Agent-Based Simulation of Unmanned Aerial Vehicles in Civilian Applications: A Systematic Literature Review and Research Directions

Yazan MUALLA[a], Amro NAJJAR[b], Alaa DAOUD[c], Stéphane GALLAND[a], Christophe NICOLLE[d], Ansar-Ul-Haque YASAR[e], Elhadi SHAKSHUKI[f]

[a]*CIAD, Univ. Bourgogne Franche-Comté, UTBM, F-90010 Belfort, France*
[b]*Umeå University, 907 36 Umeå, Sweden*
[c]*Mines Saint Étienne, 158, cours Fauriel CS 62362 42023 Saint-Étienne, France*
[d]*CIAD, Univ. Bourgogne Franche-Comté, UB, F-21000 Dijon, France.*
[e]*Transportation Research Institute (IMOB), Hasselt University, 3590 Diepenbeek, Belgium.*
[f]*Acadia University, Wolfville, NS, B4P 2R6, Canada.*

Abstract

Recently, the civil applications of Unmanned Aerial Vehicles (UAVs) are gaining more interest in several domains. Due to operational costs, safety concerns and legal regulations, Agent-Based Simulation (ABS) are commonly used to implement models and conduct tests. This has resulted in abundant research works addressing ABS in UAVs. This paper aims at providing a comprehensive overview of this domain by conducting a Systematic Literature Review (SLR) on relevant research works in the previous ten years. Eight research questions are considered at the beginning of the review, including the understanding of the evolution of UAV simulations in multi-agent systems in the last decade, identifying the key components of the agent-based UAV models and frameworks. From the SLR results, seven research directions are highlighted, including problems related to autonomy, explainability, security, flight duration, integration within smart cities regulations, and validation & verification of the models.

Keywords: Multi-Agent Systems, Agent-Based Simulation, Unmanned Aerial Vehicle, Systematic Literature Review, Civil Applications

1. Introduction

Unmanned Aerial Vehicles (UAVs), most commonly known as drones, are becoming increasingly popular for civil applications in several domains such as agriculture, transportation, products delivery, energy, emergency response, telecommunication, environment preservation and infrastructure. According to Teal Group's 2018 World Civil UAV Market Profile and Forecast report [1], civil UAV production will total US$88.3 billion in the next decade, with a 12.9% compound annual growth rate. The same report states

*Corresponding author
Email address: yazan.mualla@utbm.fr (Yazan MUALLA)

that the civil UAV sector promises to be the most dynamic growing sector of the world aerospace industry in the following years. Furthermore, fueled by a growing demand from governments and private consumers, civil UAV market is expected to quadruplicate over the next decade. The key features making the UAVs interesting to use are their small dimensions, ability to take-off and land vertically, good maneuverability, simple mechanics, and payload capability. These features make UAVs accessible for civil applications deployed in urban environment where they started to be used as a practical solution for cost-efficient and rapid delivery. One of the mostly known examples is Amazon Prime Air where UAVs are used to deliver packages to customers [2, 3]. Another important example that comes from the health-care sector is the transportation of medical samples and products using a UAV health-care delivery network [4]. Even though there were some concerns about the safety of this procedure in such transportation environments, it has been shown that the UAV transportation systems are a viable option for the transportation of medical samples and products [5]. Another notable example comes from the Oil&Gas industry. The tragic Deepwater Horizon accident in the Gulf of Mexico in 2010, as well as the increase in deepwater offshore activity, have increased public interest in Health, Safety and Environment (HSE) counter-measures for sub-surface releases of hydrocarbons. To attain a proper contingency planning, response managers urge for a system allowing instant detection and characterization of accidental releases. To meet these requirements, a heterogeneous robotic system involving UAVs was developed for early detection of hydrocarbons [6].

Despite these initial successes, UAV technology is still in its early stages of development. For this reason, considerable limitations should be addressed before a large scale deployment of UAVs in civil applications is possible. The main drawbacks to mention are related to the safety of humans facing UAV failures [7], and the high amount of energy consumed by these devices coupled with their limited battery life [8]. Moreover, since civil applications are mostly deployed in urban environments involving multiple actors, considerable research efforts should be dedicated to enhancing the UAV perceptual intelligence required to coordinate complex environments [9], and more importantly to address the possible consequences, especially on people safety, of a mechanical failure that may cause a crash and the costs of such incident.

To guarantee it is safe for UAVs to fly over people's heads and to reduce costs, different scenarios must be modeled and tested. However, currently, most of the regulations in force restrict the use of UAVs in cities. For this reason, to perform tests with real UAVs, one needs access to expensive hardware and field tests that are costly, time-consuming, and require trained and skilled people to pilot and maintain the UAVs. Moreover, in the field, it may also be hard to reproduce the same scenario several times [10]. To overcome these limitations, simulation frameworks have been developed to allow transferring real-world scenarios into executable models (*i.e.* simulating UAV activities in a digital environment).

An agent is defined as an autonomous software entity that is *situated* in some environment and where it is capable of actions and coordination with other agents to achieve specific goals [11]. For these reasons, the resulting Multi-Agent System (MAS) technology have been established as a suitable platform for implementing autonomous behavior and decision-making in computer systems [12, 13]. An Agent-Based Simulation (ABS) model is a set of interacting intelligent entities that reflect, within an artificial environment, the relationships in the real world [14]. The results make ABS a natural step forward into understanding and managing the complexity of today's business and social systems. The use of ABS frameworks (henceforth frameworks for short) for UAVs is gaining more interest in complex civil application scenarios where coordination and cooperation are necessary, like for example in the study of the swarms' formation of multiple UAVs [15].

Despite this promising research efforts, very few works were dedicated to understand and analyze existing works using ABS in civil UAV applications. Very few surveys outlined a comprehensive set of research questions pertaining to multi-agent simulations for civil UAV applications. There are works comparing frameworks in the literature. Nonetheless, these works either: *(i)* address other applications such as energy consumption, geo-spatial applications, or parallel & distributed applications, or *(ii)* focus on measuring and assessing the performance of frameworks.

Against this background, the objective of this paper is to conduct a Systematic Literature Review (SLR) of the research addressing MAS in civil UAV applications. This SLR aims to identify the most important research questions, analyze the literature, and outline key challenges and research directions. To the best of our knowledge, no systematic literature study has been conducted to review the research addressing ABS in civil UAV applications.

The rest of this paper is organized as follows: Section 2 states and defines the SLR methodology adapted from [16, 17]. Section 3 details the analysis and results of the SLR. Based on the results of the SLR, Section 4 identifies the major research directions. Section 5 discusses the related works. Section 6 concludes this paper and identifies future research perspectives.

2. SLR Methodology

Recently, research on computer science in general and on artificial intelligence, in particular, has witnessed a significant increase both qualitatively and quantitatively. For this reason, SLRs are becoming popular to help analyze the evolutions of these domains. Kitchenham and Charters [18] define SLR as follows: "*A form of secondary study that uses a well-defined methodology to identify, analyze and interpret all available evidence related to a specific research question in a way that is unbiased and (to a degree) repeatable.*" Where *secondary study* refers to "*a study that reviews all the primary studies relating to a specific research question.*" In this paper, we define a *primary study* as a research paper addressing a specific research question in the domain of UAVs. The aim of SLRs can be threefold [18]: *(i)* to summarize the existing evidence concerning a technology, *(ii)* to identify gaps in the existing research in order to suggest areas for future investigation, and *(iii)* to provide a framework/background allowing to position new research activities.

With these goals in mind, we base our systematic literature review on [16, 17], which are among the most common methodologies for computer science SLRs. Such an approach ensures rigorousness, fairness, and reproducibility. Figure 1 illustrates the review process.

This section is organized as follows. First, Section 2.1 highlights the research questions. Second, Section 2.2 explains the review protocol, how conflicts are resolved and biases overcome. Third, in Section 2.3, the defined protocol is executed and the review process is undertaken (document collection, conflict resolution, *etc.*).

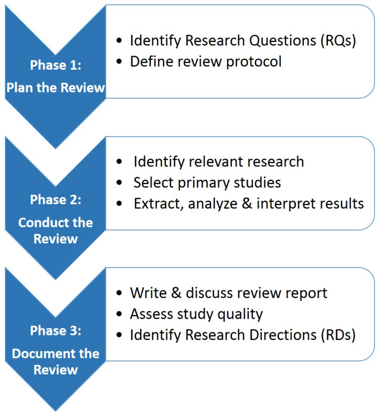


Figure 1: The systematic literature review process (the figure adapted from [19, 20]).

2.1. Key Research Questions

Following the Goal Question Metric (GQM) [17], we define our generic free-form question as "Discover and evaluate the possible scientific MAS contributions to the civil UAV applications." On the field, it may be hard to deploy UAVs because of safety and security issues. Moreover, it may be difficult to reproduce the same scenario several times in order to test hypotheses and validate the UAV behaviors. ABS is a suitable tool for overcoming these limitations. In order to reflect this aspect, the generic free-form question becomes "Discover and evaluate the possible scientific ABS contributions to the civil UAV applications." This question is broken down into Research Questions (RQs) exploring key issues in ABS for civil UAV applications. The research questions are mainly concerned with this type of applications. More specifically, these questions cover the purposes, issues, used simulation frameworks, publications date, authors, countries, *etc.* These questions were formulated based on the authors' knowledge in the UAV and ABS domains as well as the common practices from other SLRs. In what follows, eight RQs are considered within this review, and listed below:

RQ1: Understand the evolution of UAV simulations in MAS in the last decade in terms of key contributors (research labs), geographic distributions, growth over the years. Having answers to this RQ will help researchers determine the liveliness of the MAS modeling domain for civil UAV applications. Moreover, this RQ will enable highlighting the active contributors. In this way, it may help researchers to find quickly new contributions in the domain.

RQ2: Identify the main UAV *research topics* and civil *application domains* addressed in the studied papers. On one hand, we consider it is important to determine active research topics in order to highlight less active research topics where more contributions are needed. On the other hand, a synthetic view of the application domains will enable researchers to determine the typical applications for their research, and possibly identify new application domains.

RQ3: Identify the artificial intelligence models scaffolding the solutions in the reviewed papers. This RQ is set up in order to have a view on the types of agent architectures used for implementing civil UAV applications. It also helps researchers understand the potential of these agent & system architectures, and their limitations. The following sub-questions focus on specific types of models and architectures.

RQ3.1: Investigate the agent architecture used in the solution (*e.g.* cognitive agent, Belief-Desire-Intension (BDI) agent, reactive agent, *etc.*).

RQ3.2: Investigate the architecture of the system (decentralized vs centralized).

RQ3.3: Investigate whether the proposed model (agent or simulation architectures) includes the environment, and how the UAVs interact with their environment.

RQ4: Investigate whether Internet-of-Things (IoT), pervasive systems or ubiquitous systems are considered in these models. IoT is a technological domain that is more and more used within smart cities. This RQ will highlight if IoT is considered, or not, as a component of the system in civil UAV applications. It will also highlight how IoT devices and UAVs are interacting together.

RQ5: Identify the communication technology used by the UAVs to connect to other entities: In order for UAVs to be deployed and used in their environment, especially in smart cities, they could either be connected to infrastructure entities, *i.e.* Vehicle-to-Infrastructure (V2I), or to other UAVs, *i.e.* Vehicle-to-Vehicle (V2V). Understanding the communication technology of the UAV in the proposed simulated works is key to assess whether frameworks are capable of producing realistic simulations.

RQ6: Identify the main model category used by the proposed work (*e.g.* mathematical, algorithm-based, *etc.*) This RQ is set up in order to determine if the contributions to civil UAV applications are formal or semi-formal. It will lead us to a statement and arguments regarding the validation of UAV models.

RQ7: Assess the evaluation of the proposed model: Simulation for civil UAV applications needs scenarios to be set up, and the use of datasets may help to create such simulation in a realistic way. This RQ assesses if the evaluation relies on a dataset, on a generated synthetic dataset, or no dataset. This will highlight the different datasets, and the scenarios (if no dataset is used) from literature.

RQ8: Identify the simulation frameworks used to implement the proposed solutions, and the main advantages & disadvantages of each framework especially if it excels in a specific civil UAV application domain. This RQ is related to the technological means used by the researchers for implementing the MAS for civil UAV applications. It should help researchers to determine and choose the best framework for their own model implementation.

2.2. Defining The Review Protocol

As shown in Fig. 1, defining the *review protocol* is done right after having set the RQs. The protocol we used for this article involves the following steps. First Section 2.2.1 chooses the databases used as sources of information and defines the *stop criterion*. Section 2.2.2 defines the exclusion/inclusion criteria used by the reviewers to exclude/include articles chosen from the databases before the stop criterion was triggered. Section 2.2.3 presents the quality criteria used by the reviewers to assess the quality of the primary studies. Finally, Section 2.2.4 explains the policies used to mitigate subjective biases and resolve conflicts.

2.2.1. Database Selection

This process is composed of the following couple of steps:

a) IEEE Xplore, ACM Digital Library, and Google Scholar are selected as the three databases constituting the source of information. The selection of the first two databases is obvious in computer science. Google Scholar is selected because it provides a large list of documents that are not indexed into the two previous databases, *e.g.* papers from conference proceedings, Ph.D. and Master theses. Despite not being peer-reviewed, these articles obtained from Google scholar might be important given that the interest in the studied topic is rapidly increasing in the recent years.

b) The databases are queried with a set of keywords. These keywords are devised based on the authors knowledge of the UAV and MAS domains.

When queried with these keywords, each database responded with a set of articles that are considered by the reviewing process. The numbers of articles to be produced by the queries is relatively large for IEEE Xplore, ACM DL, and Google Scholar databases. However, only a few of these articles were relevant to the research questions raised in the previous section. For this reason, as in [21], the following stop criterion was applied: "*Stop the collecting of articles after a sequence of 10 titles, completely incoherent with the query, appeared in the list.*" Determining whether an article is coherent is left to the reviewers' subjective view when they deemed that there was no adherence between the query performed on the database and the title/abstract of the article appearing in the result.

2.2.2. Inclusion and exclusion criteria definition

The articles appearing in the resulting pool of articles are not necessarily useful to answer the research questions defined above. For this reason, most of literature review methodologies [20, 21] apply a set of exclusion criteria to retain only pertinent articles. The set of exclusion criteria, defined by the authors, is listed below:

ExC1: *Not a recent research work* — Papers that were published before 2008, *i.e.* with a publication year < 2008, are excluded. It is assumed that the non-recent research is not up-to-date due to the high evolution rate of the UAV technologies and usages.

ExC2: *Invalid type of paper, the document is a poster or a demo* — It is assumed that a poster or a demo cannot give enough details on the contributions, as there is no enough contributed content for evaluation. Ph.D. theses, Master theses, technical reports are included.

ExC3: *Invalid type of paper, the paper is a survey* — It is assumed that the survey papers (*i.e.* secondary studies) do not provide contributions directly on the UAV models nor UAV technologies.

ExC4: *Impossible to access the paper text* — It is impossible to evaluate a paper when its text cannot be accessed (PDF download, online text, *etc.*)

ExC5: *Extended paper* — The paper is extended by another paper by the same authors. The contributions in the extended paper are enclosing the ones from the original paper, so that the latter is excluded.

ExC6: *Unrelated to UAV* — The paper has no contribution neither in the fields of UAV models nor UAV technologies.

ExC7: *Unrelated to agent-based systems* – The paper has no contribution in the fields of agent-based technologies nor distributed artificial intelligence. Generally, only multi-agent applications are included, but if the system includes agents that communicate with other entities like Infrastructure (refer to ExC14), then they will also be included.

ExC8: *UAV manufacturing only* — The paper's contribution is related to the manufacturing of UAVs, *i.e.* it is related to the design and implementation of hardware, mechanic or electronic components.

ExC9: *Positioning system only* — The paper's contribution is related to the definition of novel positioning systems within UAVs. The contribution focuses on a perception model that enables each UAV to compute its position in the air.

ExC10: *UAV detection system only* — The paper's main concern is UAV detection within the system. In other words, the contribution is not related to UAV behavior, but to a system that is detecting the UAV in the air.

ExC11: *No civil application* — The paper contains only military applications that cannot be applied to civil fields.

ExC12: *No simulation contribution* — The paper's contribution cannot be applied to UAV simulation. In several papers, the model is deployed on real UAVs without simulation. Even if the paper has not a direct contribution to UAV simulation, if the proposed model could be deployed within a simulation environment, the corresponding paper is not excluded.

ExC13: *Simulation in 2D* — The paper's contributions include a simulation model in 2D that cannot be extended to the third dimension. It is assumed that 2D simulation of UAVs cannot achieve the highly detailed reproduction of the UAV behavior when they are in the air. Additionally, they do not provide detailed environment model. However, to estimate the portion of 2D and 3D simulations, we keep track of this exclusion criterion, and plot how many papers were excluded due to being based on 2D simulation (c.f. Section 2.3).

ExC14: *No UAV cooperation nor interaction* — The paper contains a contribution related to neither the cooperation of UAVs nor interaction between UAVs. V2I and V2V communications are assumed to be the base framework for supporting UAV interaction. If a paper contains a model for a single UAV that has V2I communication, it is not excluded since this type of models could be duplicated

Table 1: The Quality Questions

#	**Quality Question**
Q1	Do the authors provide a sound rationale (*i.e.* motivation) for their work?
Q2	Is there an adequate description of the context in which the study has been conducted?
Q3	Is there a clear statement of the findings and the results including data that support the findings?
Q4	Are the limitations of the study discussed and highlighted?

in order to set up a more complex simulation environment based on stigmergy[1] communication.

ExC15: *Human interaction with no autonomous UAV* — The paper contains only a contribution related to the interaction between humans and the UAVs, for piloting or controlling the UAVs. In other words, the contribution focuses on the human-UAV interaction without autonomous control of the UAVs.

These exclusion criteria are applied to the documents in two steps. In the first *coarse-grained* step, the articles were only eliminated if their titles and abstracts satisfied at least one of the exclusion criteria. In the second *fine-grained* step, the remaining papers are screened but this time reading the whole body of the paper.

2.2.3. Quality Criteria

As has been recommended by Kitchenham and Charters [18] and Kitchenham et al. [23], most of the SLRs rely on quality criteria allowing to assess the quality of primary studies, (c.f. [20, 21] for another example). Defining quality criteria as a list of questions is a common practice. Typical quality criteria include: *(i)* whether the authors of primary studies provided a sound rationale for their work, *(ii)* details provided about the context and the design of the technical evaluation, *(iii)* the statement of the results.

Note that, as it is the case in [20], the quality criteria are not used to exclude/include primary studies. Rather, they are used to report the overall quality of primary studies included by the SLR. To assess the quality of the reviewed works, Table 1 defines four quality questions, adapted from [20]. Note that Q3 is of particular interest since having an overview of the quality of evaluations of the set of articles dealing with a specific research question can give a good idea on the maturity of this research question.

2.2.4. Biases and disagreements

In order to mitigate the subjectivity of the reviewing process, certain measures were taken to overcome biases and resolve conflicts. In particular, each task of Phase 2 in Fig. 1 was conducted by at least 2 reviewers. Thus, as shall be discussed later, the steps of article exclusion/inclusion (*c.f.* Section 2.2.2), answering the RQs, and quality assessment (*c.f.* Section 2.2.3), were undertaken by at least two reviewers for each article. A third reviewer intervened as a referee to resolve a conflict in the exclusion/inclusion and in the RQ answering steps. As for the quality assessment task, quality assessments provided by reviewers for each article were averaged.

[1]This term has been introduced by the French biologist Pierre-Paul Grassé in 1959 for describing the termite behavior. It is defined as: "*Stimulation of the workers by the work that they performed.*" This term expresses the notion that the actions of an agent leave signs in the environment, these signs are perceived by itself and other agents, which determine their next actions [22]

Table 2: The results of the coarse-grained exclusion/inclusion step

Database	**Number of Papers**	**Percentage**
Selected from Keyword Set 1	131	$\approx 41\%$
Selected from Keyword Set 2	185	$\approx 59\%$
Sum from Set 1 & 2	316	=100%
Total Included	123	$\approx 39\%$
Total Excluded	193	$\approx 61\%$

Table 3: The results of the fine-grained exclusion/inclusion step

	Number of Papers	**Percentage**
Included	30	$\approx 24\%$
Excluded	70	$\approx 57\%$
Conflict	23	$\approx 19\%$
Referee Included	12	$\approx 10\%$
Total Included	42	$\approx 34\%$
Total Excluded	81	$\approx 66\%$

2.3. Performing The Review

This section gives an account of how the SLR has been conducted and discusses the results of the exclusion/inclusion step. Two keyword sets were applied to the three databases (IEEE Xplore, ACM DL, and Google Scholar). The first keyword set is {`UAV`, `agent`, `simulation`}, whereas the second keyword set is {`UAV`, `agent-based simulation`, `drones`, `civil`, `multi-agent systems`}. A stop criterion of 10 articles was applied to the results of each keyword set and database. After the stop criterion was applied, the total number of articles retained was 316. The next step is to apply the coarse-grained exclusion/inclusion step. Note that since this step screens papers based on their titles and abstracts, some exclusion criteria might be more helpful than others (*e.g.*ExC1 and ExC2).

Table 2 shows the results of the *coarse-grained exclusion/inclusion step*. As can be seen from the third row in the table, the total number of papers acquired from the two sets combined is 316 papers. The results listed in Table 2 show that about 39% (123 papers) of the total number of papers were included by the coarse-grained exclusion/inclusion step.

Fig. 2 plots the geographical distributions of papers before the fine-grained inclusion/exclusion step. The number of papers published by US researchers is highest worldwide. The geographical distribution of the papers could be partly explained by the investment rate in R&D in each country [24], illustrated by Fig. 3. The notable exception is China, which invests 2% of its GDP (US\$370,589.7$M) but has a number of papers equal to France (2.3% of GPP, US\$$60,781.6$M). Another notable point is the Czech Rep., which has 11 papers with an average R&D investment (2% of GPP, US\$$6,719$M). All the authors from Czech Rep. are collaborating with partners within US-funded projects. This fact may explain the high number of publications for this country. From Fig. 2, it is interesting to note that, even if civil UAV-related regulations in USA are less restrictive than in Europe (*c.f.* Section RD6), the number of papers over Europe is two times higher than the number of papers in North America. This can be attributed to the EU research policy that enforces funding on breaking technologies, such as UAVs. Fig. 4 plots the number of papers per year since 2008 after the coarse-grained exclusion/inclusion step.

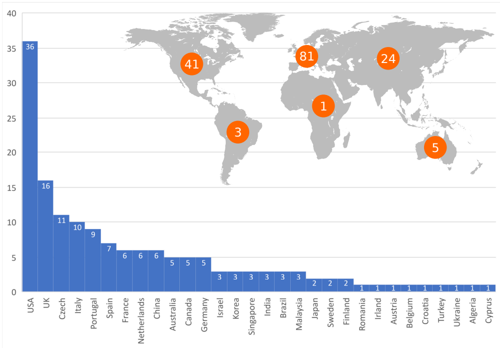


Figure 2: The geographical distribution of papers after the coarse-grained exclusion/inclusion step.

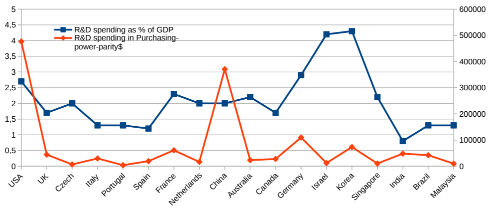


Figure 3: The investments in R&D for the 18 most publishing countries [24] after the coarse-grained exclusion/inclusion step.

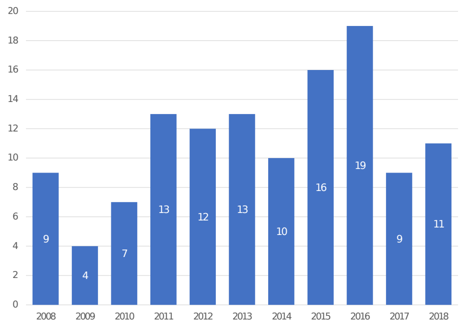


Figure 4: The number of papers per year after the coarse-grained exclusion/inclusion step.

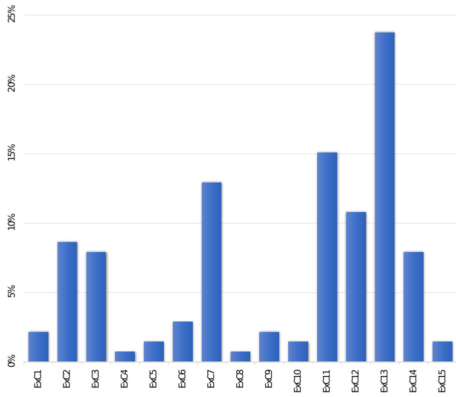


Figure 5: The percentage of excluded papers per exclusion criteria in the fine-grained exclusion/inclusion step.

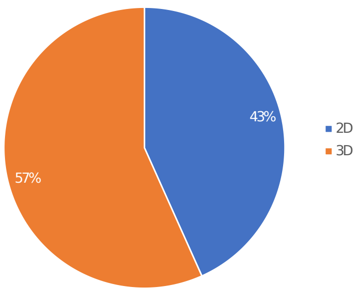


Figure 6: The percentage of papers with 2D simulation scenario vs. papers with 3D simulation scenario.

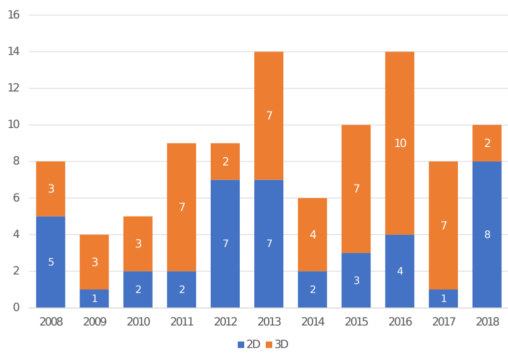


Figure 7: The number of papers with 2D and 3D simulation scenarios per year.

The number of papers grows with a slop of 0.6364.

The next step within the review process is the *fine-grained exclusion/inclusion step*. It is applied to the 123 papers selected during the previous step. More specifically, the content of the paper is screened and the paper is excluded if it satisfies at least one of the 15 exclusion criteria defined in Section 2.1. Table 3 shows the results of the fine-grained exclusion/inclusion step. Each paper was reviewed by at least two reviewers. If all the reviewers of a paper decided that it should be included in the review, the paper is included (*c.f.* the first row of the table). The paper is excluded if all of its reviewers agreed upon its exclusion (the second row of the table). Otherwise, in case of a conflict among reviewers, we relied on a referee to resolve this conflict. If the referee accepts the paper, then it is included in the review. As shown in the table, 23 papers (about 19% of the total number of the papers) generated conflicts among the reviewers. Out of these papers, 12 papers were added by the referee raising the total number of included papers to 42 (about 34% of the papers remaining after the coarse-grained exclusion/inclusion step). For a list of the 42 papers, please refer to Table 4.

Most of the papers screened in the fine-grained step were highly related to the RQs. As indicated by Table 3, 66% of them were excluded, and Fig. 5 plots the percentage of excluded papers per exclusion criterion. Note that some papers were excluded because of satisfying multiple exclusion criteria. Examining the reviews shows that approximately 24% of excluded papers were excluded because of ExC13, which filters out a paper if it is not addressing 3D simulation scenario. Fig. 6 compares the percentage of papers presenting 2D and 3D simulations in the pool of papers before the fine-grained exclusion/inclusion (whose total number is 123), excluding 26 papers that were not determined either they use simulation or not, or either they are 2D or 3D. As can be seen from the figure, despite ExC13 being the most common cause for exclusion, the majority of the papers whose simulation dimension was determined ended up addressing 3D simulations. In order to understand the general tendencies of 2D and 3D simulations, Fig. 7 plots the number of papers proposing 2D/3D simulations per year. As shown in the figure, the number of papers proposing 3D simulations is witnessing a confirmed and significant increase (2018 should not be considered since this review was conducted in August 2018). This is mainly due to the fact that UAV systems are intrinsically in three dimensions, and this third dimension must be included within the models in order to evaluate the behaviors of the UAVs regarding the safety concerns. Additionally, simulating UAVs in a 2D model forbids the deployment of the algorithms in real UAVs except in very specific cases in which the altitude of the UAVs is constant. Nevertheless, in this later case, the deployed algorithms must ensure that the UAVs remain at the same altitude regardless of the environment conditions.

This section offered a detailed account of how the review was performed and provided useful statistics about the included/excluded papers. Furthermore, it discussed the most common exclusion criteria. Next section presents and discusses the results of the SLR regarding the research questions presented in Section 2.1.

3. Results of the Review and Analysis

This section provides a detailed analysis of the SLR results. It analyzes the papers retained after the fine-grained exclusion/inclusion step and discusses each one of the RQs defined in Section 2.1 respectively. Note that the results are related to MAS in civil

UAV applications and are derived from the research questions and the exclusion criteria defined in the SLR methodology.

3.1. Demographic Data (RQ1)

To understand the evolution of UAV simulations in MAS in the last decade (stated as a question by RQ1), Fig. 8 plots the number of papers per year after the fine-grained exclusion/inclusion step. Despite a decrease in the number of papers in 2009 and 2012 (2018 should not be considered since this review was conducted in August 2018), it appears from the figure that there is a stable growth in the numbers of papers, with a slop of 0.2727. Furthermore, comparing the results of this figure with those of Fig. 4 confirms this observation since in Fig. 4, the number of papers witnesses a roughly stable growth between 2008 and 2016.

To understand the geographic distributions of the main contributors in the studied domain, Fig. 9 plots the number of papers per country after the fine-grained exclusion/inclusion step. Compared with Fig. 2, The number of papers published by US researchers is still highest worldwide. As previously noticed, researchers from the Czech Rep. are collaborating with partners within US-funding projects. This fact may explain the high number of publications for this country compared to its R&D investment, illustrated in Fig. 10. In the mentioned figure, it is interesting to note that, even if civil UAV-related regulations in USA are less restrictive than in Europe, the number of papers over Europe (32 papers) is three times higher than the number of papers in North America (9 papers). We explain this by the fact that the EU research policy enforces funding on breaking technologies, such as UAVs. Additionally, with a relatively lower R&D investment rate of EU countries (Fig. 10), researchers from these countries have fewer opportunities for funding UAV deployment on real fields. This pushes them to resort to simulation environments for validating the UAV behaviors before any deployment.

3.2. Research Topics & Application Domains (RQ2)

This section discusses the results and answers the research questions raised in RQ2 (*c.f.* Section 2.1). In particular, it deals with the research topics (Section 3.2.1) and the application domains (Section 3.2.2).

3.2.1. Research Topics

Subjects or issues that a researcher is interested in when conducting research on UAVs. These "research topics" provide the general directions to researchers for exploring, defining, and refining their ideas. Fig. 11 plots the main research topics addressed in the reviewed articles. The addressed research topics are:

T1: *Coordination* (13%), UAVs interact in order to coordinate their actions for reaching their common objectives;

T2: *Task Allocation* (11%) is the optimal dynamic (potentially distributed) assignment of tasks to the UAVs;

T3: *UAV Formation & Platooning* (11%) addresses the definition of flight formations for UAVs;

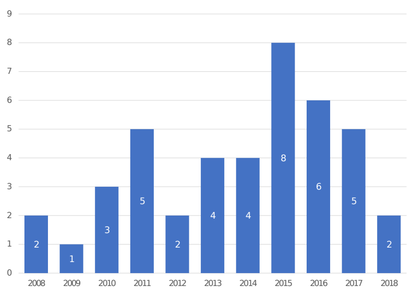


Figure 8: The number of papers per year after the fine-grained exclusion/inclusion step.

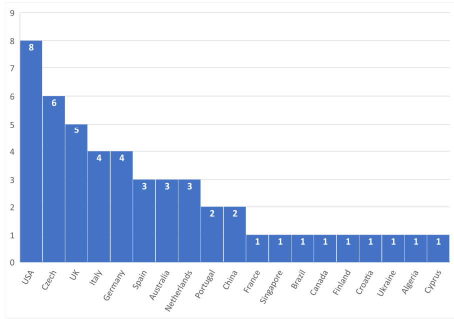


Figure 9: The geographical distribution of papers after the fine-grained exclusion/inclusion step.

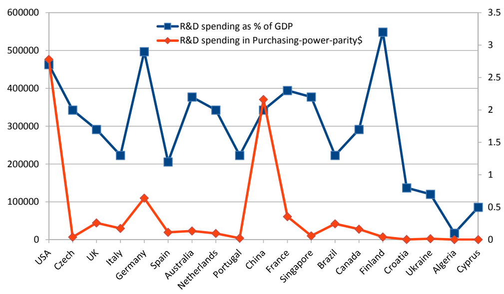


Figure 10: The investments in R&D [24] of the publishing countries after the fine-grained exclusion/inclusion step.

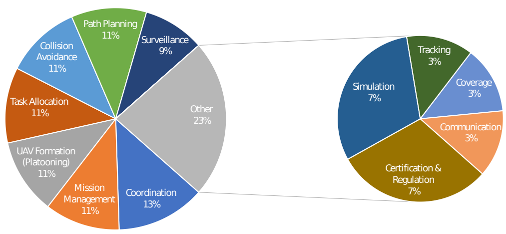


Figure 11: The main research topics related to civil UAVs applications.

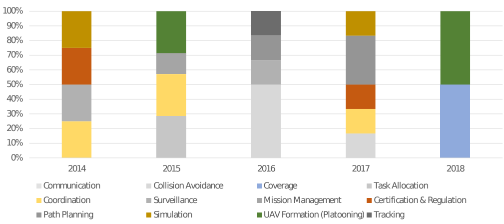


Figure 12: The main research topics related to civil UAVs in the last 5 years.

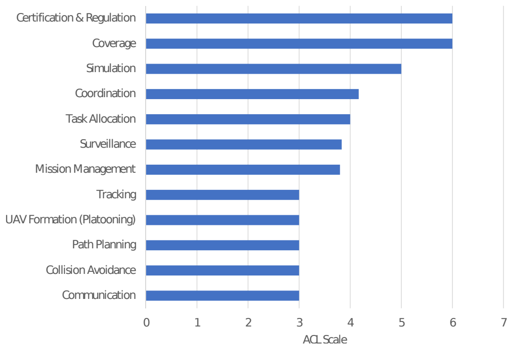


Figure 13: The average ACL for each research topic.

T4: *Collision Avoidance* (11%) allows to increase UAV safety by avoiding collisions among UAVs, persons, animals, and other objects;

T5: *Mission Management* (11%) addresses the optimal dynamic assignment of high-level missions, *i.e.* objectives, to UAVs. High-level missions are those where the UAVs rely on a high-level description of their objectives without many details and without human guidance;

T6: *Path Planning* (11%) focuses on the statical and dynamical computing of the best paths to fly along according to the environmental constraints;

T7: *Surveillance* (9%) enables UAVs to help the detection of dangerous and illegal situations;

T8: *Certification & Regulation* (7%) is related to the definition of regulations dedicated to UAVs, and of the associated certifications for UAVs or pilots;

T9: *Simulation* (7%) focuses on the design and implementation of developed simulation frameworks to understand and validate UAV behaviors;

T10: *Communication* (3%) is related to the definitions of the means of communication between the UAVs, and between a UAVs and the ground infrastructure;

T11: *Coverage* (3%) addresses the problems of map coverage;

T12: *Tracking* (3%) focuses on the detection and tracking of objects in the environment of the UAVs.

Therefore, as Fig. 11 shows, the research topics have diverse aims and tackle several aspects related to UAVs, ranging from low-level (*i.e.* close to hardware) issues, such as UAV communication, to high-level concerns that require considerable UAV autonomy. Fig. 12 shows the evolution of the research topics in the last 5 years. As can be seen from the figure, both of topics predominant in 2018 are related to MAS. Moreover, the coordination topic, a key research issue in MAS, was addressed within works in several years (2014, 2015 and 2017). Furthermore, in 2014 and 2017 the certification & regulation topic witnessed some interest, when two regulations regarding UAVs have been issued exactly in these two years by the European Aviation Safety Agency (*c.f.* Section RD6).

In order to assess the UAV autonomy involved in each research topic, we rely on an autonomy metric proposed by Clough [25] to measure Autonomous Control Levels (ACL) of UAVs. This metric is a scale ranging from 0 (for a remotely piloted non-autonomous UAVs) to 10 (for a fully autonomous UAVs). Fig. 13 plots the average ACL for each research topics. Note that ACL values were either mentioned explicitly by the authors of the primary studies or were determined by the reviewers by evaluating the UAV autonomy according to the ACL scale.

As can be seen in Fig. 13, some research topics tended to endow UAVs with more autonomy than others. For instance, coverage, coordination, surveillance, and mission management need more autonomy than path planning, collision avoidance and communications.

Note that research topics such as certification & regulation and simulation attained relatively high ACL. However, the main concerns of these works were building a simulation environment for the UAVs (in case of the simulation research topics) and certifying that UAVs adhere to the enforced regulations & norms (in case of the certification & regulation research topic). For this reason, the UAVs implementation provided by these works were mainly case-studies lacking details about the evaluations and the implementations.

Furthermore, no reviewer reported a paper with an ACL scale higher than 6. This is explained by the fact that higher level of autonomy in the ACL scale was associated with specific military application requirements (*e.g.* battle-space knowledge, battle-space cognizance, *etc.*), and this SLR focuses on work related to civil applications only. Note that this issue could be solved by relying on other metrics allowing to evaluate the maturity of the contributions. Technology Readiness Level (TRL) [26] is one metric that would help in this direction. Yet, unlike the ACL, it is not focused on UAV autonomy. For this reason, we opted for ACL in this paper.

3.2.2. Application Domains

In addition to the research topics, RQ2 addresses the application domains of UAVs. They refer to the applied research, in which scientific studies and research works aim to solve practical problems in specific application domains. Fig. 14 shows the distribution of the civil UAV application domains of studied papers. The resulting application domains are:

D1: *Urban planning* (34%);

D2: *General* (32%);

D3: *Agriculture* (13%);

D4: *Emergency response* (11%);

D5: *Border surveillance* (4%);

D6: *Telecommunication* (4%);

D7: *Mining* (2%).

The figure shows that *Urban planning* and *General* are the most common application domains. The latter domain, *i.e.* general applications, refer to UAV research works that do not address a particular application domain. This figure shows the growing attention given to UAV applications in civil and urban environments since the combined share of general and urban planning is about 66%, while other application domains such as agriculture, emergency response, border surveillance, which often take place outside the urban environment, received less attention.

In order to assess the maturity of the reviewed primary studies, we resorted to the quality criterion Q3 defined in Table 1. Q3 evaluates the quality of the experiments conducted by the authors of primary studies and the statements of the obtained results. The intuition here is that the more mature the application domain is the higher would be its score for Q3.

Fig. 15 shows the average Q3 score obtained per application domain. As can be seen from the figure, based on their maturity, the application domains can be classified into three clusters. The first cluster represents relatively mature application domains (agriculture, telecommunications, defense, and emergency response domains). The second

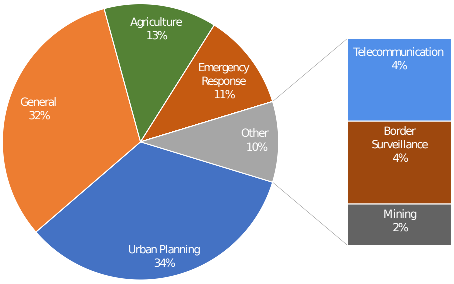


Figure 14: The main civil UAV application domains.

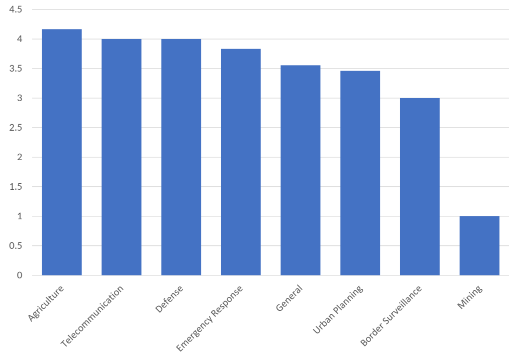


Figure 15: The average of the quality metric Q3 given by the reviewers for each of the application domains.

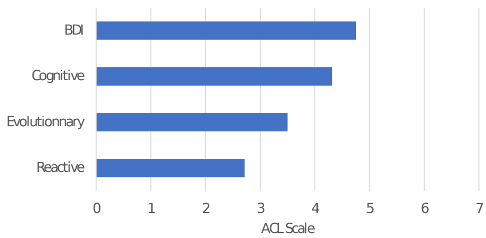


Figure 16: The average ACL per agent architecture.

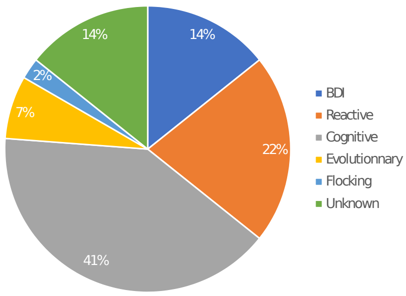


Figure 17: The agent architectures used in the reviewed papers.

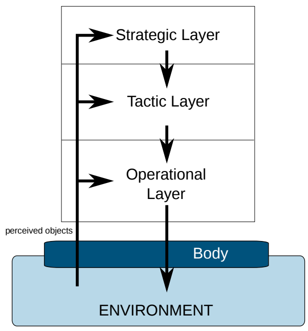


Figure 18: The multi-layer architecture of the agents, adapted from [27].

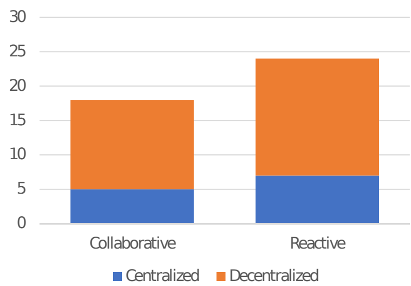
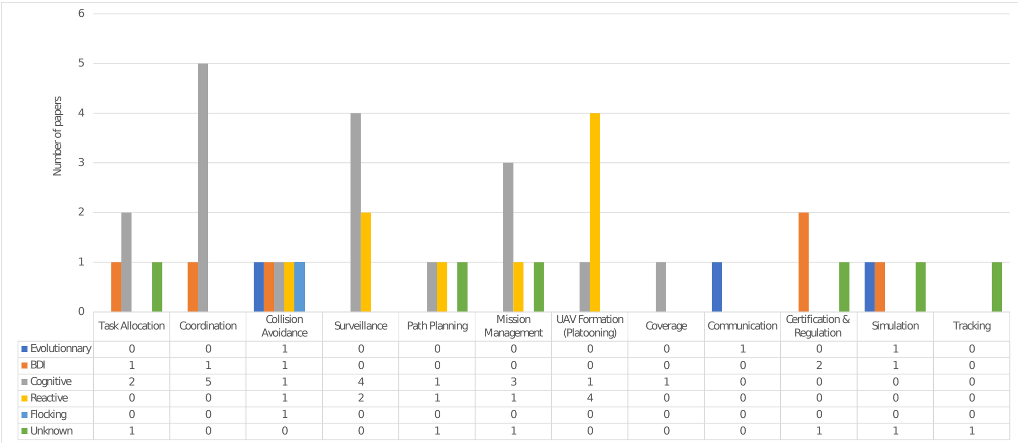


Figure 19: The number of papers with system model (collaborative/reactive) and with system architecture (decentralized/centralized).



	Task Allocation	Coordination	Collision Avoidance	Surveillance	Path Planning	Mission Management	UAV Formation (Platooning)	Coverage	Communication	Certification & Regulation	Simulation	Tracking
Evolutionnary	0	0	1	0	0	0	0	0	1	0	1	0
BDI	1	1	1	0	0	0	0	0	0	2	1	0
Cognitive	2	5	1	4	1	3	1	1	0	0	0	0
Reactive	0	0	1	2	1	1	4	0	0	0	0	0
Flocking	0	0	1	0	0	0	0	0	0	0	0	0
Unknown	1	0	0	0	1	1	0	0	0	1	1	1

Figure 20: The number of papers with agent architecture as per research topic.

cluster represents less mature application domains (general, urban planning, and border surveillance), while the third cluster contains "mining", which appears to be in its early stages of developments. Note that these assessments only concern works using ABS for civil UAV applications.

3.3. Artificial Intelligence or Agent Architecture Type (RQ3)

This section deals with the RQ3. First, in Section 3.3.1 the used agent architectures are identified and discussed. Second, in Section 3.3.2, the used system architectures are analyzed. Finally, Section 3.3.3 discusses how the primary studies dealt with the dynamicity of the environment.

3.3.1. Agent Architecture (RQ3.1)

The results of the SLR concerning the agents' architectures showed that agents used in the studied research works, mainly fall into five categories: *(i)* Reactive agents, *(ii)* Flocking agents, *(iii)* Belief–Desire–Intention (BDI) agents, *(iv)* Agents using cognitive architectures, and *(v)* Evolutionary agents. The following list presents these architectures respectively.

- **Reactive agents:** The behavior of reactive agents is driven by their reactions to external stimuli (*e.g.* a message from another agent) or a change in their environment (a perceived obstacle).

- **Flocking agents:** Within the reactive agent behaviors, flocking agent behavior is the behavior exhibited when a group of agents, *e.g.* birds, fishes are moving together. Basic architectures of flocking behavior are controlled by three simple rules: *(i)* separation for avoiding crowding neighbors, *(ii)* alignment for steering towards average heading of neighbors, *(iii)* cohesion for steering towards average position of neighbors. With these three simple rules, the flock moves in an extremely realistic way, creating complex motion and interaction that would be extremely hard to create otherwise.

- **BDI agents:** BDI agents are rational agents having a "mental attitudes" of Beliefs, Desire, and Intention representing respectively the information, the motivational, and the deliberative states of the agent [28]. BDI agents are capable of integrating planning, scheduling, execution, information gathering, and coordination with other agents [13].

- **Cognitive agents:** Agents of this type rely on cognitive architecture. The latter aims at describing human cognitive processes as precisely as possible. In contrast to BDI, whose main inspiration is *philosophical* and relies on Michael Bratman's theory of human practical reasoning and on modal logic [29], cognitive architectures are inspired by an in-depth understanding of the human brain from biological and neurological perspectives. There are many implementations of cognitive architectures. Soar [30] is one of the widely used ones.

- **Evolutionary agents:** They are agents that are based on evolutionary algorithms. An evolutionary algorithm is a subset of evolutionary computation [31], a generic population-based meta-heuristic optimization algorithm. It uses mechanisms inspired by biological evolution, such as reproduction, mutation, recombination, and selection. Candidate solutions to the optimization problem play the role of individuals in a population, and the fitness function determines the quality of the solutions. Evolution of the population then takes place after the repeated application of the above operators.

Fig. 17 shows the agent architectures used in the papers. As can be seen from the figure, cognitive architectures were the most common among the primary studies ($\approx 41\%$) followed by Reactive agents ($\approx 22\%$) and BDI ($\approx 14\%$). This result shows that proactive agents, those agents capable of goal-directed behavior (BDI agents, and cognitive agents) constitute about 55% of all the analyzed studies whereas reactive agents (including those with flocking behavior) are less common ($\approx 24\%$ of the analyzed works). This shows that most of the research works seek to equip the UAVs with greater autonomy and goal-directed behavior.

In order to understand the correlation between the agent architectures and the autonomy, Fig. 16 shows the average ACL per agent architecture (*c.f.* [25] and Section 3.2). The BDI agents offered the highest level of autonomy, followed by cognitive agents, evolutionary agent, and lastly reactive agents. This result confirms our expectations and suggests that cognitive architecture and BDI agents are promising paradigms allowing to build more autonomous UAVs.

Fig. 20 shows the number of papers with agent architecture as per research topic. The total number is 43 instead of 42, which is the number of papers in the final evaluation, because one paper was investigating two research topics. The most used agent architectures are cognitive (18) and reactive (9), considering all the research topics.

This fact is explained by the characteristics of the research topics: the ideal agent-based modeling of UAVs is usually based on a multi-layer architecture [27], illustrated by Fig. 18. The operational layer corresponds to the (very-)short term, *i.e.* the control of the UAVs. The tactic layer is associated with the planning of the UAV actions, *e.g.* path planning. The strategic layer is associated with the missions of the UAVs. In this layer, mission and task management need more complex models that are in the cognitive scope. It is interesting to note that a low number of papers contains a multi-layer model. The other papers focus on a single layer, mostly tactic or strategic.

3.3.2. Decentralization/Centralization (RQ3.2)

Fig. 19 shows the number of papers with collaborative / reactive system model, and with the system architecture used by the model (decentralized / centralized). As expected, the majority of the papers are related to decentralized architectures, which correspond to one of the major characteristics of MAS and UAV systems. However, 12 papers contain proposals that correspond to a centralized architecture, *i.e.* the model contains a central agent, or the model is formalized in such a way that it could be implemented only with centralized frameworks, *e.g.* Simulink [32] (*c.f.* Section RQ8).

3.3.3. Environment Dynamicity (RQ3.3)

Immersing agents in dynamic physical, virtual or mixed environments is still a challenge for MAS researchers. As has been established in [33], an essential part of such systems is the MAS environment, in order to provide the services allowing agents to interact with it. However, defining what is the interface between the agents and their environment is not obvious. A key aspect is to both respect their autonomy and ensure that the environment rules are enforced. Weyns et al. [33] define *agent environment* as the software layer between the external world and the agents.

Dynamic agent environments include endogenous processes that enable the environment's state to evolve dynamically outside the control of the agent. In a *static agent environment*, such process is not included. Additionally, the agent environment state could evolve only as a consequence of the agents' actions. If an action is never applied to the agent environment by the agents, it is *passive*.

Fig. 21 shows the proportion of the dynamic and static agent environments. Half of the papers propose models based on a static environment, 48% on a dynamic environment. Due to the complexity of the UAV systems, static agent environments are used in order to control the complexity of the modeling and enabling an easier validation.

Agent environments in most of the reviewed papers are passive. In these cases, UAV missions are mainly surveillance, collision detection, coordination, *etc*. However, as UAVs become involved in more application domains where acting on the environment is necessary, there are likely to become more *active* to the agent environment.

3.4. UAV Environment with IoT (RQ4)

The smart city concept integrates Information and Communication Technology (ICT) (*c.f.* Section RQ5), and various physical devices connected to the network, *e.g.* IoT or Wireless Sensor Network (WSN) [34].

Fig. 22 shows the proportion of papers that include the IoT concept against the papers that do not. 9 papers include IoT, and 33 do not. According to [34], several opportunities for UAVs use to support a smart city exist. These opportunities will be very beneficial to any smart city that would utilize UAVs for their economic growth and development. Therefore, it is important to investigate whether IoT is considered in the reviewed models. The low proportion of reviewed papers that are considered IoT indicates that it is still an open issue. According to our knowledge, this proportion may be explained by the fact that researchers focus on the UAV behavior itself, not on the UAV environment.

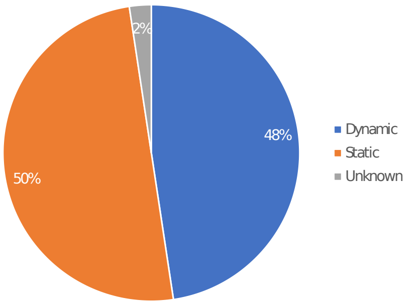


Figure 21: The proportion of dynamic and static agent environments.

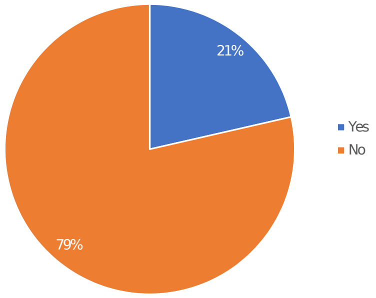


Figure 22: The proportion of the models that are including or not the IoT concept.

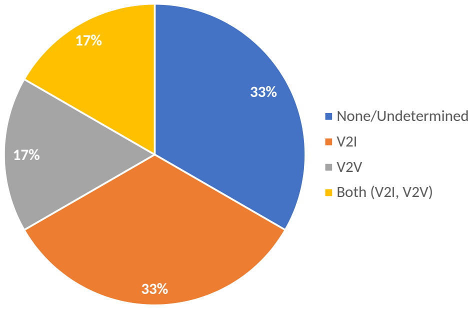


Figure 23: The types of communications.

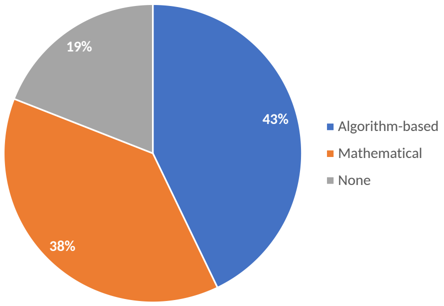


Figure 24: The main families of models.

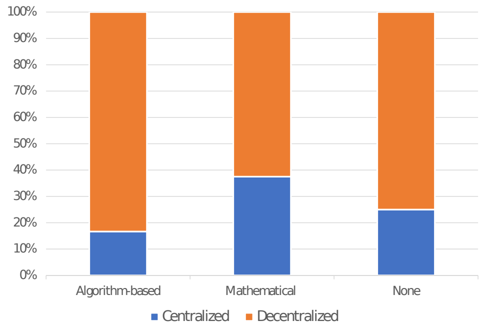


Figure 25: The main formal models correlated with the agent architecture (decentralized/centralized).

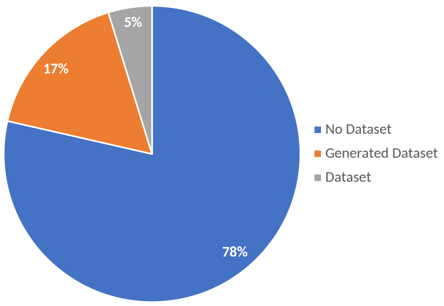


Figure 26: The use of datasets by the reviewed papers.

3.5. UAV Interaction and Communication (RQ5)

Vehicle-to-everything (V2X) communication is the passing of information from a vehicle to any entity that may affect the vehicle and vice versa [35]. It is a vehicular communication system that incorporates other more specific types of communication as Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N), Vehicle-to-Vehicle (V2V), Vehicle-to-Pedestrian (V2P), Vehicle-to-Device (V2D) and Vehicle-to-Grid (V2G). The purpose of this research question is to identify the V2X used by the UAVs to connect to other entities. Among all these types of communication, reviewers have found references to V2I and V2V only.

The main motivations for V2X are road safety, traffic efficiency, and energy savings within smart cities. UAVs are one of the means for setting up the smart city concept [34]. Therefore, it is important to highlight the V2X technologies that are considered within UAV models.

Fig. 23 plots the type of communications used: 33% of the papers includes a communication between the UAVs and the infrastructure (V2I), 17% between UAVs (V2V) by using: *(i)* implicit communication, *i.e.* the communication means are not explicitly described; *(ii)* direct communication means, *e.g.* WiFi; or *(iii)* by using stigmergy communication. 17% of the papers propose a model with both V2I and V2V components.

Finally, 33% of the papers do not consider any specific communication approach. Therefore, when communication is considered within these primary studies, it is not detailed; and the authors seem to assume that the information is exchanged whatever the communication mean is. These papers are not excluded because they contain models that support interaction among the UAV agents, even if it is in an abstract level.

It is interesting to note that 66% of the papers consider that UAVs are connected entities that need to interact with their environment or with other UAVs. This is in-line with the fact that UAVs may contribute to set up the smart city concept (*c.f.* Section RQ4).

3.6. Family of models (RQ6)

The purpose of this RQ is to identify the family of the models that are used within the proposed works. Three major families are considered:

- **Mathematical model:** including formal models enable to verify and validate the behavior of the UAVs. Formal verification is the act of proving or disproving the correctness of UAV algorithms with respect to a certain formal specification, using formal methods of mathematics. The verification of these systems is done by providing a formal proof on an abstract mathematical model of the system, the correspondence between the mathematical model and the nature of the system being otherwise known by construction.

- **Algorithm-based model:** are the models based on the general computer programming theory. These models are basically instances of a logic written in a software to produce the UAV behaviors. These algorithms are not based on mathematical models, such that it is hard to give a proof of completeness and stability.

- **Not-categorized model:** If a paper's contribution can be classified neither mathematically nor as algorithm-based, it is put into the "None" category. In most of the reviewed papers, the contributions within this category are presented with abstract or general explanations without equations, algorithms, state machine, *etc*. For example, the UAV behavior is described by a schematic drawing.

Fig. 24 shows a repartition of the models according to their family. It is interesting to note that 38% of the proposed models are mathematical, and 43% are algorithm-based. Indeed, even if mathematical models are harder to define than algorithm-based models, safety concerns related to UAVs lead researchers to give a proof of safety and stability of the UAV behaviors over the time by providing mathematical models. Safety validation is not outside the algorithm-based models. In all the related papers, simulation testbeds are used for validating the behaviors of the proposed models.

As mentioned within the RQ3 analysis, the architecture in the reviewed models could be classified as centralized or decentralized architectures. Fig. 25 shows the correlation between the system architecture classification and the mathematical/algorithm-based model classification. As expected for MAS, the architectures are mostly decentralized, whatever the type of model.

3.7. Evaluation and simulation scenarios (RQ7)

The purpose of this research question is related to the evaluation of the proposed models: whether it relies on a dataset, or on a generated synthetic dataset, or no dataset. Only a few of the reviewed papers (5%) have a reference to a dataset for setting up the UAV simulations; 17% of the papers have generated a specific dataset for evaluation; While, the majority have no dataset. In papers with no datasets, simulation scenarios are defined as ad hoc by the authors.

This relatively low number of papers with datasets may be explained by the difficulties for building such sets, *e.g.* it is hard to gather realistic data and initialize a UAV model from it. This issue is related to the research direction RD7 detailed below. Having well-established testbeds with datasets helps to unify the testing process, and allows for systematic comparisons between the solutions proposed by researchers.

3.8. Simulation Frameworks (RQ8)

Enabling early validation of a UAV system design requires the simulation of its components. This requires the development of adapted simulation environment. Identifying the frameworks used to implement the proposed solutions, and the main advantages & disadvantages of each of them is a challenge by itself.

Fig. 27 shows the used simulation frameworks in the reviewed papers. Several frameworks are used: AgentFly [56], Simulink [32], Gazebo [73], NetLogo [65], MASON [53], A-globe [62], Repast Simphony [76], JADE [82], PROMELA [60], Gwendolen [71], Neptus [78], jME3 [79], and SPADE [80]. Table 4 provides the list of these frameworks. The two most used frameworks are AgentFly (7%), Simulink (7%). However, the result indicate that no framework was favored by researchers for civil UAV applications. The larger part of the of implementations in the reviewed papers is using an ad hoc framework (43%). These simulation frameworks are typically developed by the authors of the reviewed papers from scratch. This fact leads us to consider that the existing frameworks do not cover all the needs mandatory for implementing a UAV simulation software. Moreover, and due to the abundance of frameworks with no clear distinguished features related to UAVs, the authors generally prefer to setup their own configuration and build the simulation framework from scratch even though it is time-consuming.

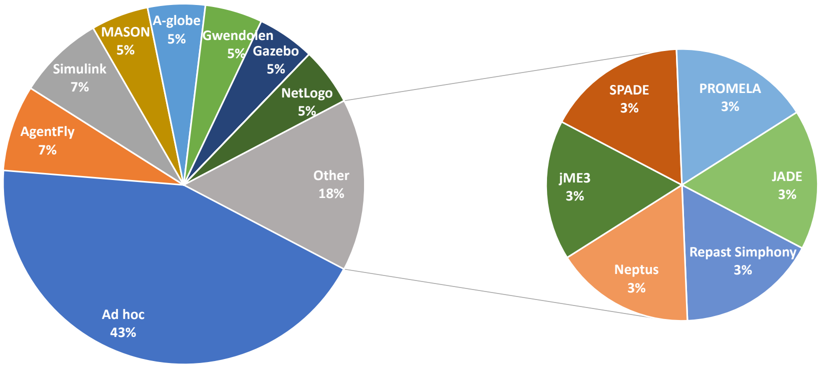


Figure 27: The used simulation frameworks.

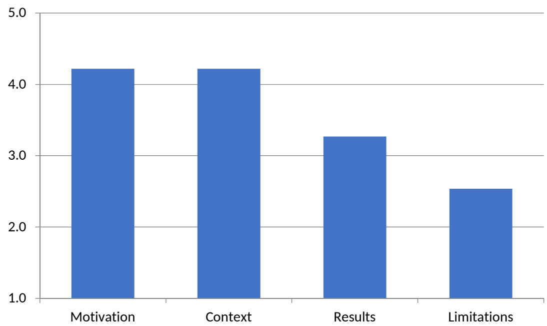


Figure 28: The qualitative evaluation of the reviewed papers.

Table 4: The reviewed papers per used framework

Framework	**Papers using the framework**
Ad hoc	Agogino et al. [36], Ashraf et al. [37], Wei et al. [38, 39], Bürkle et al. [40], Rollo et al. [41], Gunetti et al. [42], Evertsz et al. [43], Kandil et al. [44], Sampedro et al. [45], Peng et al. [46], Benedetti et al. [47], De Benedetti et al. [48, 49], Bürkle and Leuchter [50], da Silva et al. [51], Schatten [52]
MASON [53]	Albani et al. [54], Zou et al. [55]
AgentFly [56]	Semsch et al. [57], Pechoucek et al. [58], Šišlák et al. [59]
PROMELA [60]	Webster et al. [61]
A-globe [62]	Volf et al. [63], Stenger et al. [64]
NetLogo [65]	Cimino et al. [66], Zhu et al. [67]
Simulink [32]	Gunetti et al. [68], Ciarletta et al. [69], Kucherov and Kucherov [70]
Gwendolen [71]	Webster et al. [72]
Gazebo [73]	Arokiasami et al. [74], Ma et al. [75]
Repast Simphony [76]	Khaleghi et al. [77]
Neptus [78]	Vasilijevic et al. [6]
jME3 [79]	Veloso et al. [79]
SPADE [80]	Obdržálek [81]
JADE [82]	Fulford et al. [83]
n/a	Van der Walle et al. [84], Sutton et al. [85], Bentz and Panagou [86], Ferrag et al. [87]

3.9. Discussion

The results and the discussion above help to understand the recent tendencies in the studied domain. Nevertheless, the conclusions drawn in this paper are only valid within the predefined domain of ABS and MAS for civil UAV applications. Thus the tendencies discussed in Section 3 cannot be generated to all UAV applications. Their scope and validity are limited by the keywords and the exclusion criteria defined in Section 2.

Based on the quality criteria defined in Section 2.2.3, the quality of the papers were evaluated according to the four quality criteria defined in Table 1 related to the explanations on the motivations (Q1), the study context (Q2), the theoretical and experimental results (Q3), and the limitations and research directions (Q4). Fig. 28 shows the average evaluation for each of these criteria. Reviewers have provided a score, according to their background and knowledge, based on three levels of quality: "bad", "average", "good". Each paper was evaluated by at least two reviewers and the results were averaged into a scale from 1 to 5. Over the entire set of the papers, motivations and contexts are clearly explained. Presentation of the results is described with the minimum set of details to allow a researcher to reproduce the presented results. Finally, as can be seen from the figure, reviewers have considered that the limitations of the proposed models and approaches are not enough detailed within the papers. However, as UAV technology evolves and new UAV manufacturers claim new customers and social flight clubs enlist fresh enthusiast amateur pilots, these open issues and limitations are becoming significant challenges.

For instance, regulation and collision avoidance are among the prominent challenges to be settled. Yet, the air is still largely unregulated and unmarked, especially to the naked eye, unequipped with height measuring methods, without prior knowledge of any restrictions regarding the filming of surrounding people, and the seriousness of the threat a UAV poses as it zooms past or above people. Moreover, enhanced availability of better GPS-trackers, quieter copters, and smaller "footprint" also raises new legal issues and requires current and up-to-date regulation. Nevertheless, the vast majority of the world still remains behind on effective UAV control. Yet, these issues have not received enough attention in the reviewed papers. Namely, regulation is addressed directly in no more than 7% of the papers. while collision avoidance and UAV safety are addressed only by 11% of the papers.

To help address these understudied open issues and limitations, the next section identifies the main research directions.

4. Challenges and Research Directions

In this section, the major challenges and research directions related to UAVs are listed. These directions are either mentioned in the reviewed papers or identified based on our own experience. The following list provides a synthesis of these challenges and research directions.

RD1: *Making the UAV autonomous*; This research direction is neither specifically control-related, nor concerned with inner-loop feedback stability and control. Since the early UAV research works [88], several related issues have been considered: *(i)* secure communications, unjammable data link (this point is specifically addressed in RD3); *(ii)* coordination; *(iii)* target identification; *(iv)* target assignment; and *(v)* deconfliction. References cite automated decision aiding/decision making as one of the most difficult problems leading to autonomy. Man-machine interface, communications, task and path planning, and target identification are real and difficult issues.

The aim of a typical UAV planning algorithm is to determine a path through the environment while satisfying all the constraints and the mission objectives. Such a planning algorithm involves several levels of planning: *(i)* pre-mission planning where all the information is static. This is the best plan that can be made based on the available information. *(ii)* near term plan, which is executed in the air and involves the physical flying of the UAVs. This can be looked at as a trajectory tracking task, which can be completely automated through inner-loop control, autopilot design, tracking, and short-term on-line trajectory generation. It is the intermediate level of planning where the desired capability of autonomous control is achieved. *(iii)* Near real-time in-flight replanning is needed as new sensor information or commands are received by the UAVs. The challenge is to optimally update the off-line plan as per the new received information and/or the unforeseen occurred events. The optimization problem is dominated by size, complexity, uncertainty, and the fact that the mission could be shared by different UAVs. This leads to problems related to the cooperation and coordination of the autonomous UAVs.

RD2: *Explaining the UAV Behavior*; As shown in the previous section, there is a confirmed tendency towards the development of increasingly autonomous UAV systems. This evolution would minimize the human intervention by relieving the human operator from the burden of continuously monitoring the UAVs. Nevertheless, in unpredictable situations, the UAV behavior might not conform to expectations of the human operator. For instance, in a product delivery scenario, an autonomous UAV may choose to deviate from its expected path because of an unforeseen event. Enhancing the UAVs with explaining capabilities would allow the human operator to understand the reasons behind UAV behavior and raises its trust in the autonomous UAV system. Moreover, the recent developments of the domain of eXplainable AI (XAI) help UAVs to move in this direction. As a matter of fact, UAV has been cited as one of the applications where XAI would be needed [89]. Furthermore, developing explainable UAV would have a very positive impact on human-machine teaming. Recently, this research direction is being explored by military UAV applications. Similar efforts should be considered for civil applications [90]. As shown by recent studies, using BDI agents is a promising approach to develop explainable agents [91]. A key explanation for this success lies in the fact that BDI paradigm is inspired from *folk psychology* which means that "*the core concepts of the agent framework map easily to the language people use to describe their reasoning and actions in everyday conversations*" [92]. Therefore, BDI architecture offers a more straightforward description making models easier to explain for end-users. For this reason, UAV agents relying on BDI architectures, which represent only 14% of papers reviewed in this SLR (*c.f.* Figure 17), are likely to increase in numbers if the issue of explainable UAV behavior is to become a hot research topic.

RD3: *Ensuring Security and Authentication*; The quest of developing autonomous and decentralized UAV systems raises several challenges related to security and authentication. For instance, within a swarm, a UAV must be able to detect and entrust its peers, and ensure data confidentiality and integrity. Otherwise, faulty or malicious UAVs may deviate the swarm behavior [93]. These challenges are accentuated by the fact that most UAV swarms are designed to operate autonomously without a central regulating authority. Recent research has outlined *Block-Chain Technology* (BCT) as a potential solution to overcome this problem. In addition to providing a platform allowing for secured interactions among UAVs, BCT can also be used to enhance the decentralized decision making of the UAV swarm since it allows all the participants to share an identical view of the world, and facilitate agreements among UAV teams [93]. Yet, before BCT is ready to be used with UAVs, several limitations must be solved [93]: *(i) latency*: the time required to update the block-chain is too long to allow real-time compliance (a common requirement in UAV applications); *(ii)* Most of the UAVs are resource-constrained devices which might be unable to undertake the heavy computations demanded by BCT. For this reason, recent research works in BCT propose lightweight techniques (*e.g.* "proof of stake") that can be handled by resource-constrained devices such as the UAVs; *(iii)* On the long run, BCT can be very demanding in terms of bandwidth and communication overhead since all agents should share a copy of a long "ledger" of interactions [94]. This issue, known as "bloat", poses a considerable challenge to UAV teams which have limited hardware and communication capabilities.

RD4: *Increasing the flight duration*; Another problem is the UAV battery life. This well-known problem is related to the UAV design and concerns the improvement of the UAV battery life. Currently, the battery of a typical UAV allows for up to 13 to 20 minutes of continues flight. In a large number of application cases, this duration is not long enough to enable UAVs to achieve their objective before they run out of power and fall down. There are some technical solutions allowing to increase the battery life. Yet, as the battery capacity increases, its size and weight generally increase, which cause the UAVs to consume more power. Battery management can help handle this issue by managing battery consumption prediction and planning [95], scheduling [96], and replacement of battery [97, 98]. Battery wireless charging is also an option through power lines [99], or an automatic charging system that uses charging stations positioned along the path of the UAV mission [100]. For long-endurance and high-altitude flights, solar-powered UAVs could be used [101, 102, 103].

RD5: *Integrating UAVs into smart cities*; A smart city integrates heterogeneous connected objects to automate or simplify autonomous and transparent accomplishment of various daily tasks, both personal and professional [34]. A smart city is an urban area that uses different types of electronic data collection sensors to supply information which is used to manage assets and resources efficiently. This includes data collected from citizens, devices, and assets that are processed and analyzed to monitor and manage traffic and transportation systems, power plants, water supply networks, waste management, law enforcement, information systems, schools, libraries, hospitals, and other community services [104]. The smart city concept integrates ICT, and various physical devices connected to the network to optimize the efficiency of city operations and services and connect to citizens [105]. According to Farhan et al. [106], several opportunities for UAVs uses to support a smart city exist. These opportunities will be very beneficial to any smart city that would utilize UAVs for their economic growth and development.

One of the new trends in civil UAV applications in smart cities is using UAVs in geospatial surveying. The main design of a smart city requires the optimization of data flows provided by wireless sensor networks as sensors are the main component of any autonomous system such as those involving UAVs. This combination of technologies creates a wide range of applications and opportunities such as fire management in open areas where the use of UAVs and micro-UAVs is very beneficial. The potentials vary from a wide range of available solutions and innovations that are evolving quickly. Due to the reliability of most UAV designs, integration of such technologies make it possible to install wireless sensors on-board to make the UAVs usable in geospatial, land surveying and Geographic Information System (GIS) applications in smart cities in addition to being helpful for environmental analysis. These opportunities may lead to cost reduction and cutting down on the number of manpower hours involved in such activities.

The integration of UAV solutions with machine-to-machine, Radio-frequency identification (RFID) and live video streaming increased the role of UAVs in public safety areas. This new trend will move the cities management personnel from being reactive to proactive and will leverage data. Furthermore, the involvement of UAVs in surveillance activities will reduce costs and increase the efficiency of the operations. The efficiency of security and safety systems in a city has become a serious concern not only for smart cities but also for any type of cities or communities. Involvement of UAVs in smart policing activities has lately been supported by the US Congress and top level federal agencies such as the Bureau of Justice Assistance, and the US Department of Justice.

UAVs can act as a third party technology to coordinate information from various systems within a smart city. Since they are controlled at the ground station once they receive information the ground system can send commands to UAVs to direct the information to another system or UAVs.

RD6: *Proposing and Evaluating UAV regulations*; Regulations about introducing UAVs, including air traffic regulations, landing/taking off regulations, *etc.* are not yet fully developed, and there exist serious safety and privacy problems mostly due to the lack of regulations.

Globally, regulations regarding the use of UAVs are still immature. So far, at the multilateral level, the International Civil Aviation Organization (ICAO) is the lead platform for framing regulations for UAV operations. Several regulations were passed to regulate the use of UAVs; however, no proposals were made from a technological point of view. Moreover, legislation varies from region to region and between countries [107].

Recognizing the enormous potential growth of UAVs, the European Aviation Safety Agency (EASA) has been tasked by the European Commission to frame regulations for UAV operations. In 2014, the Commission published "A new era for aviation—Opening the aviation market to the civil use of remotely piloted aircraft systems in a safe and sustainable manner" [108] but this does not include the UAVs. The EASA published a comprehensive proposal in May 2017 covering the technical and operational aspects of operating UAV. According to the proposal, all UAVs above 250 g need to be registered. The proposal put the alignment of different national UAV legislations as one of Horizon 2020 goals. However, these goals have been postponed until 2050. Moreover, different European countries have different regulations – for instance, one can fly UAVs commercially in Switzerland if line-of-sight can be ensured, within certain altitude limitations and not flying near protected areas such as airports. On the other hand, France has more restrictive regulations in place where it is mandatory that any UAV operation over a city needs to be authorized by aviation authorities. In Belgium, Brussels is planning to create "Uspace" in 2019, a European controlled space for UAVs flying above 150 m in height and weighing less than 150 kg.

In India, some work examines civil UAV operations and analyses the major policy gaps in the country's evolving policy framework. It argues that ad hoc measures taken by agencies have been ineffective, whether in addressing issues of quality control, or response mechanisms, questions of privacy and trespass, air traffic, and legal liability [109].

USA has by far the most mature civil UAV regulations in place. The New Small UAS Rule (107) of the Federal Aviation Administration (FAA) that was issued in August 2016 regulates most of the UAV operations, especially those related to commercial or civil purposes. The FAA has relaxed the regulations for UAV operations in the commercial sector considering that the UAV applications are estimated to generate an additional US$82 billion for the economy of USA.

Making progress on the issue of reaching a common legislation will be a complicated task. This is because international conventions on international civil aviation, such as the Chicago Convention, apply only to civil manned aircraft but not to unmanned ones [107]. It is necessary to have a legislation that will be open and generic in the technical aspects. This is because legislations that are limited to specific aircraft types or only permit the use of remote controls with certain characteristics would become obsolete in the near future, as new advances in the field of UAVs appear Furthermore, regulations should not only consider the civil liability of these devices but also aspects that will assure the security of the citizens, for example, the protection of data in deployed vehicles [107].

RD7: *Verifying and validating the UAV behavior*; According to [110], the more complex a UAV software function gets, the more difficult it becomes to test. Furthermore, functional requirements are only one aspect of a system. Beyond the pure verification of a requirement lies the benchmark of the implemented solution. The resulting outcome may be determined by a test of the requirement, but the specific path to the solution can have different levels of quality. Therefore, additional tests have to verify that the specified safety boundaries, as well as additional constraints, are met by this algorithm. To be able to assess highly automated functions and to be able to assure a high-quality software system, it is, therefore, necessary to implement a scoring system or a benchmark to evaluate the autonomy using non-functional requirements. For example, for path planning the standardized benchmark by [111] is utilized to measure the correctness and result quality by expressing a set of pass/fail criteria from the standardized baseline solution.

It is important to notice that benchmarks are problem specific, and not implementation specific. This enables developers not only to test a path-planning algorithm automatically, without a manual review from an engineer, but also to evaluate algorithms and compare them with different implementations and solution approaches. The development of such automatic tests and benchmarks for additional problems, such as sensor fusion and computer vision, to generally assess the capability to fulfill navigation safety and performance requirements, will be critical to the progress of UAVs and the evaluation of new approaches [110].

The growing pressure to innovate and the demand for shorter development cycles require changes in the UAV development methodology. As a result, there is a shift in the demands on testbed systems. This desire for shorter development times stands opposed to the growing complexity required for developing of increasingly automated and autonomous systems [112]. Enabling early validation of such system designs requires the simulation of components. This requires the development of adapted simulation environment, possibly real-time, composed of a collection of reusable modules combining real and virtual components (also called XiL: X-in-the-Loop, where X meaning alternatively Model/Software/Hardware and Human).

5. Related Works

Recently, several works surveyed the emerging topics of UAVs. However, these works mainly focused on vertical applications without considering the aspects and challenges across multiple application domains and research topics. For instance, Hayat et al. [113] focused on the characteristics and requirements of UAV networks for envisioned civil applications between 2000 and 2015 from a communications and networking point of view. Motlagh et al. [114] reviewed Low-altitude UAVs highlighting their potential use in the delivery of IoT services from the sky. Other surveys focused on traffic management [115], environmental monitoring [116], ad hoc networks in UAV applications [117], routing and energy efficiency in UAV communication networks [118], and UAV coverage [119].

One interesting survey is provided by Chmaj and Selvaraj [120] in which the authors surveyed the applications implemented using cooperative swarms of UAVs that operate as a distributed processing system. However, this survey did not consider the challenges facing UAVs in these applications and the potential role of new technologies in UAV uses.

Shakhatreh et al. [121] reviewed civil UAV applications and challenges. They identify current research trends and future challenges for civil UAV applications, including: charging, collision avoidance, swarming, networking and security-related challenges. Yet, this survey was mainly inspired by low-level aspects of the UAV like networking and wireless communication. Moreover, the listing of the comparison was in sequence without a cross-application domain discussion.

Other surveys focused on system identification and UAV-human interactions. In particular, current methods and applications of system identification for small low-cost UAVs were provided by Hoffer et al. [122], while the interaction between UAVs and humans applications were considered in another survey [123]. In this later work, a taxonomy of control methods that enable operators to control swarms effectively was developed. With highlighting challenges, unanswered questions, and open problems for Human-Swarm interaction.

6. Conclusions

UAVs are becoming increasingly popular for civil applications. The aim of this paper is twofold. First, conduct a SLR on research addressing MAS, and specifically ABS, in civil UAV applications. Second, analyze the existing ABS frameworks used for implementing civil UAV applications. The following section states the principal findings. Note that while the SLR concentrated on research using ABS for civil UAV applications, some of the findings below pertain to key research issues in agent and MAS (*e.g.* agent architectures, decentralization, *etc.*).

6.1. Principal Findings

Following a well established SLR methodology, we identified 8 Research Questions (RQ) helping to asses the contributions of MAS and ABS in civil UAV applications. The main findings were:

1. Research on MAS and ABS for civil UAV applications has witnessed a considerable increase in the past decade, and most of the reviewed papers were written in Europe followed by North America and Asia.

2. Coordination, mission management, UAV formation (platooning), collision avoidance, task allocation, and path planning were the most studied research topics while “Urban planning” and “General” accounted for the majority of application domains.

3. The majority of papers covered by the SLR opted for a goal-directed agent architecture to model their agents. Furthermore, most of these studies adopted a decentralized system architecture.

4. Despite the key role that the UAV is expected to assume in smart cities and connected smart environments, only a fifth of the reviewed paper integrate IoT technologies in their research works.

5. The majority of the reviewed papers address UAV connectivity. This shows that most of the reviewed papers view UAVs as connected entities both among themselves and with their environment.

6. Algorithm-based models were used slightly more than the mathematical models by the reviewed papers.

7. To evaluate their contributions, only 5% of papers rely on public datasets and less than 20% use generated datasets. The remaining majority do not use any dataset for evaluation purposes. This underlines the absence of common testbeds and datasets allowing to evaluate and compare these works.

8. In a related finding, the results showed that to conduct their experiments, about 40% of the studied papers implement their own ad hoc simulations. This might be an indication that existing frameworks are not meeting all the needs required for implementing UAV simulations.

As a result of this analysis, we outlined the following key challenges and research directions: *(i)* Model design of fully autonomous UAV; *(ii)* Explanation of the UAV behaviors when they are part of a complex system; *(iii)* Security and authentication of UAV; *(iv)* Increasing of the flight duration; *(v)* Technical integration of UAV into smart cities; *(vi)* Proposal and evaluation of UAV-related regulations; and *(vii)* Verification and validation the UAV behaviors.

Additionally, a methodology to compare ABS frameworks was also defined focusing on features of civil UAV applications. The results were provided for general application domain and two specific applications domains, namely "Urban and traffic management" and "Agriculture". The preliminary results showed that Repast Simphony [76] achieved the highest score for simulating both general and specific civil UAV applications. The runner-ups followed with a slightly lower score (general domain: Gazebo [73], urban and traffic management domain: Janus [124, 125], agriculture domain: Gazebo [73]).

6.2. Implications for Future Research

Regarding the SLR, a future work will be to compare the contributions based on MAS to those using real UAVs. In this way, it will be possible to highlight the position and the growth of MAS within the UAV community.

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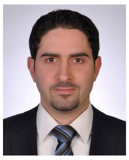

Yazan MUALLA is a Ph.D. candidate at the Belfort-Montbéliard University of Technology (comUE Université Bourgogne Franche-Comté), France. His research interests include Multi-Agent Systems, Agent-Based Modeling & Simulation, Smart Environments and Intelligent Transport Systems. He obtained his MSc in Cyber-Physical Social Systems from Mines Saint Étienne, France. He obtained his BSc and MSc in Information Technology Engineering from Damascus University, Syria. From 2010 to 2014, he was a field engineer at Schlumberger international company in the Measurements & Logging while Drilling segment.

Dr. Amro NAJJAR is a post-doc at the Umea University, Sweden. His research interests include Multi-Agent Systems, Multi-agent Simulation, Explainable AI and Human-Computer Interaction. He received his Ph.D. in Computer Science from Mines Saint Étienne, France, with the title “Multi-Agent Negotiation for QoE-Aware Cloud Elasticity Management”.

Alaa DAOUD is a Ph.D. candidate at Mines Saint Étienne, France. His research interests are Multi-Agent Systems , Web of Things, Connected Objects, and Semantic Web. He obtained his MSc in Cyber-Physical Social Systems from the Université Jean Monnet of Saint Étienne, France, with the title “Semantic Web Environments for Multi-Agent Systems”. He obtained his BSc in Information Technology Engineering from Damascus University, Syria.

Prof. Dr. Stéphane Galland is a full professor at the Belfort-Montbéliard University of Technology (UTBM), France. His research interests include Agent-Oriented Software Engineering and Simulation, Smart Environments, and Intelligent Transport Systems. He received his Ph.D. in Computer Science from Mines
1351 Saint Étienne, France. He is the founder and deputy director of the Distributed Artificial Intelligence and Knowledge Laboratory of Université Bourgogne Franche-Comté, France. He is the head of the "smart environment" research group at UTBM. He has authored more than 80 research articles in international journals, conferences
1352 and workshops.

Prof. Dr. Christophe NICOLLE is a full professor at Université de Bourgogne (UB), France. His research interests include Knowledge Representation and Reasoning. He is founder and director of the Distributed Artificial Intelligence and
1353 Knowledge Laboratory of Université Bourgogne Franche-Comté, France. He is the founder and head of the "Checksem" business unit at UB. He has authored more
1354 than 120 research articles in international journals, conferences and workshops.

Prof. Dr. Eng. Ansar-Ul-Haque YASAR is a professor at the Transportation Research Institute (IMOB), Hasselt University, Belgium. His broader research interests include Ubiquitous Computing, Intelligent Transport Systems
1355 and Mobility Management. He received his Ph.D. in Engineering from Katholieke Universiteit Leuven, Belgium. He has authored more than 60 research articles in
1356 international journals, conferences and workshops.

Prof. Dr. Elhadi SHAKSHUKI is a professor in the Jodrey School of Computer Science at Acadia University, Canada. His research interests include Intelligent Agents, Pervasive and Ubiquitous Computing, Distributed Systems,
1357 and Wireless Sensor Networks. He received his Ph.D. in Engineering from University of Waterloo, Canada. He has authored more than 200 research articles in
1358 international journals, conferences and workshops.