones as an enabling technology for more innovative and faster LMD systems are under investigation in the past years. As developed by [15], a suite of software for operating in urban areas is essential for effective deployment. However, new methods are still required for telemetry and forward current state information to controlling agencies. As pointed by [16], despite privacy constitutes one of the primary concerns, the use of drones is a well-accepted idea for delivery. Environmental benefits should be in discussing, as indicated considerable gains adopting drones versus motorcycle-based [17]. Thereby, developing a holistic system to support a concrete roadmap towards the conceptualization of this application can improve the state-of-the-art in the field.

In this context, controlling and synchronizing possessing the airspace is a challenging task. Indeed, UAVs occupy a physical space in a temporal-based model. As the results obtained in Salamanca, Spain [18], the vehicles must be aware of their routes and report their status to an external system. However, an actual implementation needs more communication infrastructure efforts (*e.g.*, 5G and multi-access edge computing (MEC)) and safety mechanisms to address unreliability of the wireless medium, duration of batteries, high mobility degree, and other issues [19]. Also, control layers need to deal with complex scenarios to coordinate heterogeneous entities [20].

Reservation and route planning constitutes the initial phase in the operation of the airspace dedicated to urban applications. [21] describe a flight-planning system and highlight the importance of mapping the terrain model to the system. Therefore, identifying and specifying the currently enabled airspace is essential for this modality. Moreover, it requires the space segmentation to be available a priori for a free dispute to acquire operational permission.

Capacity planning also must be considered. Differently from terrestrial mode, traffic jams are impractical and can lead to catastrophic scenarios. [22] presents results in favor of vertical lanes to improve the system capacity. Therefore, players and the regulatory body must interact from the early stages of the permission process, identifying constraints to mitigate posterior allocation conflicts. In that regard, [23], [24] presents a framework to estimate the traffic density to cities in Europe. However, safety operations require a tightly coupled integration with other systems and subsystems.

As we can see from the related works, there is increasing effort to use drones for urban applications. However, as a complex system by nature, most scientific findings approach a part of the problem, missing the integration and losing the holistic view of the system. To address this gap, our work differs from the others in two main points: (i) *we devise a set of essential services assuring the safety, civilian access to the airspace, and communication during flights (benefiting from the previous existing cellular infrastructure);* and (ii) *by considering the chaining of different systems in order to emerge as concise and seamless scalability*. To the best of our knowledge, this is the first work considering the use of drones for delivery systems backed by services of safety, communication, geofencing, airspace control and reservation, navigation, and multi-modal endpoints for delivery and pickup.

## III. PROPOSED CPS FOR LMDD

The CPS for LMDD comprises a) airspace control and reservation, b) geofencing service, c) drone navigation, d) communication infrastructure, e) safety mechanisms, and f) delivery and pick-up infrastructure. Together they form a SoS and must be tightly coupled to produce an enhanced operation to enable smart city governance.

In Fig. 1, we propose an layered architecture where the use of drones for delivery and pick-up forms a vertical application in the context of communication, *i.e.* 5G. This layered architecture allows drones to control navigation and geofencing within a corridor, requiring low-latency and massive machine-type communication. Safety is crucial to signal tackle with different situations, such as emergency landing, *i.e.* forced landing. The airspace traffic control (a supervisory system) monitors the flight lifecycle (plan, takeoff, ongoing, cruise and transients, and landing) and permits adherence. Moreover, it sends safety-related messages to assure proper operations. The layered approach also supports other applications: surveillance, weather forecasts, and mobile network cells.

Figure 2 illustrates the proposed CPS and the relationships among their subsystems. The *airspace control and reservation* provides *geofencing services* (within a drone corridor) with minimal human intervention using decentralized control and bookkeeping. *Drones* in the system must be equipped with appropriate sensors and radios to interact with the *communication infrastructure*. *Safety mechanisms* provide to the drones the information to navigate, including fencing block information. Finally, a *delivery and pick-up infrastructure* relies on the other subsystems to enable LMDD applications.

Following, we discuss each of the subsystems in our proposed CPS.

*a) The airspace control and reservation:* A groundbreaking feature is to bring the airspace's reservation and utilization to a civilian context, allowing the private sector to operate without the burden of the human-in-the-loop process. As a smart city resource, the airspace can be segmented and objected to allocating a specific space during a specific timespan to a tenant. We propose an economic model to permit sustainability with revenue and constant upgrading, conducive to a public-private partnership.

*b) Geofencing service:* The airspace segmentation allows reserving a specific location for a given set of aircraft, defining four-dimensional fencing block: altitude, longitude, latitude, and timespan. The block size is location-dependent, but small sizes supply flexibility and efficiency to airspace utilization, granted after an auction process. The complete workflow consists of a sequence of bids where players (organizations willing to operate in the system) intent to acquire a set of permits to form a path. In the end, a blockchain system persists all exchanges. Then, the player submits a mission to start the operation. It results in an auction-oriented mission, where only authorized players can operate in a path. The geofencing service also plays a role in the safety mechanisms. Specific paths can be reserved for emergency flights, for instance. Moreover, players must be notified when bad weather or other unsuitable conditions restrict the operational airspace. In this sense, geofencing service is a specialized concept that can take place in a more general concept, *i.e.* drone corridor. Therefore, it is possible to have different geofencing services within the same drone corridor.

*c) Drones and navigation:* Drones need to have onboard sensors and communication radios to provide safety and reduce variance in operation. A player-owned ground control station (GCS) must manage its fleet, enabling adaptive algorithms to tackle changes in the state system dynamically. Furthermore, the smart city administration can interrupt ongoing missions, which is crucial to implement city-wide safety services concerning weather conditions, such as wind, rain, fog, and snow.

*d) Communication infrastructure:* The communication infrastructure must perform missions accordingly. It requires massive machine-type communications (mMTC) and ultra-reliable low-latency communications (URLLC). It is also important to incorporate security aspects for authentication and authorization.

*e) Safety mechanisms:* A set of physical points must be available throughout the airspace, serving as a safe spot in which drones can land in case of unappropriated operation conditions. Due to the operational environment's natural volatility, a safe point is strategical to emergencies including battery drained, erratic weather, among others. A safety notification system is also required. Players must be notified about the weather forecast, drones that are detected outside their reserved fencing blocks, and other important events that affect flight conditions.

*f) Delivery and pick-up infrastructure:* They correspond to places where missions start and also where they end. The starting terminal is potentially a logistic center where operators dispatch packets to delivery, yet they realize advanced approaches such as Amazon's zeppelin. At the delivery place (the mission ending point) must exist a spot to automatically receive the packet. It can be static (in buildings or houses), or mobile like the top of cars (Uber use case).

## IV. AIRSPACE RESERVATION AND MOBILITY MODEL

The volume of urban UAVs is expected to grow in the next years. One of the foreseen challenges of this growth is how to manage that traffic. In this matter, we argue that schemes available in the literature about urban motorways traffic (UMT) can be adapted to urban UAV traffic (UAT).

Even though many traffic models have been proposed and employed for UMT [25], their application to UAT is not trivial. We highlight the following reasons:

- Constraints related to the airways are inherently less restrictive than motorways. As a result, optimal flight planning in airways commonly becomes unfeasible for many agents, *e.g.* drones. Constraints in the airspace must be imposed carefully to achieve a reasonable scenario; and
- Although airspace congestion is less likely than motorways congestion, the consequences regarding failures are far more serious. Thus, safety considerations must not be undermined.

Traditional ATM schemes avoid congestions, and collisions altogether, by using a central unit. Such a unit plans strict paths for each aircraft and oversees them. However, traditional schemes are not appropriate to deal with the responsiveness requirements of LMD.

*Tradable permit model* (TPM) is a novel approach to cope with a capacity allocation that uses a market mechanism to

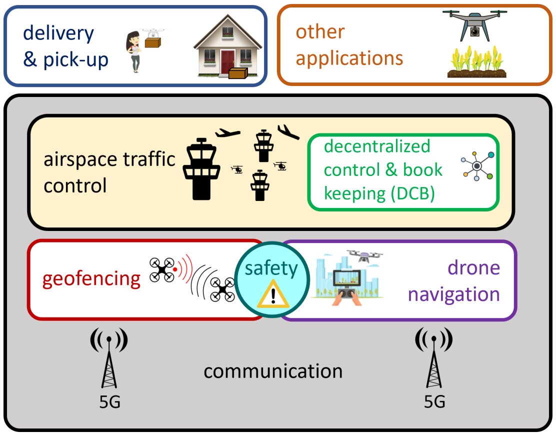

Figure 1: Proposed layered architecture, where the gray color rectangle at the bottom represents the application infrastructure, while the layers at the top are the actual application and services.

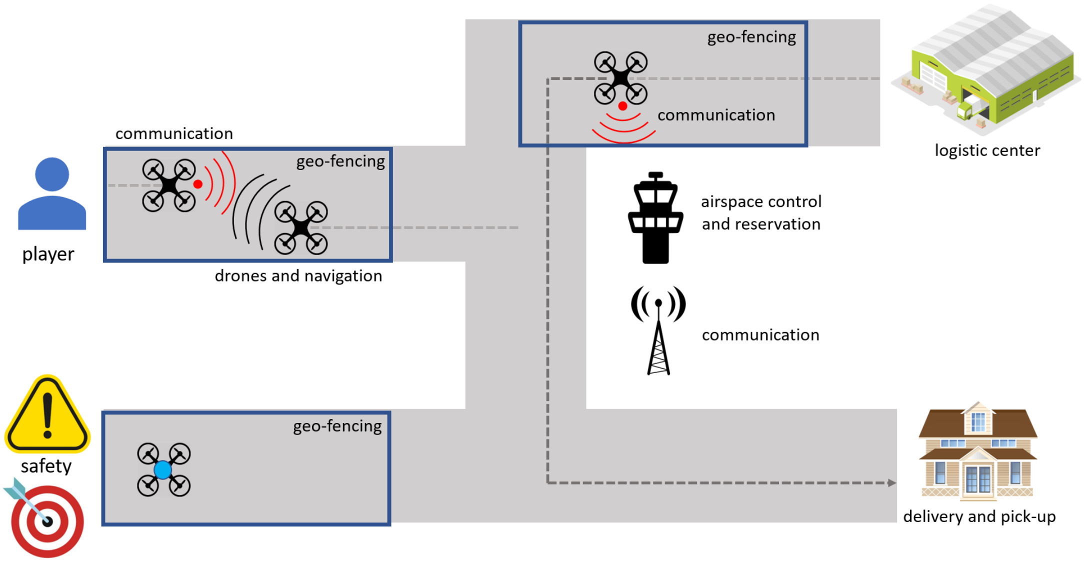

Figure 2: Relationship among subsystems of the proposed CPS.

assign rights to users of a particular resource [25]. Permit schemes have received growing attention in the academic literature. Permit's decentralized nature brings advantages over centralized approaches [26]. In the context of LMDD, the airspace is the resource of interest.

Several researchers study the coordination of swarms of cooperating drones [27] or the optimization of planned routes globally [28]. We argue that both approaches are not suitable for managing the mobility of LMDD if it is taken individually. Let's consider the *players*, which are companies or individuals that own LMDDs and desire to use the airspace. First, in real-world scenarios, it is unfeasible to constrain different players to use the same given strategy to coordinate their drones. Moreover, a central entity that calculates the optimal route for each LMDD in the airspace would require an impractical computational power.

Given this, we propose a TPM that serves as a guideline to nextgen aircraft control for LMDD. Related schemes have been proposed [26]–[29]. However, our approach raises the novel challenge of cooperation and competition in a much more realistic scenario. We describe such a mobility model in the following subsections.

### A. *Free-Market Permit Concession*

In real scenarios, many players have specific interests in the usage of the airspace. Some interests, however, will certainly conflict. For instance, two players might want to use the same space at the same time to accomplish the delivery mission within the expected time.

Solving the conflicts in a decentralized cooperative way, *e.g.* relying on common strategies among different players, would require impractical regulatory and expensive oversight mechanisms. Conversely, in the competitive view, each player must obtain beforehand a permit to use the desired airspace at the desired time. In this context, a *permit* is an authorization to use a specific volume in the airspace for a specific timespan, that is, a fencing block. As a result, the regulatory oversight would focus on inspecting whether LMDDs have a permit instead of scrutinizing each flight for compliance with a given policy.

Still, a centralized permit concession procedure has some limitations: a) optimizing routes, airspace usage, and financial gains becomes computationally unfeasible as the number of players increases; b) response time of the central system might not be feasible for LMDD; c) a centralized system is not robust to failure or attacks, making it as a *single point of attack*; and d) the downtime of the system would result in catastrophic, *i.e.* financial-related, outcomes.

As a possible yet strong solution, the free-market distributed permit concession is in place. In this scheme, each player would bid for a sequence of adjacent permits that accomplishes its mission. Once a player acquires permits, it can freely use or trade them. Each permit is always owned by some entity. That means regions of the airspace, and consequently, a portion of the permits would be previously assigned to public- or private-sector organizations.

To assert the feasibility of such an approach, we designed a multi-agent system simulation of the TPM scheme for UAV. In [12], we simulate players in a TPM under different arrival rates, *i.e.* number of players competing in the auction, by focusing on two main perspectives: a) an assessment on the time and cost agents have to complete their mission; and b) an estimate of the effective airspace usage. The results from that research showed that even a naïve decentralized competitive approach yields satisfactory results under high traffic conditions. Also, there was evidence that smarter agents can behave better. From a practical perspective, such a study found out interesting properties emerging from the agents' collective behavior that could drive how airspace policies are defined.

In our proposal, some research questions regarding the parameters of the concession mechanism are central. For instance, one must address the kind of auction and the appropriate time and space scales of the permits for each practical scenario.

### B. Optimal Usage of the Airspace and Collision Avoidance

Although we argue that full cooperative schemes and full centralized schemes are not practical, central cooperative instructions are unavoidable inside the player's perspective.

Once a player owns the sequence of permits to use the airspace, it uses the respective airspace as desired, of course, by respecting the security and safety regulations. For instance, each player surely owns several LMDDs to fulfill many delivery missions. Then, it needs to coordinate its resources to optimize its gains while satisfying the space and time constraints.

Given a set of drones owned by the same player, they can work cooperatively. We discuss the details about the coordination of drones, including collision avoidance, at this level in Section VI. Another fundamental aspect of coordination is the communication infrastructure and the requirements of the real-time control system.

## V. COMMUNICATION SYSTEM INFRASTRUCTURE

To cope with the LMDD system's complexity, we assume full connected infrastructure and battery-bound operation requirements. In this communication system infrastructure context, researchers also take into account common UAV communication protocols over cellular links [30], passive sensor nodes in a local sensor network [31], and mobile target tracking [32].

We consider the smart city scenario typical for deployment and key-technologies to support this system's viable implementation. Thus, it will be feasible to exist communication amongst the aircraft in the system and aircraft to the ground base station, resembling vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication model. Offload of processing must be another resource available as a service in this infrastructure, possibly in the form of MEC.

Our TPM for LMD [12] enables large-scale operations with multiple layers in altitude, each one segmented to form four-dimensional geofencing units. Hence, many mMTC problems can arise, as drones share the same media for communication. On the other hand, the GCS requires an URLLC to provide an offload of challenging computational tasks involved in achieving global consensus of operations. Each drone sends the sensor's information to GCS periodically, allowing the creation of discrete-time snapshots, optimizing configuration parameters, and sending the new setup back to the aircraft. Communications play a critical role in this feedback control loop, acting as a bottleneck in this infrastructure.

Aircraft to aircraft (A2A) communication is typically in line of sight and makes it possible to implement essential services such as collision avoidance and trajectory planning. A2A impacts not only in the same origin fleet but also on other tenants using the airspace. Problems here include spectral sharing and security issues involving authentication and authorization. In this context, there are some protocols including Mavlink. It is a protocol for message passing with drones, and so security needs severe scrutiny. Aircraft to infrastructure (A2I) communication, as a combination of access-network and computational resources, enables the offload of critical functions to the edge. It includes a global vision of a tenant fleet, and the smart city takes control of the whole system to provide safety (emergency or catastrophic situations). 5G and beyond have addressed the problems we list here. However, it requires more workload characterization to expose new knobs not yet pondered for A2I.

Those requirements can culminate in new studies to provide realist service-level agreements (SLA) and quality of service (QoS) to LMDD scenarios. The presence of MEC is essential to cope with communications and processing demands. Latency is another crucial metric, and all the elements in the communication system, including front-haul and backhaul, must carefully be engineered to meet SLA and QoS constraints. The GCS efficiency is as good as the capacity of the system in providing a lower latency experience. Public-private partnerships can be meaningful for LMDD to deploy adequate infrastructure to operations. In this sense, our economic model of trade permit model supports a sustainable modality, providing capital expenditure (CapEx) and operating expenses (OpEx) resources.

Battery-aware aircraft provides efficiency to operations as it can self-adapt to condiction dynamically. During operations, expected and unexpected events impact energy consumption, causing deviance on mission-planned versus actual conditions. The main problem is in the sources of uncertainty, as on commissioning is possible to estimate the minimal capacity planning required. For example, due to uncontrollable weather changes, more processing power can arise during the mission, making it different from the original. Thus, we can divide resource utilization into two: bare-minimal and exceeding. The former is about the basal resources consumed and known before the mission. The latter is the unexpected and unknown events that emerge dynamically. Processing the exceeding demands MEC, provided an ecosystem with enough latency, reliable, and cloud-enabled computing providers.

Such an infrastructure allows players to operate safely and the smart city to implement an UTM architecture. Path planning works as a core service for both and needs in-depth analysis.

## VI. ROUTE PLANNING

In a real context, UAVs can be simply considered as one more transportation vector to existing supply chain management and logistic systems. In such systems, decision-making should consider not only profitability, but also service quality, equity, consistency, simplicity, reliability, and externalities [33]. The interrelations of these enterprise-wide challenges play a key role, especially when seeking optimal solutions. For LMD, this holistic view is even more important once it represents a 13-75% economic opportunity of the total supply chain [3]. Additionally, we consider the near future LMDD to be autonomous, imposing strict safety constraints and dynamic responses to unexpected events.

Although the integration of these challenges is crucial for better solutions, optimizing all of them at once may become infeasible and unrealistic, *e.g.* some decisions must be taken only after the realization of an event. In order to address the complexity of the LMDD, our proposed CPS suggests handling the complexity of strategic decision-making by two virtually decoupled perspectives: cooperative and free-market (or competitive), while the dynamic responses are addressed basically by the geofencing and drone navigation layers.

The cooperative perspective is responsible for the traditional operation research (OR) tasks, *e.g.* fleet routing and path planning, packing, scheduling, and others. This allows the benefits from systems with decades of developments, current system infrastructure, easy and cheap integration, multi-objective optimization, and some level of isolation between the LMDD problem modeling and the already deployed business policies and strategies. This integration is simply achieved by the interface of our application layer (highest layer of Fig. 1).

In OR, the vehicle routing problem (VRP) is the classical approach when planning optimal routes for a fleet of delivery vehicles from a depot to a set of geographically scattered customers, subject to constraints [34]. It is a rich and broad area of research with many variations, so VRP may be better defined as a class of problems.

According to taxonomies [35], [36], LMDD can be better described as a class of capacitated VRPs (CVRPs) and distance-constrained VRP (DCVRP), respectively, when the modeling has to consider limited carrying capacity for the vehicles and the total length of the path in a route cannot exceed a maximum limit. The VRP may be considered with many other variations related to the LMDD, such as: VRP with time windows (VRPTW) constraints, where allowable times or time intervals are associated with every customer; periodic VRP (PVRP), when the scheduling extends from one to many days; and VRP with pickup and delivery (VRPPD) or VRP with Backhauls (VRPB), where customers may return items.

Many solution strategies have been devised for VRP: exact algorithms often employ formal optimization methods with optimality guarantees but are limited to solving relatively small instances of the problem; classical heuristics use heuristics especially tailored to VRP; and metaheuristics employ general black-box optimization algorithms, such as simulated annealing and genetic algorithms. Despite the loss of optimality and feasibility guarantees, in practice, metaheuristics typically work well and can find close to optimal solutions for large instances of VRP in a reasonable amount of time [34].

During the cooperative decision-making, some level of integration to the competitive perspective is expected due to unknowns introduced by the free-market dynamics supported by the airspace control layer. Specifically, it imposes additional restrictions for geofencing blocks of high interest: an auctioning block may not be granted and its cost may be stochastic.

There are many ways to integrate the competition in the VRP, however, the most direct approach is by modeling the stochastic cost of the blocks as part of the distances to be traversed by a UAV. In [12], we show that players can obtain routes close to the optimal length using a naïve decentralized approach at a satisfactory cost even in regions with very dense competition. In other words, the competition introduced by our CPS does not result in a considerable loss of optimality for the OR tasks. Furthermore, we expect the players can focus only on the neighboring blocks it desires, ignoring most of the other blocks during optimization. We also expect homogeneous costs for regions with low competition.

While the cooperative and competitive perspectives do not necessarily require immediate responses, events from the geofencing and the drone navigation layers may impose, respectively, fast adaptative responses or instant actions for safety reasons.

A common approach in OR for adaptative responses is two or more stage models. These models are especially interesting when just part of the variables must be defined before some realization, while the other decisions may benefit from the information of the realizations. After one event, a re-optimization is required to adapt the decision to a new reality [37]. In this case, the recourse decision must be feasible or there is no way to optimize it. Another advantage of this approach is that the original problem is broken into smaller problems, making the solution more practical. Many other solutions may be implemented for adaptative responses, *e.g.* reinforcement learning may be used to learn new strategies for the auction and routing optimizations.

Depending on the nature of the event, fast or real-time decisions will be required for safety or security reasons. For safety purposes, robust decisions to stochastic variables may be required by the authorities to avoid harmful outcomes and high losses for the players. Some examples of fast decisions that can be avoided with robust approaches are a new weather event identified by the airspace control layer imposing more restrictive conditions to the geofencing layer and the scheduling of a path of geofencing blocks to a safe point due to a battery drain event. The level of robustness required for safe geofencing and navigation depends on many factors: the environment, competition, amount of available safe points, and others, and it is still an open issue. However, once the airspace control and geofencing layer have autonomy for changing the controlling parameters, they can mitigate harmful outcomes as desired and by a third-party member independent of the competitive interests of the players.

The most critical challenge to the LMDD is the real-time decisions required for collision avoidance. The drone navigation layer requires an infrastructure with real-time monitoring and responses to perform fast maneuvers to avoid collisions. These maneuvers reduce the battery autonomy and may result in the abortion of delivery or pick-up missions, causing important impacts to other players. This is the reason our CPS forces collision events to be extremely rare by construction. In addition to avoiding losses, it also prevents the need for various re-optimizations needed if collisions were not rare.

Inter-agent collision avoidance is typically not dealt with in VRP. This is theoretically possible and the interested researcher could in principle benefit from the literature regarding multi-agent trajectory planning through model predictive control (MPC) [38], [39], where inter-agent collision avoidance is achieved by imposing additional constraints in an optimization problem. Nevertheless, considering current processing power and optimization solver technology, we consider that direct inclusion of inter-agent collision avoidance in VRP would make the optimization problem computationally intractable, and certainly not suitable for real-time applications such as the one proposed here.

A low-level solution is required for safety reasons. There is a vast literature in robotics path planning that may be employed [40], [41]. Due to the existence of a drone navigation layer with low-latency communication infrastructure, sophisticated control algorithms such as MPC-based trajectory planners may be used [38], depending on the number of UAVs and the available computational resources. These algorithms could operate in a closed-loop fashion, taking into account recent information collected by the drones and the communication infrastructure. Independent to the approach taken, an embedded local and decentralized obstacle avoidance system based on the drone's sensor readings should always be present to permit quick reactions to unexpected obstacles and continue mission execution when communication with the drone navigation layer is lost.

## VII. REGULATORY DIRECTIONS

The use of drones, from recreational flying to commercial uses, is a concern for safety and certification. Whether manned or unmanned aircraft, the Federal Aviation Administration (FAA) requires that all operators follow specific guidelines for the operations they request. Currently, the Part 135 addresses a set of rules for the certification of UAV. Basically, the Part 135 is not dedicated to UAV but is the only path for small drones to carry the property of another for compensation beyond the visual line of sight.

UAV considers that operation is outside the aircraft, and no human is onboard, but the vehicle is controlled from the ground. The UAV certification has some regulations for vehicles and operators, to ensure safety. The use of drones, in connection with a business activity, is allowed in many countries, but under very strict conditions. In most countries, one will need different authorizations or licenses from the National Aviation Authority before starting any operation.

However, for autonomous UAVs (AUAVs), few or no regulations are available at this point and it is very unclear if current regulation for manned aircraft vehicles will fit this need. The operator is an automatic onboard pilot system (AOBPS), which refers to the level of automation of the drone when, at the highest level of automation, this is about piloting functions and on-board decision making with little or no human intervention. In this paper, we are considering the AUAV are drones used for package delivery.

The central issue is related to the concept of "explainability" of AI, which refers to the fact that, unlike traditional software code that can be read and understood logically, the inner workings of a neural network can be difficult to understand. Today all systems and software development revolves around a tripod: requirements, development and tests, where requirements describe the behavior that will be developed and tests confirm that the development was carried out according to the specified requirements.

The use of machine learning, or any other AI technology, is still a challenge. If in large aircraft there is still a certain restriction, or even fear of passengers boarding a remotely piloted aircraft, the same happens, but to a lesser extent in AUAV. While automation has been a function of aircraft systems for decades, AI – which, unlike automation, enables high-level machine decision making [42].

The authors of this work believe that autonomously functioning algorithms, especially with machine learning implementations, need requirements not for the direction of development, but rather to ensure that the learning algorithms are suitable so that the AUAVs in their operations do not incur in some marginal safety condition. In June 2020, interested members from leading companies in the aerospace engineering community came together to answer this critical question with the creation of a new standards effort focused on certifying autonomous systems with machine learning and other AI-related items. From this work a new joint international committee was born, SAE G-34/Eurocae WG-114.

We should especially analyze the certification regulations in the following areas:

- Safety assessment; and
- Software and hardware certification.

### A. *Safety Assessment*

This process is focused on identifying functional failure conditions leading to hazards that are closely related to development assurance levels (DALs). Currently, there are five DALs, as presented in Table I with their respective maximum probability per flight hour (MPFH).

Table I: Hazard Classification and DAL

| **Hazard Classification** | **DAL** | **MPFH** |
|---|---|---|
| Catastrophic | A | $10^{-9}$ |
| Hazardous | B | $10^{-7}$ |
| Major | C | $10^{-5}$ |
| Minor | D | $10^{-3}$ |
| No Effect | E | – |

Then, some questions are needed to be answered. Is the MPFH of $10^{-9}$ acceptable for the most critical hazard classification of system failures for AUAV, especially for LMDD vehicles? We believe that yes, this is acceptable. Basically, if an aircraft with about 600 passengers uses this concept, why a small drone for LMDD can't use the same approach? Another question is the industry of drones perform a traditional safety-assessment process during drone projects, according to our research and literature review: no, they do not. Then, regulations can be used as is, but the industry should adapt its development processes to allow compliance with regulations.

### *B. Software and Hardware Certifications*

The RTCA DO-178C and DO-254 have been used as acceptable means of compliance for software and hardware to ensure safety in the appropriate level of rigor, according to the safety assessment. However, the AOBPS will coordinate the operation of other systems of the AUAV. So, the study of additional characteristics must be performed to ensure if the software and hardware level must be increased to level A+, as traditionally, software and hardware systems follow a process rigor considering a non-autonomous flight. Additionally, current software standards, as DO-178C, use a concept that behavior must be deterministic and the software is specified with an enormous amount of detailed requirements that describe its behavior. The use of technologies such as machine learning, which make the solutions present an evolutionary behavior, cause some incompatibility with the way these regulations were conceived.

## VIII. A DECENTRALIZED CONTROL AND BOOKKEEPING

As a CPS representing a critical infrastructure and composed of multiple players, the system's fundamental responsibility concerns how data dissemination throughout the communications systems (potentially the Internet) occurs. Cybersecurity is the main focus of this service, guaranteeing integrity, availability, consistency, resistance to distributed denial of service (DDoS), and 51% attacks and authorization and authentication [43]. Blockchain-based systems provide a robust framework to this end, allowing rapid evaluation of different alternatives and configurations to scenarios in future study cases. Therefore, this framework supports the bookkeeping of crucial information inside and across the subsystems.

The airspace reservation procedure consists of a sequence of bids to acquire a permit associated with a particular geofencing block. Players race to achieve a list of adjacent permits, and, during a period, the reservation converges to a consistent state, where each player has the right to use a path. Thus, a set of transactions can be stored as a public resource, as players use the airspace concurrently, whereas the entities responsible for the ATM govern the system utilization. The sharing mechanism is a critical point of failure in this context: malicious users can intentionally manipulate data to induce error-prone operational conditions, potentially causing malfunctioning, leading to hazard situations.

Adopting a blockchain-based system for data dissemination leverages benefits to the system as a whole [44]. When a new set of transactions is ready, it is signed and included as a block after being validated by more the half of peers present in the system. The system hashes all data and stores it in a Merkle tree structure. Tampering the information in blocks will require substantial computing resources, as players and other entities store replicas. It is worth mentioning that the game-theoretic method to insert information must be under investigation. Consensus models, such as proof-of-work, can lead to advantages to specific scenarios. However, other schemes can outperform it, *e.g.* proof-of-event, proof-of-stake, and proof-of-authority.

The workload imposed on the system is dependent on the permits' size. More oversized permits decrease the number of combinations to form a path, and vice-versa. Thus, smaller permits occasion more degrees of freedom, which increases the number of transactions in the system. Consensus mechanisms dominate the throughput and consequently impact availability. A careful study investigating different mechanisms is encouraged and can yield useful insights to tackle the variables' trade-off between consensus speed and security level [45], [46].

The replicas' distributed nature in the blockchain allows consistency, serving as a fault-tolerance feature and a source of truth in the system. Another advantage of it is the robustness in the face of DDoS attacks since there is no centralized entity in the system. A malicious user intending to insert poisoned data needs to compromise 51% of the participants in the system. Assuming blockchain is flexible enough to scale out the nodes participating in the process, 51% attacks are costly, and there are mechanisms to mitigate them, *e.g.* by adding more nodes.

## IX. SUMMARY

In this paper, we tackled an emerging topic for research: LMDD. Particularly, we proposed a high-level CPS to this topic in order to enhance smart city governance. Our system is a SoS that is composed of six different subsystems: (1) airspace control and reservation, (2) geofencing service, (3) drone navigation, (4) communication infrastructure, (5) safety mechanisms, and (6) delivery and pick-up infrastructure. These subsystems are expected to work together to increase the quality of the whole ecosystem.

Our proposed guidelines provide a path towards future CPS applicable to LMDD.

For next research works, we intend to address two different directions. The first direction is micro-level research. The development of each one of the six subsystems of our cyber system individually. And the second direction is macro-level research. The integration of those subsystems aiming to enhance our cyber system as a whole.

Other interesting topics for future research are those related to some limitations of our current approach. Although the previous work [12] shows that the planning and acquisition of tradable permits are feasible through a simple heuristic, we expect efficient results to be obtained only by complex computational strategies and dependent on the latency of the platform in persisting the current state of the system. Considering a persistence layer in a distributed manner, *e.g.* blockchain, may limit the efficiency of such solutions. In such case, decision-making under uncertainty may be a solution to this problem.

The proposed solution was developed for the context of LMDD services. Thus, further studies should be conducted to verify its feasibility in the context of other applications.

Finally, the current approach only considers drones with communication capabilities. While this is a limitation to be explored, we consider the prohibition of drones without communication capability as pertinent for safety reasons.

## ACRONYMS LIST

Table II: List of acronyms.

| **Acronym** | **Meaning** |
|---|---|
| A2A | Aircraft to Aircraft |
| A2I | Aircraft to Infrastructure |
| AAM | Advanced Air Mobility |
| AI | Artificial Intelligence |
| AOBPS | Automatic Onboard Pilot System |
| ATM | Air Traffic Management |
| AUAV | Autonomous UAV |
| CapEx | Capital Expenditure |
| CPS | Cyber-Physical System |
| CVRP | Capacitated VRP |
| DAL | Development Assurance Level |
| DCVRP | Distance-Contrained VRP |
| DDoS | Distributed Denial of Service |
| FAA | Federal Aviation Administration |
| GCS | Ground Control Station |
| HAP | High-Altitude Plataform |
| LAP | Low-Altitude Platform |
| LMD | Last-Mile Delivery |
| LMDD | Last-Mile Delivery Drone |
| MEC | Multi-Access Edge Computing |
| mMTC | Massive Machine-Type Communication |
| MPC | Model Predictive Control |
| OP | Operation Research |
| OpEx | Operating Expenses |
| POW | Proof-of-Work |
| PVRP | Periodic VRP |
| QoS | Quality of Service |
| SLA | Service-Level Agreement |
| SoS | System of Systems |
| TPM | Tradable Permit Model |
| UAS | Unmanned Aircraft Systems |
| UAT | Urban UAV Traffic |
| UAV | Unmanned Aerial Vehicle |
| UMT | Urban Motorways Traffic |
| URLLC | Ultra-Reliable Low-Latency Communication |
| UTM | Unmanned Traffic Management |
| V2I | Vehicle to Infrastructure |
| V2V | Vehicle to Vehicle |
| VRP | Vehicle Routing Problem |
| VRPB | VRP with Backhauls |
| VRPPD | VRP with Pickup and Delivery |
| VRPTW | VRP with Time-Window Constraints |

## REFERENCES

[1] K. Dorling, J. Heinrichs, G. G. Messier, and S. Magierowski, “Vehicle routing problems for drone delivery,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 47, no. 1, pp. 70–85, 2017.

[2] V. Chamola, V. Hassija, V. Gupta, and M. Guizani, “A comprehensive review of the covid-19 pandemic and the role of iot, drones, ai, blockchain, and 5g in managing its impact,” *IEEE Access*, vol. 8, pp. 90 225–90 265, 2020.

[3] J. Olsson, D. Hellström, and H. Pålsson, “Framework of last mile logistics research: A systematic review of the literature,” *Sustainability*, vol. 11, no. 24, 2019.

[4] D. Schneider, “The delivery drones are coming,” *IEEE Spectrum*, vol. 57, no. 1, pp. 28–29, 2020.

[5] F. Borghetti, C. Caballini, A. Carboni, G. Grossato, R. Maja, and B. Barabino, “The use of drones for last-mile delivery: A numerical case study in milan, italy,” *Sustainability*, vol. 14, no. 3, 2022. [Online]. Available: https://www.mdpi.com/2071-1050/14/3/1766

[6] Q. M. Ha, Y. Deville, Q. D. Pham, and M. H. Hà, “On the min-cost traveling salesman problem with drone,” *Transportation Research Part C: Emerging Technologies*, vol. 86, pp. 597 – 621, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0968090X17303327

[7] M. Mozaffari, W. Saad, M. Bennis, Y. Nam, and M. Debbah, “A tutorial on uavs for wireless networks: Applications, challenges, and open problems,” *IEEE Communications Surveys Tutorials*, vol. 21, no. 3, pp. 2334–2360, 2019.

[8] M. Alwateer and S. W. Loke, “On-drone decision making for service delivery: Concept and simulation,” in *2019 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, 2019, pp. 937–942.

[9] NASA, “What is Unmanned Aircraft Systems Traffic Management?” https://www.nasa.gov/ames/utm, 2021, accessed: 2022-10-14.

[10] ——, “Advanced Air Mobility Mission Overview,” https://www.nasa.gov/aam/overview/, 2021, accessed: 2022-10-14.

[11] E. Frachtenberg, “Practical drone delivery,” *Computer*, vol. 52, no. 12, pp. 53–57, 2019.

[12] F. A. N. Verri, C. A. C. Marcondes, D. S. Loubach, E. F. Sbruzzi, J. C. Marques, L. A. P. Júnior, and M. R. O. A. Máximo, “An analysis on tradable permit models for last-mile delivery drones,” *IEEE Access*, vol. 8, pp. 186 279–186 290, 2020.

[13] E. Frachtenberg, “Practical drone delivery,” *Computer*, vol. 52, no. 12, pp. 53–57, 2019.

[14] S. Kern, D. Geister, and B. Korn, “City-atm — demonstration of traffic management in urban airspace in case of bridge inspection,” in *2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC)*, 2019, pp. 1–10.

[15] G. Brunner, B. Szebedy, S. Tanner, and R. Wattenhofer, “The urban last mile problem: Autonomous drone delivery to your balcony,” in *2019 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2019, pp. 1005–1012.

[16] R. Khan, S. Tausif, and A. Javed Malik, “Consumer acceptance of delivery drones in urban areas,” *International Journal of Consumer Studies*, vol. 43, no. 1, pp. 87–101, 2019.

[17] J. Park, S. Kim, and K. Suh, “A comparative analysis of the

environmental benefits of drone-based delivery services in urban and rural areas," *Sustainability*, vol. 10, no. 3, 2018. [Online]. Available: https://www.mdpi.com/2071-1050/10/3/888

[18] P. Chamoso, A. González-Briones, A. Rivas, F. Bueno De Mata, and J. M. Corchado, "The use of drones in spain: Towards a platform for controlling uavs in urban environments," *Sensors*, vol. 18, no. 5, 2018. [Online]. Available: https://www.mdpi.com/1424-8220/18/5/1416

[19] P. Boccadoro, D. Striccoli, and L. A. Grieco, "An extensive survey on the internet of drones," *Ad Hoc Networks*, vol. 122, p. 102600, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1570870521001335

[20] G. Grieco, G. Iacovelli, P. Boccadoro, and L. A. Grieco, "On the design of the drone control layer," in *European Wireless 2021; 26th European Wireless Conference*. VDE, 2021, pp. 1–7.

[21] J. Besada, I. Campaña, L. Bergesio, A. Bernardos, and G. de Miguel, "Drone flight planning for safe urban operations," *Personal and Ubiquitous Computing*, pp. 1–20, 2020.

[22] M. Doole, J. Ellerbroek, V. L. Knoop, and J. M. Hoekstra, "Constrained urban airspace design for large-scale drone-based delivery traffic," *Aerospace*, vol. 8, no. 2, 2021. [Online]. Available: https://www.mdpi.com/2226-4310/8/2/38

[23] M. Doole, J. Ellerbroek, and J. Hoekstra, "Estimation of traffic density from drone-based delivery in very low level urban airspace," *Journal of Air Transport Management*, vol. 88, p. 101862, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0969699719304004

[24] ——, "Drone delivery: Urban airspace traffic density estimation," *8th SESAR Innovation Days, 2018*, 2018.

[25] W. Fan and X. Jiang, "Tradable mobility permits in roadway capacity allocation: Review and appraisal," *Transport Policy*, vol. 30, pp. 132–142, nov 2013. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0967070X13001352

[26] D. K. Brands, E. T. Verhoef, J. Knockaert, and P. R. Koster, "Tradable permits to manage urban mobility: Market design and experimental implementation," *Transportation Research Part A: Policy and Practice*, vol. 137, pp. 34 – 46, 2020.

[27] J. Wang, C. Jiang, Z. Han, Y. Ren, R. G. Maunder, and L. Hanzo, "Taking drones to the next level: Cooperative distributed unmanned-aerial-vehicular networks for small and mini drones," *IEEE Vehicular Technology Magazine*, vol. 12, no. 3, pp. 73–82, 2017.

[28] T. Akamatsu and K. Wada, "Tradable network permits: A new scheme for the most efficient use of network capacity," *Transportation Research Part C: Emerging Technologies*, vol. 79, pp. 178–195, 2017.

[29] Z. R. Bogdanowicz, "Flying swarm of drones over circulant digraph," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 53, no. 6, pp. 2662–2670, 2017.

[30] J. Morales, G. Rodriguez, G. Huang, and D. Akopian, "Toward uav control via cellular networks: Delay profiles, delay modeling, and a case study within the 5-mile range," *IEEE Transactions on Aerospace and Electronic Systems*, pp. 1–1, 2020.

[31] S. Siewert, M. Andalibi, S. Bruder, I. Gentilini, and J. Buchholz, "Drone net architecture for uas traffic management multi-modal sensor networking experiments," in *2018 IEEE Aerospace Conference*, 2018, pp. 1–18.

[32] A. Das, S. Shirazipourazad, D. Hay, and A. Sen, "Tracking of multiple targets using optimal number of uavs," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 55, no. 4, pp. 1769–1784, 2019.

[33] T. Vidal, G. Laporte, and P. Matl, "A concise guide to existing and emerging vehicle routing problem variants," *European Journal of Operational Research*, 2019.

[34] G. Laporte, "Fifty years of vehicle routing," *Transportation Science*, vol. 43, no. 4, p. 408–416, Nov. 2009. [Online]. Available: https://doi.org/10.1287/trsc.1090.0301

[35] B. Eksioglu, A. V. Vural, and A. Reisman, "The vehicle routing problem: A taxonomic review," *Computers & Industrial Engineering*, vol. 57, no. 4, pp. 1472–1483, 2009.

[36] J. Caceres-Cruz, P. Arias, D. Guimarans, D. Riera, and A. A. Juan, "Rich vehicle routing problem: Survey," *ACM Comput. Surv.*, vol. 47, no. 2, Dec. 2014.

[37] H. N. Psaraftis, M. Wen, and C. A. Kontovas, "Dynamic vehicle routing problems: Three decades and counting," *Networks*, vol. 67, no. 1, pp. 3–31, 2016.

[38] A. Richards and J. P. How, "Robust variable horizon model predictive control for vehicle maneuvering," *International Journal of Robust and Nonlinear Control*, vol. 16, no. 7, pp. 333–351, 2006.

[39] R. J. Afonso, M. R. Maximo, and R. K. Galvão, "Task allocation and trajectory planning for multiple agents in the presence of obstacle and connectivity constraints with mixed-integer linear programming," *International Journal of Robust and Nonlinear Control*, vol. 30, no. 14, pp. 5464–5491, 2020. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/rnc.5092

[40] R. Siegwart, I. R. Nourbakhsh, and D. Scaramuzza, *Introduction to Autonomous Mobile Robots*. Cambridge, Massachusetts, USA: The MIT Press, February 2011.

[41] S. M. LaValle, *Planning Algorithms*. Cambridge, U.K.: Cambridge University Press, 2006, available at http://planning.cs.uiuc.edu/.

[42] Mark Roboff, "Opinion: How To Demonstrate AI System's Safety," https://aviationweek.com/aerospace/emerging-technologies/opinion-how-demonstrate-ai-systems-safety, 2020, accessed: 2022-10-14.

[43] M. Saad, J. Spaulding, L. Njilla, C. Kamhoua, S. Shetty, D. Nyang, and D. Mohaisen, "Exploring the attack surface of blockchain: A comprehensive survey," *IEEE Communications Surveys Tutorials*, vol. 22, no. 3, pp. 1977–2008, 2020.

[44] A. Kumari, S. Tanwar, S. Tyagi, and N. Kumar, "Blockchain-based massive data dissemination handling in iiot environment," *IEEE Network*, vol. 35, no. 1, pp. 318–325, 2021.

[45] L. Lao, Z. Li, S. Hou, B. Xiao, S. Guo, and Y. Yang, "A survey of iot applications in blockchain systems: Architecture, consensus, and traffic modeling," *ACM Comput. Surv.*, vol. 53, no. 1, Feb. 2020. [Online]. Available: https://doi.org/10.1145/3372136

[46] Y. Xiao, N. Zhang, W. Lou, and Y. T. Hou, "A survey of distributed consensus protocols for blockchain networks," *IEEE Communications Surveys Tutorials*, vol. 22, no. 2, pp. 1432–1465, 2020.