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

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Abstract

Recently, the civilian 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, Civilian Applications

1 1. Introduction

Unmanned Aerial Vehicles (UAVs), most commonly known as drones, are becoming increasingly popular for civilian applications in several domains such as agriculture, transportation, products delivery, energy, emergency response, telecommunication, environment preservation and infrastructure. According to

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Teal Group's 2018 World civilian UAV Market Profile and Forecast report [1], civilian UAV production will total US\$88.3 billion in the next decade, with a 12.9% compound annual growth rate. The same report states that the civil-8 ian UAV sector promises to be the most dynamic growing sector of the world aerospace industry in the following years. Furthermore, fueled by a growing de-10 mand from governments and private consumers, civilian UAV market is expected 11 to quadruplicate over the next decade. The key features making the UAVs inter-12 esting to use are their small dimensions, ability to take-off and land vertically, 13 good maneuverability, simple mechanics, and payload capability. These features 14 make UAVs accessible for civilian applications deployed in urban environment 15 where they started to be used as a practical solution for cost-efficient and rapid 16 delivery. One of the mostly known examples is Amazon Prime Air where UAVs 17 are used to deliver packages to customers [2, 3]. Another important example 18 that comes from the health-care sector is the transportation of medical sam-19 ples and products using a UAV health-care delivery network [4]. Even though 20 there were some concerns about the safety of this procedure in such transporta-21 tion environments, it has been shown that the UAV transportation systems 22 are a viable option for the transportation of medical samples and products [5]. 23 Another notable example comes from the Oil&Gas industry. The tragic Deep-24 water Horizon accident in the Gulf of Mexico in 2010, as well as the increase 25 in deepwater offshore activity, have increased public interest in Health, Safety 26 and Environment (HSE) counter-measures for sub-surface releases of hydrocar-27 bons. To attain a proper contingency planning, response managers urge for a 28 system allowing instant detection and characterization of accidental releases. To 29 meet these requirements, a heterogeneous robotic system involving UAVs was 30 developed for early detection of hydrocarbons [6]. 31

Despite these initial successes, UAV technology is still in its early stages 32 of development. For this reason, considerable limitations should be addressed 33 before a large scale deployment of UAVs in civilian applications is possible. The 34 main drawbacks to mention are related to the safety of humans facing UAV 35 failures [7], and the high amount of energy consumed by these devices cou-36 pled with their limited battery life [8]. Moreover, since civilian applications are 37 mostly deployed in urban environments involving multiple actors, considerable 38 research efforts should be dedicated to enhancing the UAV perceptual intelli-39 gence required to coordinate complex environments [9], and more importantly to 40 address the possible consequences, especially on people safety, of a mechanical 41 failure that may cause a crash and the costs of such incident. 42

To guarantee it is safe for UAVs to fly over people's heads and to reduce costs, 43 different scenarios must be modeled and tested. However, currently, most of the 44 regulations in force restrict the use of UAVs in cities. For this reason, to perform 45 tests with real UAVs, one needs access to expensive hardware and field tests that 46 are costly, time-consuming, and require trained and skilled people to pilot and 47 maintain the UAVs. Moreover, in the field, it may also be hard to reproduce 48 the same scenario several times [10]. To overcome these limitations, simulation 49 frameworks have been developed to allow transferring real-world scenarios into 50 executable models (*i.e.* simulating UAV activities in a digital environment). 51

An agent is defined as an autonomous software entity that is *situated* in 52 some environment and where it is capable of actions and coordination with 53 other agents to achieve specific goals [11]. For these reasons, the resulting Multi-54 Agent System (MAS) technology have been established as a suitable platform 55 for implementing autonomous behavior and decision-making in computer sys-56 tems [12, 13]. An Agent-Based Simulation (ABS) model is a set of interacting 57 intelligent entities that reflect, within an artificial environment, the relation-58 ships in the real world [14]. The results make ABS a natural step forward 59 into understanding and managing the complexity of today's business and social 60 systems. 61

Despite this promising research efforts, very few works were dedicated to understand and analyze existing works using ABS in civilian UAV applications. Very few surveys outlined a comprehensive set of research questions pertaining to multi-agent simulations for civilian UAV applications.

⁶⁶ Against this background, the objective of this paper is two-fold:

Conduct a Systematic Literature Review (SLR) of the research address ing MAS in civilian UAV applications. This SLR aims to identify the
 most important research questions, analyze the literature, and outline key
 challenges and research directions.

⁷¹ 2. Outline and discuss the research directions of UAVs in civilian applications

To the best of our knowledge, no systematic literature study has been conducted
to review the research addressing ABS in civilian UAV applications.

The rest of this paper is organized as follows: Section 2 states and defines the SLR methodology adapted from [15, 16]. 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.

79 2. SLR Methodology

Recently, research on computer science in general and on artificial intelli-80 gence, in particular, has witnessed a significant increase both qualitatively and 81 quantitatively. For this reason, SLRs are becoming popular to help analyze 82 the evolutions of these domains. Kitchenham and Charters [17] define SLR 83 as follows: "A form of secondary study that uses a well-defined methodology 84 to identify, analyze and interpret all available evidence related to a specific re-85 search question in a way that is unbiased and (to a degree) repeatable." Where 86 secondary study refers to "a study that reviews all the primary studies relating 87 to a specific research question." In this paper, we define a primary study as a 88 research paper addressing a specific research question in the domain of UAVs. 89 The aim of SLRs can be threefold [17]: (i) to summarize the existing evidence 90 concerning a specific technology that is being used broadly, (ii) to identify gaps 91 in the existing research in order to suggest areas for future investigation, and 92 *(iii)* to provide a background allowing to position new research activities. 93

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Figure 1: The systematic literature review process (the figure adapted from [18, 19]).

With these goals in mind, we base our systematic literature review on [15, 16], 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.*).

103 2.1. Key Research Questions

Following the Goal Question Metric (GQM) [16], we define our generic free-104 form question as "Discover and evaluate the possible scientific MAS contribu-105 tions to the civilian UAV applications." On the field, it may be hard to deploy 106 UAVs because of safety and security issues. Moreover, it may be difficult to re-107 produce the same scenario several times in order to test hypotheses and validate 108 the UAV behaviors. ABS is a suitable tool for overcoming these limitations. In 109 order to reflect this aspect, the generic free-form question becomes "Discover and 110 evaluate the possible scientific ABS contributions to the civilian UAV applica-111 tions." This question is broken down into Research Questions (RQs) exploring 112 key issues in ABS for civilian UAV applications. The research questions are 113 mainly concerned with this type of applications. More specifically, these ques-114 tions cover the purposes, issues, used simulation frameworks, publications date, 115 authors, countries, etc. These questions were formulated based on the authors' 116 knowledge in the UAV and ABS domains as well as the common practices from 117 other SLRs. In what follows, eight RQs are considered within this review, and 118 listed below: 119

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

123 124 125 126		determine the liveliness of the MAS modeling domain for civilian 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.
127 128 129 130 131 132 133 134	RQ2:	Identify the main UAV research topics and civilian application domains addressed in the studied papers. On one hand, we consider it is impor- tant to determine active research topics in order to highlight less active research topics where more contributions are needed. On the other hand, and as the market of civilian UAVs is expanding rapidly in several ap- plication domains [1], a synthetic view of these application domains will enable researchers to determine the typical applications for their research, and possibly identify new application domains.
135 136 137 138 139 140	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 civilian 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.
141 142 143 144 145 146 147		 RQ3.1: Investigate the agent architecture used in the solution (<i>e.g.</i> cognitive agent, Belief-Desire-Intension (BDI) agent, reactive agent, <i>etc.</i>). RQ3.2: Investigate the architecture of the system in the studied papers (decentralized vs centralized). RQ3.3: Investigate whether the proposed model (agent or simulation architectures) includes the environment, and how the UAVs in-
148 149 150 151 152 153 154 155 156 157 158	RQ4:	teract with their environment. Investigate whether models and technologies enabling to implement con- cepts related to Internet-of-Things (IoT), pervasive systems or ubiqui- tous systems are considered in the studied papers. IoT is a technological domain that is more and more used within smart cities. This RQ will highlight if technologies like wireless sensor networks, connected vehicles, connected buildings, etc. are considered as a component of the agent- based system in the studied papers. In such systems, IoT contributes to the model at the agent level (objects may be modeled as agents) and at the agent environment level (objects are not agents). This RQ will also highlight how IoT devices and UAVs are interacting together.
159 160 161 162 163 164 165	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>i.e.</i> Vehicle-to-Infrastructure (V2I), or to other UAVs, <i>i.e.</i> 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 civilian 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 civilian 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 civilian UAV application domain. This **RQ** is related to the technological means used by the researchers for implementing the MAS for civilian UAV applications. It should help researchers to determine and choose the best framework for their own model implementation.

184 2.2. Defining The Review Protocol

As shown in Fig. 1, defining the *review protocol* is done right after having set 185 the RQs. The protocol we used for this article involves the following steps. First 186 Section 2.2.1 chooses the databases used as sources of information and defines 187 the stop criterion. Section 2.2.2 defines the exclusion/inclusion criteria used by 188 the reviewers to exclude/include articles chosen from the databases before the 189 stop criterion was triggered. Section 2.2.3 presents the quality criteria used by 190 the reviewers to assess the quality of the primary studies. Finally, Section 2.2.4 191 explains the policies used to mitigate subjective biases and resolve conflicts. 192

193 2.2.1. Database Selection

¹⁹⁴ 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 205 articles that are considered by the reviewing process. The numbers of articles 206 to be produced by the queries is relatively large for IEEE Xplore, ACM DL, and 207 Google Scholar databases. However, only a few of these articles were relevant 208 to the research questions raised in the previous section. For this reason, as in 209 [20], the following stop criterion was applied: "Stop the collecting of articles 210 after a sequence of 10 titles, completely incoherent with the query, appeared in 211 the list." Determining whether an article is coherent is left to the reviewers' 212 subjective view when they deemed that there was no adherence between the 213 query performed on the database and the title/abstract of the article appearing 214 in the result. 215

216 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 [19, 20] 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 245 manufacturing of UAVs, *i.e.* it is related to the design and implemen-246 tation of hardware, mechanic or electronic components. 247 **ExC9**: Positioning system only — The paper's contribution is related to the 248 definition of novel positioning systems within UAVs. The contribution 249 focuses on a perception model that enables each UAV to compute its 250 position in the air. 251 **ExC10:** UAV detection system only — The paper's main concern is UAV detec-252 tion within the system. In other words, the contribution is not related 253 to UAV behavior, but to a system that is detecting the UAV in the air. 254 **ExC11:** No civilian application — The paper contains only military applications 255 that cannot be applied to civilian fields. 256 ExC12: No simulation contribution — The paper's contribution cannot be ap-257 plied to UAV simulation. In several papers, the model is deployed on 258 real UAVs without simulation. Even if the paper has not a direct con-259 tribution to UAV simulation, if the proposed model could be deployed 260 within a simulation environment, the corresponding paper is not ex-261 cluded. 262 ExC13: Simulation in 2D — The paper's contributions include a simulation 263 model in 2D that cannot be extended to the third dimension. It is as-264 sumed that 2D simulation of UAVs cannot achieve the highly detailed 265 reproduction of the UAV behavior when they are in the air. Addi-266 tionally, they do not provide detailed environment model. However, to 267 estimate the portion of 2D and 3D simulations, we keep track of this 268 exclusion criterion, and plot how many papers were excluded due to 269 being based on 2D simulation (c.f. Section 2.3). 270 **ExC14:** No UAV cooperation nor interaction — The paper contains a contribu-271 tion related to neither the cooperation of UAVs nor interaction between 272 UAVs. V2I and V2V communications are assumed to be the base frame-273 work for supporting UAV interaction. If a paper contains a model for 274 a single UAV that has V2I communication, it is not excluded since this 275 type of models could be duplicated in order to set up a more complex 276 simulation environment based on stigmergy¹ communication. 277 278 ExC15: Human interaction with no autonomous UAV — The paper contains

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random metaction with no autonomous <math>CAV — The paper contains only a contribution related to the interaction between humans and the

¹This 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 [21]

Table 1: The Quality Questions

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

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 *finegrained* step, the remaining papers are screened but this time reading the whole body of the paper.

288 2.2.3. Quality Criteria

As has been recommended by Kitchenham and Charters [17] and Kitchenham et al. [22], most of the SLRs rely on quality criteria allowing to assess the quality of primary studies, (c.f. [19, 20] 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 [19], 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 [19]. 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.

303 2.2.4. Biases and disagreements

In order to mitigate the subjectivity of the reviewing process, certain mea-304 sures were taken to overcome biases and resolve conflicts. In particular, each 305 task of Phase 2 in Fig. 1 was conducted by at least 2 reviewers. Thus, as shall 306 be discussed later, the steps of article exclusion/inclusion (c.f. Section 2.2.2), 307 answering the RQs, and quality assessment (*c.f.* Section 2.2.3), were under-308 taken by at least two reviewers for each article. A third reviewer intervened as 309 a referee to resolve a conflict in the exclusion/inclusion and in the RQ answer-310 ing steps. As for the quality assessment task, quality assessments provided by 311 reviewers for each article were averaged. 312

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

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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	pprox 66%

313 2.3. Performing The Review

This section gives an account of how the SLR has been conducted and dis-314 cusses the results of the exclusion/inclusion step. Two keyword sets were ap-315 plied to the three databases (IEEE Xplore, ACM DL, and Google Scholar). The 316 first keyword set is {UAV, agent, simulation}, whereas the second keyword set 317 is {UAV, agent-based simulation, drones, civil, multi-agent systems}. A 318 stop criterion of 10 articles was applied to the results of each keyword set and 319 database. After the stop criterion was applied, the total number of articles re-320 tained was 316. The next step is to apply the coarse-grained exclusion/inclusion 321 step. Note that since this step screens papers based on their titles and abstracts, 322 some exclusion criteria might be more helpful than others (e.q.ExC1 and ExC2). 323

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 329 inclusion/exclusion step. The number of papers published by US researchers 330 is highest worldwide. The geographical distribution of the papers could be 331 partly explained by the investment rate in R&D in each country [23], illustrated 332 by Fig. 3. The notable exception is China, which invests 2% of its GDP 333 (US\$370, 589.7M) but has a number of papers equal to France (2.3% of GPP, 334 US\$60, 781.6M). Another notable point is the Czech Rep., which has 11 papers 335 with an average R&D investment (2% of GPP, US\$6,719M). All the authors 336 from Czech Rep. are collaborating with partners within US-funded projects. 337 This fact may explain the high number of publications for this country. From 338 Fig. 2, it is interesting to note that, even if civilian UAV-related regulations 330 in USA are less restrictive than in Europe (c.f. Section RD6), the number 340 of papers over Europe is two times higher than the number of papers in North 341





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

The geographical distribution Figure 3: The investments in R&D for the 18 most publishing countries [23] after the coarsegrained exclusion/inclusion step.



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



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

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



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

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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. The number
of papers grows with a slop of 0.6364.

The next step within the review process is the *fine-grained exclusion/inclusion* 346 step. It is applied to the 123 papers selected during the previous step. More 347 specifically, the content of the paper is screened and the paper is excluded if 348 it satisfies at least one of the 15 exclusion criteria defined in Section 2.1. Ta-349 ble 3 shows the results of the fine-grained exclusion/inclusion step. Each paper 350 was reviewed by at least two reviewers. If all the reviewers of a paper decided 351 that it should be included in the review, the paper is included (*c.f.* the first 352 row of the table). The paper is excluded if all of its reviewers agreed upon its 353 exclusion (the second row of the table). Otherwise, in case of a conflict among 354 reviewers, we relied on a referee to resolve this conflict. If the referee accepts 355 the paper, then it is included in the review. As shown in the table, 23 papers 356 (about 19% of the total number of the papers) generated conflicts among the 357 reviewers. Out of these papers, 12 papers were added by the referee raising the 358 total number of included papers to 42 (about 34% of the papers remaining after 359 the coarse-grained exclusion/inclusion step). For a list of the 42 papers, please 360 refer to Table 6. 361

Most of the papers screened in the fine-grained step were highly related 362 to the RQs. As indicated by Table 3, 66% of them were excluded, and Fig. 363 5 plots the percentage of excluded papers per exclusion criterion. Note that 364 some papers were excluded because of satisfying multiple exclusion criteria. 365 Examining the reviews shows that approximately 24% of excluded papers were 366 excluded because of ExC13, which filters out a paper if it is not addressing 3D 367 simulation scenario. Fig. 6 compares the percentage of papers presenting 2D and 368 3D simulations in the pool of papers before the fine-grained exclusion/inclusion 369 (whose total number is 123), excluding 26 papers that were not determined 370 either they use simulation or not, or either they are 2D or 3D. As can be seen 371 from the figure, despite ExC13 being the most common cause for exclusion, the 372 majority of the papers whose simulation dimension was determined ended up 373 addressing 3D simulations. In order to understand the general tendencies of 374 2D and 3D simulations, Fig. 7 plots the number of papers proposing 2D/3D375 simulations per year. As shown in the figure, the number of papers proposing 3D 376 simulations is witnessing a confirmed and significant increase (2018 should not 377 be considered since this review was conducted in August 2018). This is mainly 378 due to the fact that UAV systems are intrinsically in three dimensions, and this 379 third dimension must be included within the models in order to evaluate the 380 behaviors of the UAVs regarding the safety concerns. Additionally, simulating 381 UAVs in a 2D model forbids the deployment of the algorithms in real UAVs 382 except in very specific cases in which the altitude of the UAVs is constant. 383 Nevertheless, in this later case, the deployed algorithms must ensure that the 384 UAVs remain at the same altitude regardless of the environment conditions. 385

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.

³⁹¹ 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 civilian UAV applications and are derived from the research questions and the exclusion criteria defined in the SLR methodology.

397 3.1. Demographic Data (RQ1)

To understand the evolution of UAV simulations in MAS in the last decade 398 (stated as a question by RQ1), Fig. 8 plots the number of papers per year after 399 the fine-grained exclusion/inclusion step. Despite a decrease in the number 400 of papers in 2009 and 2012 (2018 should not be considered since this review 401 was conducted in August 2018), it appears from the figure that there is a stable 402 growth in the numbers of papers, with a slop of 0.2727. Furthermore, comparing 403 the results of this figure with those of Fig. 4 confirms this observation since in 404 Fig. 4, the number of papers witnesses a roughly stable growth between 2008 405 and 2016. 406

To understand the geographic distributions of the main contributors in the 407 studied domain, Fig. 9 plots the number of papers per country after the fine-408 grained exclusion/inclusion step. Compared with Fig. 2, The number of papers 409 published by US researchers is still highest worldwide. As previously noticed, 410 researchers from the Czech Rep. are collaborating with partners within US-411 funding projects. This fact may explain the high number of publications for 412 this country compared to its R&D investment, illustrated in Fig. 10. In the 413 mentioned figure, it is interesting to note that, even if civilian UAV-related 414 regulations in USA are less restrictive than in Europe, the number of papers 415 over Europe (32 papers) is three times higher than the number of papers in North 416 America (9 papers). We explain this by the fact that the EU research policy 417 enforces funding on breaking technologies, such as UAVs. Additionally, with 418 a relatively lower R&D investment rate of EU countries (Fig. 10), researchers 419 from these countries have fewer opportunities for funding UAV deployment on 420 real fields. This pushes them to resort to simulation environments for validating 421 the UAV behaviors before any deployment. 422

423 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).





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 [23] of the publishing countries after the fine-grained Figure 11: The main research topics related exclusion/inclusion step.



to civilian UAVs applications.





Figure 12: The average ACL for each research Figure 13: The main civilian UAV application topic. domains.

427 3.2.1. Research Topics

Subjects or issues that a researcher is interested in when conducting research 428 on UAVs. These "research topics" provide the general directions to researchers 429 for exploring, defining, and refining their ideas. Fig. 11 plots the main research 430 topics addressed in the reviewed articles, and Table 4 lists the papers per each 431 research topic. It is worth mentioning that some papers were flagged as having 432 more than one research topic. Therefore, and to normalize the weights given 433 by each paper to the research topics distribution, we have decided to assign the 434 most dominant research topic per paper. The addressed research topics are: 435

- T1: Coordination (17%), UAVs interact in order to coordinate their actions for
 reaching their common objectives;
- T2: Mission Management (14%) 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;
- T3: Collision Avoidance (14%) allows to increase UAV safety by avoiding collisions among UAVs, persons, animals, and other objects;
- **T4:** UAV Formation (Platooning) (9%) addresses the definition of flight formations for UAVs;
- T5: Surveillance (9%) enables UAVs to help the detection of dangerous and
 illegal situations;
- T6: Path Planning (7%) focuses on the statical and dynamical computing of
 the best paths to fly along according to the environmental constraints;
- T7: Task Allocation (7%) is the optimal dynamic (potentially distributed) as signment of tasks to the UAVs;
- 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;
- 456 T10: Communication (3%) is related to the definitions of the means of commu 457 nication between the UAVs, and between a UAVs and the ground infras 458 tructure;
- $_{459}$ T11: Coverage (3%) addresses the problems of map coverage;
- ⁴⁶⁰ **T12:** *Tracking* (3%) focuses on the detection and tracking of objects in the en-⁴⁶¹ vironment of the UAVs.

Table 4: The reviewed papers per research topic

Research topic	Papers per topic
Coordination	Bürkle et al. [24], Zhu et al. [25], Rollo et al. [26],
	De Benedetti et al. [27], Cimino et al. [28], Ciarletta et al.
	[29], Obdržálek [30]
Mission Management	Wei et al. [31], Gunetti et al. [32, 33], Stenger et al. [34],
	Sampedro et al. [35], Fulford et al. [36]
Collision Avoidance	Ashraf et al. [37], Kandil et al. [38], Šišlák et al.
	[39], Arokiasami et al. [40], Zou et al. [41], Kucherov and
	Kucherov [42]
UAV Formation (Platooning)	Van der Walle et al. [43], Sutton et al. [44], Benedetti
	et al. [45], Bürkle and Leuchter [46]
Surveillance	Semsch et al. [47], Khaleghi et al. [48], Bentz and
	Panagou [49], da Silva et al. [50]
Task Allocation	Wei et al. [51], Evertsz et al. [52], Vasilijevic et al. [6]
Path Planning	Volf et al. [53], Peng et al. [54], Ma et al. [55]
Certification & Regulation	Webster et al. [56, 57], Schatten [58]
Simulation	Pechoucek et al. [59], Veloso et al. [60], De Benedetti et al.
	[61]
Communication	Agogino et al. [62]
Coverage	Albani et al. [63]
Tracking	Ferrag et al. [64]

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 (*e.g.* mission management).

In order to assess the UAV autonomy involved in each research topic, we 466 rely on an autonomy metric proposed by Clough [65] to measure Autonomous 467 Control Levels (ACL) of UAVs. This metric is a scale ranging from 0 (for a 468 remotely piloted non-autonomous UAVs) to 10 (for a fully autonomous UAVs). 469 Fig. 12 plots the average ACL for each research topics. Note that ACL values 470 were either mentioned explicitly by the authors of the primary studies or were 471 determined by the reviewers by evaluating the UAV autonomy according to the 472 ACL scale. 473

As can be seen in Fig. 12, 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.

⁴⁷⁸ Note that research topics such as certification & regulation and simulation
⁴⁷⁹ attained relatively high ACL. However, the main concerns of these works were
⁴⁸⁰ building a simulation environment for the UAVs (in case of the simulation re⁴⁸¹ search topic) and certifying that UAVs adhere to the enforced regulations &
⁴⁸² norms (in case of the certification & regulation research topic). For this reason,
⁴⁸³ the UAVs implementation provided by these works were mainly case-studies
⁴⁸⁴ 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 levels of autonomy in the ACL scale ⁴⁸⁷ were associated with specific military application requirements (*e.g.* battle-⁴⁸⁸ space knowledge, battle-space cognizance, *etc.*), and this SLR focuses on work ⁴⁸⁹ related to civilian applications only. Note that this issue could be solved by ⁴⁹⁰ relying on other metrics allowing to evaluate the maturity of the contributions. ⁴⁹¹ Technology Readiness Level (TRL) [66] is one metric that would help in this ⁴⁹² direction. Yet, unlike the ACL, it is not focused on UAV autonomy. For this ⁴⁹³ reason, we opted for ACL in this paper.

494 3.2.2. Application Domains

In addition to the research topics, RQ2 addresses the application domains of 495 UAVs. They refer to the applied research, in which scientific studies and research 496 works aim to solve practical problems in specific application domains. Fig. 497 13 shows the distribution of the civilian UAV application domains of studied 498 papers, and Table 5 lists the papers per each application domain. It is worth 499 mentioning that some papers tackle several application domains. Therefore, 500 and to normalize the weights given by each paper to the application domains 501 distribution, we have decided to assign the most dominant application domain 502 per paper. For the paper that has no dominant application domain, or if its 503 contribution is application independent, it is considered to be in the General 504 domain. The resulting application domains are: 505

- 506 **D1:** General (53%);
- 507 **D2:** Urban Planning (26%);
- 508 **D3:** Emergency Response (12%);
- 509 **D4:** Telecommunication (5%);
- 510 **D5:** Agriculture (2%);
- ⁵¹¹ **D6:** Border surveillance (2%).

As seen in Figure Fig. 13, *Urban planning* and *General* are the most common application domains. This figure shows the growing attention given to UAV applications in civilian and urban environments since the share of urban planning is about 26%, 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. 14 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 two clusters. The first cluster represents relatively mature application domains (agriculture, telecommunications, and emergency response).



Figure 14: The average of quality metric Q3 Figure 15: The average ACL per agent archigiven by reviewers per application domain. tecture.



Figure 16: The agent architectures used in the Figure 17: The multi-layer architecture of the reviewed papers. agents, adapted from [67].



Figure 18: The number of papers with system model (direct collaboration/reactive) and with system architecture (central-Figure 19: The proportion of dynamic and ized/decentralized).

static agent environments.

Table 9. The fevre apples per application domain				
Application domain	Papers per application domain			
General	Ashraf et al. [37], Wei et al. [51], Bürkle et al. [24], Wei et al.			
	[31], Rollo et al. [26], Gunetti et al. [32, 33], Evertsz et al. [52],			
	Webster et al. [57], Sampedro et al. [35], Sutton et al. [44], Peng			
	et al. [54], Zou et al. [41], Ma et al. [55], Bentz and Panagou			
	[49], da Silva et al. [50], De Benedetti et al. [27, 61], Obdržálek			
	[30], Fulford et al. [36], Kucherov and Kucherov [42], Ferrag et al.			
	[64]			
Urban Planning	Semsch et al. [47], Volf et al. [53], Webster et al. [56], Kandil			
	et al. [38], Arokiasami et al. [40], Pechoucek et al. [59], Veloso			
	et al. [60], Šišlák et al. [39], Khaleghi et al. [48], Bürkle and			
	Leuchter [46], Schatten [58]			
Emergency Response	Zhu et al. [25], Van der Walle et al. [43], Benedetti et al. [45],			
	Cimino et al. [28], Vasilijevic et al. [6]			
Telecommunication	Agogino et al. [62], Ciarletta et al. [29]			
Border Surveillance	Stenger et al. [34]			
Agriculture	Albani et al. [63]			

Table 5: The reviewed papers per application domain



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

The second cluster represents less mature application domains (general, urban planning, and border surveillance). Note that these assessments only concern works using ABS for civilian UAV applications.

530 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.

⁵³⁵ 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).

Within the reactive agent behaviors, Flocking agents behavior is the 544 behavior exhibited when a group of agents, e.g. birds, fishes are moving 545 together. Basic architectures of flocking behavior are controlled by three 546 simple rules: (i) separation for avoiding crowding neighbors, (ii) align-547 ment for steering towards average heading of neighbors, *(iii)* cohesion for 548 steering towards average position of neighbors. With these three sim-549 ple rules, the flock moves in an extremely realistic way, creating complex 550 motion and interaction that would be extremely hard to create otherwise. 551

Cognitive agents: Agents of this type rely on cognitive architecture. 552 The latter aims at describing human cognitive processes as precisely as 553 possible. In contrast to BDI, whose main inspiration is *philosophical* and 554 relies on Michael Bratman's theory of human practical reasoning and on 555 modal logic [68], cognitive architectures are inspired by an in-depth under-556 standing of the human brain from biological and neurological perspectives. 557 There are many implementations of cognitive architectures. Soar [69] is 558 one of the widely used ones. 559

A special type of cognitive agents are **BDI agents**. They are rational agents that having a "mental attitudes" of Beliefs, Desire, and Intention representing respectively the information, the motivational, and the deliberative states of the agent [70]. BDI agents are capable of integrating planning, scheduling, execution, information gathering, and coordination with other agents [13].

• Evolutionary agents: They are agents that are based on evolution-566 ary algorithms. An evolutionary algorithm is a subset of evolutionary 567 computation [71], a generic population-based meta-heuristic optimization 568 algorithm. It uses mechanisms inspired by biological evolution, such as re-569 production, mutation, recombination, and selection. Candidate solutions 570 to the optimization problem play the role of individuals in a population, 571 and the fitness function determines the quality of the solutions. Evolution 572 of the population then takes place after the repeated application of the 573 above operators. 574

Fig. 16 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. 15 shows the average ACL per agent architecture (*c.f.* [65] 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 most used agent architectures are cognitive (without BDI) (17) and reactive (without flocking) (9), considering all the research topics.

This fact is explained by the characteristics of the research topics: the ideal 593 agent-based modeling of UAVs is usually based on a multi-layer architecture 594 [67], illustrated by Fig. 17. The operational layer corresponds to the (very-595)short term, *i.e.* the control of the UAVs. The tactic layer is associated with 596 the planning of the UAV actions, e.g. path planning. The strategic layer is 597 associated with the missions of the UAVs. In this layer, mission and task man-598 agement need more complex models typically found in the cognitive scope. It is interesting to note that a low number of papers contains a multi-layer model. 600 The other papers focus on a single layer, mostly tactic or strategic. 601

602 3.3.2. Decentralization/Centralization (RQ3.2)

Fig. 18 shows the number of papers with reactive / direct collaboration sys-603 tem model, and with the system architecture used by the model (decentralized 604 / centralized). As expected, the majority of the papers are related to decentral-605 ized architectures, which correspond to one of the major characteristics of MAS 606 and UAV systems. However, 12 papers contain proposals that correspond to a 607 centralized architecture, *i.e.* the model contains a central agent, or the model 608 is formalized in such a way that it could be implemented only with centralized 609 frameworks, e.g. Simulink [72] (c.f. Section RQ8). 610

611 3.3.3. Environment Dynamicity (RQ3.3)

Immersing agents in dynamic physical, virtual or mixed environments is still 612 a challenge for MAS researchers. As has been established in [73], an essential 613 part of such systems is the MAS environment, in order to provide the services 614 allowing agents to interact with it. However, defining what is the interface 615 between the agents and their environment is not obvious. A key aspect is to 616 both respect their autonomy and ensure that the environment rules are enforced. 617 Weyns et al. [73] define agent environment as the software layer between the 618 external world and the agents. 619

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*.



Figure 21: The proportion of the models that are including or not the IoT concept.



None/Undetermined V2I ≡ V2V Both (V2I, V2V)

Figure 22: The types of communications.



Figure 23: The main families of models.



5.0

lated with the agent architecture (decentral-

ized/centralized).



papers.



Fig. 19 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.

635 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) [74].

Fig. 21 shows the proportion of papers that include the IoT concept against 639 the papers that do not. 9 papers include IoT, and 33 do not. According to 640 [74], several opportunities for UAVs use to support a smart city exist. These 641 opportunities will be very beneficial to any smart city that would utilize UAVs 642 for their economic growth and development. Therefore, it is important to inves-643 tigate whether IoT is considered in the reviewed models. The low proportion of 644 reviewed papers that are considered IoT indicates that it is still an open issue. 645 According to our knowledge, this proportion may be explained by the fact that 646 researchers focus on the UAV behavior itself, not on the UAV environment. 647

⁶⁴⁸ 3.5. UAV Interaction and Communication (RQ5)

Vehicle-to-everything (V2X) communication is the passing of information 649 from a vehicle to any entity that may affect the vehicle and vice versa [75]. It is 650 a vehicular communication system that incorporates other more specific types 651 of communication as Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N), 652 Vehicle-to-Vehicle (V2V), Vehicle-to-Pedestrian (V2P), Vehicle-to-Device (V2D) 653 and Vehicle-to-Grid (V2G). The purpose of this research question is to identify 654 the V2X used by the UAVs to connect to other entities. Among all these types 655 of communication, reviewers have found references to V2I and V2V only. 656

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 [74]. Therefore, it is important to highlight the V2X technologies that are considered within UAV models.

Fig. 22 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.* Wireless; or *(iii)* by using stigmergy communication. 17% of the papers propose a model with both V2I and V2V components.

⁶⁶⁷ Finally, 33% of the papers do not consider any specific communication ap-⁶⁶⁸ proach. 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).

677 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 680 validate the behavior of the UAVs. Formal verification is the act of prov-681 ing or disproving the correctness of UAV algorithms with respect to a 682 certain formal specification, using formal methods of mathematics. The 683 verification of these systems is done by providing a formal proof on an 684 abstract mathematical model of the system, the correspondence between 685 the mathematical model and the nature of the system being otherwise 686 known by construction. 687

• 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. 23 shows a repartition of the models according to their family. It is 699 interesting to note that 38% of the proposed models are mathematical, and 700 43% are algorithm-based. Indeed, even if mathematical models are harder to 701 define than algorithm-based models, safety concerns related to UAVs lead re-702 searchers to give a proof of safety and stability of the UAV behaviors over the 703 time by providing mathematical models. Safety validation is not outside the 704 algorithm-based models. In all the related papers, simulation testbeds are used 705 for validating the behaviors of the proposed models. 706

As mentioned within the RQ3 analysis, the architecture in the reviewed models could be classified as centralized or decentralized architectures. Fig. 24 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.



Figure 27: The used simulation frameworks.

712 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.

726 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. Sev-732 eral frameworks are used: AgentFly [76], Simulink [72], Gazebo [77], NetLogo 733 [78], MASON [79], A-globe [80], Repast Simphony [81], JADE [82], PROMELA 734 [83], Gwendolen [84], Neptus [85], jME3 [60], and SPADE [86]. Table 6 pro-735 vides the list of these frameworks. All used frameworks are open source except 736 for AgentFly, A-globe and Simulink. In our previous work [87], a comparison 737 between open-source ABS frameworks was provided. However, the comparison 738 lacked some frameworks that were revealed by the SLR provided in this work. 730

Table 6: The reviewed papers per used framework				
Framework	Papers using the framework			
Ad hoc	Agogino et al. [62], Ashraf et al. [37], Wei et al. [51, 31], Bürkle			
	et al. [24], Rollo et al. [26], Gunetti et al. [33], Evertsz et al.			
	[52], Kandil et al. [38], Sampedro et al. [35], Peng et al. [54],			
	Benedetti et al. [45], De Benedetti et al. [27, 61], Bürkle and			
	Leuchter [46], da Silva et al. [50], Schatten [58]			
MASON [79]	Albani et al. [63], Zou et al. [41]			
AgentFly [76]	Semsch et al. [47], Pechoucek et al. [59], Šišlák et al. [39]			
PROMELA [83]	Webster et al. [56]			
A-globe [80]	Volf et al. [53], Stenger et al. [34]			
NetLogo [78]	Cimino et al. [28], Zhu et al. [25]			
Simulink [72]	Gunetti et al. [32], Ciarletta et al. [29], Kucherov and Kucherov			
	[42]			
Gwendolen [84]	Webster et al. [57]			
Gazebo [77]	Arokiasami et al. [40], Ma et al. [55]			
Repast Simphony [81]	Khaleghi et al. [48]			
Neptus [85]	Vasilijevic et al. [6]			
jME3 [60]	Veloso et al. [60]			
SPADE [86]	Obdržálek [30]			
JADE [82]	Fulford et al. [36]			
n/a	Van der Walle et al. [43], Sutton et al. [44], Bentz and Panagou			
	[49], Ferrag et al. [64]			

The two most used frameworks by the papers in the SLR are AgentFly (7%), 740 Simulink (7%). However, the result indicate that no framework was favored by 741 researchers for civilian UAV applications. The larger part of the of implemen-742 tations in the reviewed papers is using an ad hoc framework (43%). These 743 simulation frameworks are typically developed by the authors of the reviewed 744 papers from scratch. This fact leads us to consider that the existing frame-745 works do not cover all the needs mandatory for implementing a UAV simulation 746 software. Moreover, and due to the abundance of frameworks with no clear 747 distinguished features related to UAVs, the authors generally prefer to setup 748 their own configuration and build the simulation framework from scratch even 749 though it is time-consuming. Regarding the public availability of the imple-750 mented solution, only one paper has provided full access to the code [41], and 751 some papers provided partial access to pieces of code or to open source tools 752 that they used [35, 48, 6, 55, 60, 29, 58, 30], while the rest of papers did not 753 provide any access. 754

755 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 civilian 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), 764 the theoretical and experimental results (Q3), and the limitations and research 765 directions (Q4). Fig. 26 shows the average evaluation for each of these criteria. 766 Reviewers have provided a score, according to their background and knowledge, 767 based on three levels of quality: "bad", "average", "good". Each paper was 768 evaluated by at least two reviewers and the results were averaged into a scale 769 from 1 to 5. Over the entire set of the papers, motivations and contexts are 770 clearly explained. Presentation of the results is described with the minimum 771 set of details to allow a researcher to reproduce the presented results. Finally, 772 as can be seen from the figure, reviewers have considered that the limitations of 773 the proposed models and approaches are not enough detailed within the papers. 774 However, as UAV technology evolves and new UAV manufacturers claim new 775 customers and social flight clubs enlist fresh enthusiast amateur pilots, these 776 open issues and limitations are becoming significant challenges. 777

For instance, regulation and collision avoidance are among the prominent 778 challenges to be settled. Yet, the air is still largely unregulated and unmarked, 779 especially to the naked eye, unequipped with height measuring methods, without 780 prior knowledge of any restrictions regarding the filming of surrounding people, 781 and the seriousness of the threat a UAV poses as it zooms past or above people. 782 Moreover, enhanced availability of better GPS-trackers, quieter copters, and 783 smaller "footprint" also raises new legal issues and requires current and up-784 to-date regulation. Nevertheless, the vast majority of the world still remains 785 behind on effective UAV control. Yet, these issues have not received enough 786 attention in the reviewed papers. Namely, regulation is addressed directly in 787 no more than 7% of the papers. while collision avoidance and UAV safety are 788 addressed only by 11% of the papers. 789

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

⁷⁹² 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 specif-797 ically control-related, nor concerned with inner-loop feedback stability 798 and control. Since the early UAV research works [88], several related 799 issues have been considered: (i) secure communications, unjammable 800 data link (this point is specifically addressed in RD3); (ii) coordination; 801 (iii) target identification; (iv) target assignment; and (v) deconfliction. 802 References cite automated decision aiding/decision making as one of the 803 most difficult problems leading to autonomy. Man-machine interface, 804 communications, task and path planning, and target identification are 805 real and difficult issues. 806

The aim of a typical UAV planning algorithm is to determine a path 807 through the environment while satisfying all the constraints and the 808 mission objectives. Such a planning algorithm involves several levels of 809 planning: (i) pre-mission planning where all the information is static. 810 This is the best plan that can be made based on the available informa-811 tion. (ii) near term plan, which is executed in the air and involves the 812 physical flying of the UAVs. This can be looked at as a trajectory track-813 ing task, which can be completely automated through inner-loop control, 814 autopilot design, tracking, and short-term on-line trajectory generation. 815 It is the intermediate level of planning where the desired capability of 816 autonomous control is achieved. *(iii)* Near real-time in-flight replanning 817 is needed as new sensor information or commands are received by the 818 UAVs. The challenge is to optimally update the off-line plan as per the 819 new received information and/or the unforeseen occurred events. The 820 optimization problem is dominated by size, complexity, uncertainty, and 821 the fact that the mission could be shared by different UAVs. This leads to 822 problems related to the cooperation and coordination of the autonomous 823 UAVs, and opens the door for challenges like flexible autonomy [24] and 824 initiative decision-making [89]. 825

RD2: Explaining the UAV Behavior; As shown in the previous section, there 826 is a confirmed tendency towards the development of increasingly au-827 tonomous UAV systems. This evolution would minimize the human in-828 tervention by relieving the human operator from the burden of contin-829 uously monitoring the UAVs. Nevertheless, in unpredictable situations. 830 the UAV behavior might not conform to expectations of the human oper-831 ator. For instance, in a product delivery scenario, an autonomous UAV 832 may choose to deviate from its expected path because of an unforeseen 833 event. Enhancing the UAVs with explaining capabilities would allow 834 the human operator to understand the reasons behind UAV behavior 835 and raises its trust in the autonomous UAV system. Moreover, the re-836 cent developments of the domain of eXplainable AI (XAI) help UAVs 837 to move in this direction. As a matter of fact, UAV has been cited 838 as one of the applications where XAI would be needed [90]. Further-839 more, developing explainable UAV would have a very positive impact 840 on human-machine teaming. Recently, this research direction is being 841 explored by military UAV applications. Similar efforts should be con-842 sidered for civilian applications [91]. As shown by recent studies, using 843 BDI agents is a promising approach to develop explainable agents [92]. 844 A key explanation for this success lies in the fact that BDI paradigm 845 is inspired from folk psychology which means that "the core concepts of 846 the agent framework map easily to the language people use to describe 847 their reasoning and actions in everyday conversations" [93]. Therefore, 848 BDI architecture offers a more straightforward description making mod-849 els easier to explain for end-users. For this reason, UAV agents relying 850 on BDI architectures, which represent only 14% of papers reviewed in 851

this SLR (*c.f.* Figure 16), are likely to increase in numbers if the issue of explainable UAV behavior is to become a hot research topic.

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RD3: Ensuring Security and Authentication; The quest of developing auto-854 nomous and decentralized UAV systems raises several challenges related 855 to security and authentication. For instance, within a swarm, a UAV 856 must be able to detect and entrust its peers, and ensure data confiden-857 tiality and integrity. Otherwise, faulty or malicious UAVs may deviate 858 859 the swarm behavior [94]. These challenges are accentuated by the fact that most UAV swarms are designed to operate autonomously without 860 a central regulating authority. Recent research has outlined Block-Chain 861 Technology (BCT) as a potential solution to overcome this problem. In 862 addition to providing a platform allowing for secured interactions among 863 UAVs, BCT can also be used to enhance the decentralized decision mak-864 ing of the UAV swarm since it allows all the participants to share an 865 identical view of the world, and facilitate agreements among UAV teams 866 [94]. Yet, before BCT is ready to be used with UAVs, several limitations 867 must be solved [94]: (i) latency: the time required to update the blockchain is too long to allow real-time compliance (a common requirement 869 in UAV applications); (ii) Most of the UAVs are resource-constrained 870 devices which might be unable to undertake the heavy computations de-871 manded by BCT. For this reason, recent research works in BCT propose 872 lightweight techniques (e.g. "proof of stake") that can be handled by 873 resource-constrained devices such as the UAVs; (iii) On the long run, 874 BCT can be very demanding in terms of bandwidth and communication 875 overhead since all agents should share a copy of a long "ledger" of inter-876 actions [95]. This issue, known as "bloat", poses a considerable challenge 877 to UAV teams which have limited hardware and communication capa-878 bilities. 879

RD4: Increasing the flight duration; Another problem is the UAV battery life. 880 This well-known problem is related to the UAV design and concerns the 881 improvement of the UAV battery life. Currently, the battery of a typical 882 UAV allows for up to 13 to 20 minutes of continues flight. In a large 883 number of application cases, this duration is not long enough to enable 884 UAVs to achieve their objective before they run out of power and fall 885 down. There are some technical solutions allowing to increase the battery 886 life. Yet, as the battery capacity increases, its size and weight generally 887 increase, which cause the UAVs to consume more power. Battery man-888 agement can help handle this issue by managing battery consumption prediction and planning [96], scheduling [97], and replacement of battery 890 [98, 99]. Battery wireless charging is also an option through power lines 891 [100], or an automatic charging system that uses charging stations posi-892 tioned along the path of the UAV mission [101]. For long-endurance and 893 high-altitude flights, solar-powered UAVs could be used [102, 103, 104]. 894

RD5: Integrating UAVs into smart cities; A smart city integrates heteroge-895 neous connected objects to automate or simplify autonomous and trans-896 parent accomplishment of various daily tasks, both personal and pro-897 fessional [74]. A smart city is an urban area that uses different types 898 of electronic data collection sensors to supply information which is used 899 to manage assets and resources efficiently. This includes data collected 900 from citizens, devices, and assets that are processed and analyzed to mon-901 itor and manage traffic and transportation systems, power plants, water 902 supply networks, waste management, law enforcement, information sys-903 tems, schools, libraries, hospitals, and other community services [105]. 904 The smart city concept integrates ICT, and various physical devices con-905 nected to the network to optimize the efficiency of city operations and 906 services and connect to citizens [106]. According to Farhan et al. [107], 907 several opportunities for UAVs uses to support a smart city exist. These 908 opportunities will be very beneficial to any smart city that would utilize 909 UAVs for their economic growth and development. 910

One of the new trends in civilian UAV applications in smart cities is using 911 UAVs in geospatial surveying. The main design of a smart city requires 912 the optimization of data flows provided by wireless sensor networks as 913 sensors are the main component of any autonomous system such as those 914 involving UAVs. This combination of technologies creates a wide range 915 of applications and opportunities such as fire management in open areas 916 where the use of UAVs and micro-UAVs is very beneficial. The potentials 917 vary from a wide range of available solutions and innovations that are 918 evolving quickly. Due to the reliability of most UAV designs, integration 919 of such technologies make it possible to install wireless sensors on-board 920 to make the UAVs usable in geospatial, land surveying and Geographic 921 Information System (GIS) applications in smart cities in addition to 922 being helpful for environmental analysis. These opportunities may lead 923 to cost reduction and cutting down on the number of manpower hours 924 involved in such activities. 925

The integration of UAV solutions with machine-to-machine, Radio-926 frequency identification (RFID) and live video streaming increased the 927 role of UAVs in public safety areas. This new trend will move the cities 928 management personnel from being reactive to proactive and will lever-929 age data. Furthermore, the involvement of UAVs in surveillance activi-930 ties will reduce costs and increase the efficiency of the operations. The 931 efficiency of security and safety systems in a city has become a serious 932 concern not only for smart cities but also for any type of cities or com-933 munities. Involvement of UAVs in smart policing activities has lately 934 been supported by the US Congress and top level federal agencies such 935 as the Bureau of Justice Assistance, and the US Department of Justice. 936

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 orUAVs.
- In addition to integrating UAVs into smart cities, integrating them into large, open and isolated space is another research direction. Applications in agriculture, environment preservation and sustainable energy (*e.g.* solar farms monitoring, electric transport, *etc.*) are countless.
- 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 [108].
- Recognizing the enormous potential growth of UAVs, the European Avi-957 ation Safety Agency (EASA) has been tasked by the European Commis-958 sion to frame regulations for UAV operations. In 2014, the Commission 959 published "A new era for aviation—Opening the aviation market to the 960 civilian use of remotely piloted aircraft systems in a safe and sustainable 961 manner" [109] but this does not include the UAVs. The EASA published 962 a comprehensive proposal in May 2017 covering the technical and oper-963 ational aspects of operating UAV. According to the proposal, all UAVs 964 above 250 g need to be registered. The proposal put the alignment of 965 different national UAV legislations as one of Horizon 2020 goals. How-966 ever, these goals have been postponed until 2050. Moreover, different 967 European countries have different regulations – for instance, one can fly 968 UAVs commercially in Switzerland if line-of-sight can be ensured, within 969 certain altitude limitations and not flying near protected areas such as 970 airports. On the other hand, France has more restrictive regulations in 971 place where it is mandatory that any UAV operation over a city needs to 972 be authorized by aviation authorities. In Belgium, Brussels is planning 973 to create "Uspace" in 2019, a European controlled space for UAVs flying 974 above 150 m in height and weighing less than 150 kg. 975
- In India, some work examines civilian 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 [110].
- USA has by far the most mature civilian 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 civilian 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 988 a complicated task. This is because international conventions on inter-989 national civilian aviation, such as the Chicago Convention, apply only 990 to civilian manned aircraft but not to unmanned ones [108]. It is neces-991 sary to have a legislation that will be open and generic in the technical 992 aspects. This is because legislations that are limited to specific aircraft 993 types or only permit the use of remote controls with certain character-994 istics would become obsolete in the near future, as new advances in the 995 field of UAVs appear Furthermore, regulations should not only consider 996 the civilian liability of these devices but also aspects that will assure the 997 security of the citizens, for example, the protection of data in deployed 998 vehicles [108]. ggg

RD7: Verifying and validating the UAV behavior; According to [111], the more 1000 complex a UAV software function gets, the more difficult it becomes 1001 to test. Furthermore, functional requirements are only one aspect of a 1002 system. Beyond the pure verification of a requirement lies the benchmark 1003 of the implemented solution. The resulting outcome may be determined 1004 by a test of the requirement, but the specific path to the solution can 1005 have different levels of quality. Therefore, additional tests have to verify 1006 that the specified safety boundaries, as well as additional constraints, are 1007 met by this algorithm. To be able to assess highly automated functions 1008 and to be able to assure a high-quality software system, it is, therefore, 1009 necessary to implement a scoring system or a benchmark to evaluate 1010 the autonomy using non-functional requirements. For example, for path 1011 planning the standardized benchmark by [112] is utilized to measure the 1012 correctness and result quality by expressing a set of pass/fail criteria 1013 from the standardized baseline solution. 1014

It is important to notice that benchmarks are problem specific, and not 1015 implementation specific. This enables developers not only to test a path-1016 planning algorithm automatically, without a manual review from an en-1017 gineer, but also to evaluate algorithms and compare them with different 1018 implementations and solution approaches. The development of such au-1019 tomatic tests and benchmarks for additional problems, such as sensor 1020 fusion and computer vision, to generally assess the capability to fulfill 1021 navigation safety and performance requirements, will be critical to the 1022 progress of UAVs and the evaluation of new approaches [111]. 1023

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 re1028quired for developing of increasingly automated and autonomous systems1029[113]. Enabling early validation of such system designs requires the simulation of components. This requires the development of adapted simula-1030lation of components. This requires the development of adapted simula-1031tion environment, possibly real-time, composed of a collection of reusable1032modules combining real and virtual components (also called XiL: X-in-1033the-Loop, where X meaning alternatively Model/Software/Hardware and1034Human).

1035 5. Related Works

Recently, several works surveyed the emerging topics of UAVs. However, 1036 these works mainly focused on vertical applications without considering the 1037 aspects and challenges across multiple application domains and research topics. 1038 For instance, Hayat et al. [114] focused on the characteristics and requirements 1039 of UAV networks for envisioned civilian applications between 2000 and 2015 1040 from a communications and networking point of view. Motlagh et al. [115] 1041 reviewed Low-altitude UAVs highlighting their potential use in the delivery of 1042 IoT services from the sky. Other surveys focused on traffic management [116]. 1043 environmental monitoring [117], ad hoc networks in UAV applications [118], 1044 routing and energy efficiency in UAV communication networks [119], and UAV 1045 coverage [120]. 1046

One interesting survey is provided by Chmaj and Selvaraj [121] 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.

¹⁰⁵² Shakhatreh et al. [122] reviewed civilian UAV applications and challenges. ¹⁰⁵³ They identify current research trends and future challenges for civilian UAV ¹⁰⁵⁴ applications, including: charging, collision avoidance, swarming, networking and ¹⁰⁵⁵ security-related challenges. Yet, this survey was mainly inspired by low-level ¹⁰⁵⁶ aspects of the UAV like networking and wireless communication. Moreover, the ¹⁰⁵⁷ listing of the comparison was in sequence without a cross-application domain ¹⁰⁵⁸ 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. [123], while the interaction between UAVs and humans applications were considered in another survey [124]. 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.

1066 6. Conclusions

¹⁰⁶⁷ UAVs are becoming increasingly popular for civilian applications. The aim ¹⁰⁶⁸ of this paper is twofold. First, conduct a SLR on research addressing MAS, and specifically ABS, in civilian UAV applications. Second, outline and analyze the challenging research direction of civilian UAV applications. The following section states the principal findings. Note that while the SLR concentrated on research using ABS for civilian UAV applications, some of the findings below pertain to key research issues in agent and MAS (*e.g.* agent architectures, decentralization, *etc.*).

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

- Research on MAS and ABS for civilian 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.
- 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.
- 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.
- 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 UAVrelated regulations; and (vii) Verification and validation the UAV behaviors.

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.

Additionally, RD7 and the need for simulation testbeds suggest that the use of ABS frameworks for UAVs will gain more interest in complex civilian applications scenarios. Therefore, one future work is to rely on the results of this SLR to select specific criteria allowing to define a methodology to compare ABS frameworks and evaluate them based on civilian UAV application considerations.

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