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Design Principles for Distributed Context Modeling of Autonomous Systems

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ABSTRACT The use of unmanned aerial vehicles (UAV) has seen a rapid increase due to the advancements in drone technology and the wide range of applications. Their adaptability and versatility make them suitable for a great variety of tasks. To fully realize their potential, an autonomous operation is crucial. For modeling environmental perception (i.e., contextual information) as a key enabler of autonomous operations, guiding principles are needed to support system designers in modeling contextual information for autonomous systems. This article precisely addresses this concern and seeks to establish a set of design principles for the distributed context modeling of autonomous systems, such as autonomous UAVs. This is achieved through a systematic review of the literature and the identification of meta-requirements by leveraging a generic context classification model, which serves as the foundation for deriving the design principles. Subsequently, these design principles undergo evaluation within the context of autonomous UAVs through a use case analysis. The goal of this research is to provide a foundation for the development of autonomous systems that can effectively perceive, interpret, and distribute their context. The design principles can serve as a prescriptive guide for the future development of autonomous systems, ensuring efficient and effective operations.

INDEX TERMS Autonomous systems, context modeling, design principles, distributed systems, situation awareness.

I. INTRODUCTION

While unmanned aerial vehicles (UAV), commonly referred to as drones, have been utilized in military contexts for a while, their civilian application has advanced considerably in recent times. The crucial factors for a sharp increase in commercial use are the rapid development in the field of drone technology and the wide range of possible applications. [1]

In this regard, drones are particularly well-suited for surveying extensive terrains that are challenging to access. Drones can be used for a variety of purposes and in various applications, such as the observation, monitoring, and inspection of facilities, transportation of goods, or the support of postdisaster operations. However, drones can only realize their full potential if they can be deployed autonomously. Autonomous drones, equivalent to autonomous systems in general, are capable of performing a task assigned to them autonomously and largely without human intervention. [2]

Autonomous systems differ from the automated systems widely used today in their high adaptability, for which it is necessary, among other things, that the autonomous system can perceive and interpret their environment, which is also referred to as context. Thus, the perception and interpretation of contextual information are essential prerequisites for fully autonomous behavior [3]. Additionally, context information distribution between individual system participants offers enormous opportunities and can efficiently improve the overall system by providing additional contextual information and expanding the perception range. However, special requirements arise for a distributed context modeling of autonomous systems and require prescriptive knowledge for the development of such complex dependencies. Design principles can help to document such prescriptive knowledge and are a suitable medium to capture prescriptive design knowledge [4].

The goal of this research is to develop design principles for distributed context modeling of autonomous systems. For this purpose, a systematic literature review of distributed context models in the area of autonomous drones was conducted, but also other systems were considered, such as autonomous

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TABLE 1. Classification of Context Modeling (Acc. to [8])

Dimension	Characteristics					
Context Aquisition	Sensed		Derived		Externally Provided	
Context Modeling	Object Based	Logic Based	Ontolgy Based	Graphical	Markup Scheme	Key-Value Based
Context Filtering/Fusion	Statistical		Probabilistic		Artificial Intelligence	
Context Storage	Centralized			Distributed		
Context Application	Presentation of Information and Services		Automatic Execution of Services		Tagging of context to information	

robots, industrial environments, or ubiquitous computing. The rest of this article is organized as follows. In Section II, a theoretical background is given to serve as a basis for context modeling of autonomous, cooperative systems. Section III presents the applied research method of developing design principles for distributed context modeling, and introduces a use case, which represents a cooperative system. The meta-requirement generation is described in Section IV and finally, the design principles are elaborated in Section V. After an evaluation (Section VI), a short summary concludes this article and a research outlook is given in Section VII.

II. THEORETICAL BACKGROUND

A. CONTEXT MODELING

Since the early 1990s, there has been a long-lasting interest in context-aware, intelligent systems that can adapt their behavior accordingly based on contextual inputs [5]. For the development of such sophisticated and context-aware systems, an understanding of the notion of "context" is essential. While some researchers have tried to define what context is, the approach of Dey and Abowd in the field of ubiquitous computing prevailed, defining context as "any information that can be used to characterize the situation of an entity" [6].

Apart from defining context through conceptualization, efforts have also been made to categorize and subcategorize it into various types [7]. Structuring relevant context information in the initial stages of engineering is known as "context modeling." A context model is a simplified depiction of context utilized to delineate and structure context elements. Additionally, a context element is defined as a fragment of context that characterizes a contextual aspect, such as the present location of the system being considered. With the high complexity of context modeling, some researchers elaborated on the fundamental characteristics that may influence a context model in its creation. For instance, Liu's classification [8] of context modeling presents a thorough outline of the fundamental conceptual aspects of context modeling. This categorization draws upon studies of context awareness and highlights five crucial dimensions and 17 distinctive characteristics of context modeling (see Table 1).

The conceptual approach of context modeling has since been applied by researchers to other domains as well. In addition to an intensive investigation in the domain of ubiquitous computing, attempts have been made to transfer context modeling to the domain of industrial applications [9], [10], [11] and to the domain of autonomous systems [12], [13], [14], [15]. In most cases, current methods concentrate on the development of individual systems rather than explicitly emphasizing the elicitation and documentation of context information, regardless of the application domain. However, for autonomous, collaborating systems, it is crucial and also challenging to give adequate attention to the system's context. This is due to the fact that not only the individual system perceives its context with the help of sensors in order to derive its individual behavior, but rather a group of systems exchanges context information with each other. This exchange of context information enhances perception considerably, but simultaneously introduces novel challenges, such as grappling with contextual uncertainty stemming from divergent sensor measurements.

B. AUTONOMOUS SYSTEMS

A system that can achieve a given goal independently and can adapt to the situation without human control or detailed programming is referred to as "autonomous" [16]. The capabilities of such systems and their areas of application domains have expanded significantly in recent years, with widely acclaimed successes in several applications [17]. The notion "autonomous system" is very broad in this sense, whereas two main types can be distinguished.

1) Autonomous systems that operate only in a virtual world such as the Internet.
2) Autonomous systems that have an impact on the physical world, such as robots, UAVs, an autonomous energy management system, or an entire smart city that autonomously controls processes.

This article will primarily focus on autonomous robot systems, which constitute the second type of autonomous systems mentioned before. To achieve their objectives, such systems must accurately perceive and evaluate the environment, the system's state, and the task's comprehension. Based on the system's state and the situation at hand, the system independently formulates and selects various actions to accomplish the respective objectives.

Autonomous systems possess the capability to perceive and operate in complex and dynamic environments [18], [19] and accomplish diverse actions and tasks independently compared to automated systems [20], [21]. Autonomy typically requires a system equipped with multisource sensors and software that can process complex tasks, enabling the system to achieve its goals and objectives independently without external communication or with limited communication with the outside world within a specific timeframe, and without the assistance of external intervention. Furthermore, such systems can learn and develop in unfamiliar environments, continually enhancing their task-completion capabilities and maintaining exceptional performance. Autonomy can be regarded as an advancement of automation, leading toward higher mobility and intelligence [22].

It can be recognized that incremental and agile software development processes become more and more important in the domain of autonomous system design [23]. Although the applicability of agile methodologies to autonomous system design is subject to shifts in emphasis and preference within the engineering and development community, standardized design principles provide a structured framework for design decision-making, promote collaboration, enhance efficiency, and ensure a user-centered focus throughout agile software development processes. They are a valuable tool for agile teams looking to consistently deliver high-quality products that meet both user needs and business objectives. Thus, incorporating agile principles into the design paradigm can enhance the responsiveness and effectiveness of agile autonomous system development, particularly in addressing dynamic requirements gathering challenges.

III. RESEARCH METHOD

A. STUDY DESIGN

Design principles, as a form of formalized knowledge, are becoming increasingly popular in many scientific fields because they allow researchers to capture abstract knowledge that relates to a class of problems rather than a single problem [4], [24]. To ensure practical relevance and applicability, design principles should imply accessibility, effectiveness, and, most importantly, guidance for action.

This scientific analysis uses a rigorous method to create design principles, which is based on paper [25]. A graphical description of the method is shown in Fig. 1. This method not only supports various approaches to the formation of design principles (Design Expert Observation, Derivation from Laboratory Base Design Practice, Derivation from Design Practice, Experience, Review of existing Principles, Analysis of Existing Designs, etc. [26]) but has also been used by several researchers in the past to create design principle [27], [28], [29].

First, in accordance with the method for creating design principles from Möller et al. [25], it was defined what purpose the design principles to be formed should serve. The aim of the so-called *Solution Objective* (methodical step—see Section I) is to state the purpose of the design principles concisely and precisely.

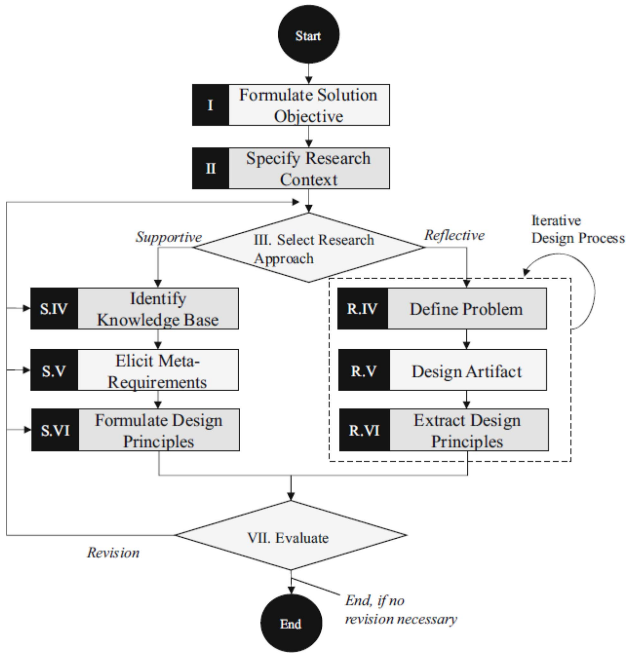

FIGURE 1. Method for design principle development [24].

In the next step, the *Research Context* and the *Research Approach* (see Sections II and III) were defined. For the creation of design principles in this article, an empirical approach was chosen and existing designs of context models in different application areas were analyzed. Since the design principles to be created aim at providing design knowledge in advance to support the design of a context model before the design process has taken place, a supportive approach was chosen.

Since context modeling for autonomous robot systems is still under development and thus subject to continuous change, existing concepts from relevant literature were evaluated for the creation of the design principles (empirical approach). A literature search was conducted, which was carried out according to established guidelines [30], [31]. Various combinations of search terms (e.g., "context modeling" or "environment model") were used in a Google Scholar search. In order to investigate a broad spectrum of context modeling, different application domains were not narrowed down. To ensure timeliness, only articles no older than the year of publication in 2000 were reviewed. Furthermore, only articles that have undergone a peer review process were considered in order to meet a qualitative standard. In the case of suitable content, corresponding cross-references of the considered literature were also considered. In the end, 31 papers (see the Appendix) were considered as the *Knowledge Base* (see Section IV) of the analysis.

Initially, *Meta-Requirements* (see Section V) were identified as a typical avenue for design principle generation. Following the advice of Koppenhagen et al. [32] the array of

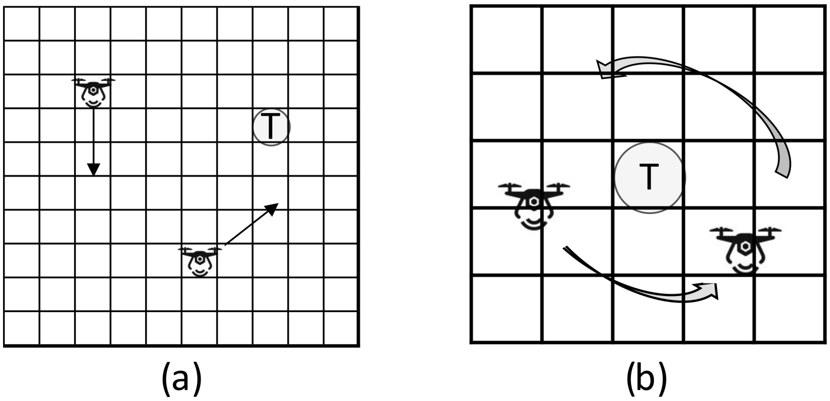

FIGURE 2. Schematic illustration of "tracking (a) and surrounding (b) a stationary target with UAVs."

requirements has been clustered before the design principle formulation. This also guarantees that the design principles produced aim for issues that are of significant importance, rather than merely addressing a wide range of specific problems [25].

In the following, the design knowledge for the creation of context models of autonomous systems was derived in the form of *Design Principles* (see Section VI). The design principles follow the general concept of Gregor et al. [24], who defined the anatomy of design principles so that design principles are "understandable and useful in real-world design contexts." A linguistic template from Chandra et al. [4] was used because it provides conceptual guidance on the building blocks of the design principles in addition to linguistic guidance. The template is as follows [4]:

"Provide the system with [material property – in terms of form and function] in order for users to [activity of user/group of users – in terms of action], given that [boundary conditions – user group's characteristics or implementation settings]."

The evaluation of constructed artifacts such as design principles is an essential step in the design cycle to generate rigorous design knowledge. For preliminary *Evaluation* (see Section VII) each design principle has been applied to the use case "Tracking and Surrounding a Stationary Target with UAVs" after the creation process. Additionally, the collection of design principles has been assessed regarding their reusability following the framework of Iivari et al. [33]. During evaluation, parts of the design principles and their characteristics were revised and whenever useful the descriptions were extended to increase the common understanding.

B. USE CASE—TRACKING AND SURROUNDING A STATIONARY TARGET WITH UAVS

For preliminary use case validation, a group of two homogenous, autonomous UAVs is considered, which means both UAVs have the same context perception and action capabilities. The UAVs use decentralized coordination, lacking a centralized control or leader who possesses complete information about the environment and makes decisions for each UAV. To simplify the process, the environment is divided into a square grid, allowing for the identification of specific grid cells in the scenario. Utilizing this information, each UAV is able to determine its coordinates and the current heading, specifying the UAV's orientation. The use case consists of two phases: the tracking phase and the surrounding phase, which are illustrated in Fig. 2(a) and (b).

In the tracking phase, each UAV flies straight with constant speed and altitude until it detects the target ahead or the border of the area to be searched, which is known by the UAVs. It is assumed that the target T (i.e., a tower) is higher than the initial altitude of the UAVs. When a UAV reaches the end of the area to be searched, it rotates 120° and continues tracking. This blind search is continued until the target is found. As soon as the target is found, the surround phase is initialized. For this, the first UAV that finds the target transmits the coordinates of the target to the other UAV. The UAVs use direct communication and have the goal of staying equidistant from the target and from each other while surrounding the target. The surround task of the stationary target is the main goal of the UAVs in the proposed use case. The UAVs have to perceive their context and have to communicate this perception in order to be able to fulfill a collaborative task. Therefore, coordination mechanisms are necessary. However, this work focuses only on the creation of a context model for the design of a collaborative robot system. The design principles formulated in this study provide substantial guidance for the implementation of collaborative use cases involving robot systems.

IV. META-REQUIREMENTS FOR DISTRIBUTED CONTEXT MODELS

Meta-requirements concern a collection of requirements and are therefore formulated in an abstract and general way. Applying meta-requirements provides an effective method to support requirements specification completeness [34]. The collected meta-requirements rely on the generic classification for context modeling (see Table 2), which acts as a structure for organizing them because it facilitates a comprehensive understanding of the context modeling subject. To achieve this, the 17 distinctive characteristics within the five dimensions

TABLE 2. Short Description of the Meta-Requirements

Meta requirement (MR)	Characteristics	Description
Context Aquisition (MR 1)	Sensed	Refers to the ability of the context model to capture, store and process sensed data from an autonomous system
	Derived	Refers to the ability of the context model to capture, store and process derived data from an autonomous system
	Externally provided	Refers to the ability of the context model to capture, store and process data, which is provided from external sources
Context Modeling (MR 2)	Integration	Refers to the requirement that the chosen context model is easy to integrate into all engineering steps during the entire lifecycle of the autonomous system
	Vizualization	Refers to the requirement that the chosen context visualizes the data structure and interdependencies of the several context information
	Implementation	Refers to the requirement that the chosen context model is easy to implement during the design of the autonomous system
Context Filtering/Fusion (MR 3)	Statistical	Refers to a context model that filters and fuses information on a statistical basis
	Probabilistic	Refers to a context model that filters and fuses information on a probabilistic basis
	Artificial Intelligence	Refers to a context model that filters and fuses information using artificial intelligence
Context Distribution (MR 4)	Centralized	Refers to a context model architecture, where all distributed context information are centrally stored an processed
	Decentralized	Refers to a context model architecture, where all distributed context information are directly shared between system contributers
Context Interoperability (MR 5)	Fully interoperable	Refers to a context model whose semantic models are completely identical without the need of any translation
	Interoberable via interface	Refers to a context model whose semantic models differ and where context information need to be translated via an interface
Context Reasoning (MR 6)	Uncertainty handling	Refers to the capability to handle and process uncertainties of context information to derive new context information

of the classification are used as a baseline: *Context Acquisition, Context Modeling, Context Filtering and Fusion, Context Storage,* and *Context Application*.

The dimensions *Context Acquisition, Context Modeling,* and *Context Filtering/Fusion* were adopted unchanged for the creation of the meta-requirements, whereas *Context Storage* was renamed to *Context Distribution* to emphasize the architectural character of this dimension. These four dimensions can directly be used for the creation of technology-oriented design principles, as they have relevant implications for the context modeling of autonomous robot systems and are equally relevant for generic context modeling as well as for use cases in the field of autonomous robot systems.

The dimension *Context Application* remains unconsidered, as the initial definition of its characteristics is exclusively focused on the field of mobile computing. However, in the field of autonomous systems, context information is used for the generation of situational awareness. The autonomous system shall be put in a state to perceive and understand its contextual environment. Based on this perception and its individual and collective goals, decisions shall be made to achieve these goals. Therefore, a distinction between different context applications for autonomous systems is not required and was not considered further for the creation of the meta-requirements.

The aspect of *Context Interoperability* is also relevant, as several approaches of modeling the context typically lack formality and interoperability. An early proposal of Strang et al. [35] tried to close the formality gap by using ontologies as a fundament to describe contextual facts and interdependencies. Several researchers [36], [37], [38], [39] followed this approach and tried to countersteer the lack of formality. Additionally, IEEE introduced the standard 1872 “Standard Ontologies for Robotics and Automation” [40] to further formalize the creation of ontologies for robotic systems, which has been extended in 2021 to represent additional domain-specific concepts, definitions and axioms commonly used in autonomous robotics.

Representing context information in a formal and standardized way is the key enabler for an intelligent use of this information. This task is often referred to as *Context Reasoning*, which has been included in the meta-requirements, as many researchers exploit it to approach the inherent complexity of context-aware applications [41], [42], [43], [44]. As highlighted by Nurmi [45] context reasoning can be used for checking the correctness on the one hand and also for deducing new and relevant information from the various sources of context-data. Table 2 summarizes the six meta-requirements for distributed context models derived from the literature and the generic classification as introduced in Chapter II.

V. DESIGN PRINCIPLES FOR DISTRIBUTED CONTEXT MODELING

A. CONTEXT ACQUISITION

1) DESIGN PRINCIPLE 1

Provide the context model with convenient functionalities in order to allow the autonomous system to process sensed, derived, and externally provided context information, given that the context model enables efficient cooperation and multilateral information distribution.

This design principle considers the different ways how context information can be acquired. Damak et al. [12], for example, define the importance of including the "system's environment, and external interfaces, as well as the system's features and characteristics" in their operational context model to include all instances of information of an autonomous system and the expected behavior. Therefore, context models must fulfill all three dimensions of context information acquisition to be used for autonomous systems.

2) USE CASE ILLUSTRATION

For the considered use case, the UAVs need to be able to directly sense context information (e.g., GPS coordinates, motor RPM, etc.) and to derive information as well (e.g., flight speed and distance to target derived from GPS). For the collaborative part, it is also important that they are able to capture and process context information that is externally provided by other UAVs (e.g., position, surrounding speed, and distance).

B. CONTEXT MODELING

1) DESIGN PRINCIPLE 2

Provide the context model with capabilities to represent context information in a structured and comprehensible way in order to allow the designers of an autonomous system to visualize, integrate, and implement the relevant context information, given that the context model makes efficient cooperation and multilateral information distribution possible.

Model-based approaches are of particular relevance if persons with different working backgrounds have to interact during the design of complex systems. Models improve communication and information sharing as the problem is presented in a simple and comprehensible form. While some authors use graphical modeling approaches [46], [47], it can be recognized that ontology exploitation can be seen as quasi-standard [36], [37], [42], [48], which is also summarized by Bayat et al. [38]: "The concepts in an ontology are, in general, the concepts that are shared by most of the community. Thus, we can say that an ontology captures a common understanding, or the consensual knowledge, about the domain."

2) USE CASE ILLUSTRATION

The aspects are relevant for the Tracking and Surrounding use case. The representation of context information within an ontology allows the semantic visualization of all relevant context information and can, therefore, foster visualization among stakeholders. Thus, the rigorous specification in a machine-processable and formal way supports the integration and implementation of the context model into the autonomous system.

C. CONTEXT FILTERING/FUSION

1) DESIGN PRINCIPLE 3

Provide the context model with filtering and fusion capabilities in order to allow the autonomous system to only use relevant and valuable context information, given that the context model enables efficient cooperation and multilateral information distribution.

It is necessary to effectively reduce the large amount of context information by selective filtering since raw sensor data is simple, unstable, and inaccurate after acquisition. On one hand, semantic information can already be extracted from the sensor data, on the other hand, only relevant context information has to be processed by the autonomous system. The issue is summarized by Yeong et al. by highlighting that "it is always essential to consider the advantages, disadvantages, and limitations of the selected group of sensors …" [49].

The goal of context fusion is to generate a maximum gain from inconsistent information. This inconsistent, sometimes even contradictory information, results from the generation of context information via different sensor devices within a single system or the exchange of context information by cooperative system participants. Various researchers are exploring approaches and rules to maximize the gain from context fusion [15], [18], [49].

2) USE CASE ILLUSTRATION

Although Tracking and Surrounding a Stationary Target is a simplified use case representing cooperative tasks, the amount of possible context information could already be huge. However, for an efficient context model, it is not necessary to process more obstacles than necessary, as only the target or the other UAV are foreseen in the use case. Also, the implementation of knowledge fusion techniques can help to enhance the efficiency of this simplified use case whenever inconsistent information is generated.

D. CONTEXT DISTRIBUTION

1) DESIGN PRINCIPLE 4

Provide the context model with capable interfaces that allow decentralized distribution of the relevant context information if there is no central distribution architecture applied in order to share context information between system contributors, given that the context model enables efficient cooperation and multilateral information distribution.

This design principle is critical, especially for the cooperative and architectural aspects of the autonomous robot system. Distributed context models must either be designed in such a way that context information can directly be shared between system contributors or are collected and merged together by a collector (often a ground control station), which then distributes the information centrally. An example for a centrally organized architecture can be found by Cavaliere et al. [50], whereas de Freitas et al. [51] discusses a decentralized architecture for a "Multipurpose Localization Service for Cooperative Multi-UAV Systems."

2) USE CASE ILLUSTRATION

Similar, for the considered use case, the UAVs would directly share the relevant context information during use case execution, as there is no central collector like a ground control station available.

E. CONTEXT INTEROPERABILITY

1) DESIGN PRINCIPLE 5

Provide the context model with standardized data formats and communication protocols in order to enable interoperability of the context information between system contributors, given that the context model enables efficient cooperation and multilateral information distribution.

This design principle refers to the capability of system contributors to be able to share context information by using common data formats and communication protocols. With the help of semantic interoperability, the system contributors are able to interpret the information exchanged meaningfully and accurately. Rode and Turner [52] emphasize the necessity "that there is a way for different agents to represent contexts and agree on the meaning of contextual knowledge. This implies that there exists a representation language for contextual knowledge."

2) USE CASE ILLUSTRATION

The aspect of interoperability is of high relevance because the distribution of context information is the key enabler for cooperation for the use case "Tracking and Surrounding a Stationary Target with UAVs." An easy solution would be a consent to adopt identical semantic standards for the individual UAVs, which is straightforward for the simplified use case with two UAVs. However, this agreement becomes much more difficult and complex for larger system networks, especially if these are deployed by different operators.

F. CONTEXT REASONING

1) DESIGN PRINCIPLE 6

Provide the context model with sufficient reasoning capabilities in order to allow system contributors to deduce new information from uncertain context information, given that the context model enables efficient cooperation and multilateral information distribution.

Since context data are fundamentally characterized by uncertainty and imperfection [53], there is a need for reasoning of context information in autonomous systems. Even in a single system, sensor inaccuracies or connectivity failures results in the problem that not all context information is available with certainty at all times. Furthermore, if a context information comes from multiple sources, the information may become ambiguous. In this case, the task of reasoning is to identify possible errors, make predictions about missing values, and decide on the quality and validity of the collected information.

For this rationale, reasoning plays an essential role in the decision-making process of the autonomous system, which defines its behavior based on the collected context information and a set of decision rules.

2) USE CASE ILLUSTRATION

Considering the problem of imperfect context information is relevant for the use case "Tracking and Surrounding a Stationary Target with UAVs." Due to the nature of imperfect sensory data, it can be assumed that both UAVs generate different information about a specific sensed context information. With the integration of context reasoning, the error can possibly be identified, and the UAVs combine the probabilistic context information to act cooperatively.

VI. PRELIMINARY EVALUATION AND DISCUSSION

In this section, the created design principles for distributed context modeling of autonomous systems are examined and preliminary evaluated in an analytical way. Additionally, contributing aspects and limitations to the proposed design principles are discussed.

A. PRELIMINARY EVALUATION

As prescriptive statements, the proposed design principles are adequately general in order to address a class of artifacts rather than one specific instance [4], [24]. For the evaluation of reusability, the "light reusability evaluation of design principles" framework proposed by Iivari et al. [33] is used, which uses the criteria *Accessibility, Importance, Novelty and Insightfulness, Actability and Guidance*, and *Effectiveness*, for the evaluation.

For A*ccessibility,* the set of design principles needs to be understandable and comprehendible for the target community. The proposed design principles are created for domain experts in the field of context modeling for autonomous systems and are expressed in understandable language. The understandable language and a recurring structure ensure successful communication with the domain experts, who can exploit the set of design principles as a practical guideline. The *Importance* to domain experts and practitioners is given by addressing distributed context modeling of autonomous systems as a real-world problem. Developments and innovations in the field of autonomous systems enable their use in various areas of society and bring the technology from the laboratory into public life. The complexity rises even further with distributed autonomous systems, and it is of crucial importance to consider all relevant aspects of the system design, including distributed context modeling. Regarding *Novelty & Insightfulness*, one can recognize that a collection of six design principles focusing on distributed context modeling to enable efficient cooperation and multilateral data distribution is a novel approach to the best of our knowledge. Relevant insights are given to meet expectations of the practitioners. The set of design principles is based on a context modeling classification model [8] and is derived from a case study including various context modeling approaches. Using this broad knowledge base and providing an exemplary use case, it is assured that the design principles "can be acted and carried out in practice" [33]. Therefore, the requirements are met for both *Actability and Guidance*. By focusing only on the main dimensions of context modeling, a sound balance between guidance and flexibility is assured so that the design principles provide appropriate guidance without being too restrictive. A complete evaluation of *Effectiveness*, as mentioned by Iivari et al., would require a long-lasting "naturalistic approach so that a real instantiated system is used by real users in a real organizational context over a longer period so that possible effects of the system can be identified." However, the design principles are derived from practitioners for practitioners and are tailored for application level. Thus, they prove effective for the design and development of distributed context models in autonomous systems. The analytical evaluation refers to the entirety of all six design principles and is consistent with the evaluation framework of Iivari et al. [33]. Despite their abstractness and reusability, the proposed design principles, as a form of generic and descriptive knowledge, provide sufficient guidelines for standardized implementation measures.

B. PRACTICAL AND RESEARCH CONTRIBUTIONS

The proposed design principles, drawn from existing literature, yield numerous practical insights, as exemplified in design principles 4 and 5, which pertain to distribution and interoperability. These two principles play pivotal roles in establishing collaborative systems, enabling assets with distributed context models to seamlessly exchange information with other system participants. Concurrently, the presented design principles offer a practical roadmap for the implementation of distributed context models in autonomous systems, providing practitioners with a clear framework encompassing the six meta-requirements and their associated technical implications. In the use case of "Tracking and Surrounding a stationary target with UAVs," these principles empower unmanned vehicles to autonomously execute missions, enhancing service performance. They are likely applicable to various similar use cases, serving as a starting point for guiding the next generation of practitioners who may need to address similar challenges [54].

This article consolidates knowledge from existing literature, focusing on prescriptive knowledge for designing distributed context models in autonomous systems, making notable research contributions. Design principles, traditionally subject to infrequent evaluation, become a central point of discussion in this article, addressing the need for their increased reusability. Moreover, this study not only spotlights open research inquiries and ongoing endeavors but also emphasizes the essential requirement for further evaluation. This emphasis is critical for bridging the gap that often exists between theoretical context modeling and its practical implementation.

C. LIMITATIONS

One of the limiting aspects is that the proposed design principles primarily focus on technical aspects, as they are derived from existing contextual models found in the available literature. It should be noted that these contextual models may not encompass all relevant factors that could exert an influence. Consequently, achieving a comprehensive, universally applicable set of design principles is uncertain. Thus, exploring the field of context modeling for autonomous systems requires a multimethod approach that extends beyond technical considerations, encompassing methodologies such as use case analysis, case studies, expert interviews, and more. Additionally, this contribution underscores the inadequacy of relying solely on literature-based approaches for developing comprehensive taxonomies of descriptive knowledge. Particularly, it highlights the need to enhance and expand upon Liu et al.'s [8] classification by introducing dimensions such as context distribution, context interoperability, and context reasoning. Moreover, it is important to recognize that the completeness of the proposed design principles remains elusive. As per Fu et al. [26], the definition of design principles is inherently use-case dependent and ever-evolving, representing a snapshot at a specific moment in time. Therefore, future assessments should adopt a broader perspective on completeness, incorporating diverse opinions and expert feedback.

VII. CONCLUSION AND OUTLOOK

In this article, design principles for distributed context modeling of autonomous systems have been elaborated. Based on an existing classification for context models, the essential aspects were summarized in meta-requirements to finally derive the design principles for distributed context modeling. The concept aims at the cooperative use of context information in a network of different actors. During the elaboration, special emphasis was put on improving and standardizing the creation and application of a distributed context model for autonomous systems. Furthermore, the conceptual approaches of classical context modeling were extended to consider requirements for distributed context information. On one hand, this distribution promotes cooperation among system participants, but on the other hand, it requires a higher focus in the area of context structuring and interoperability. Overall, the proposed design principles simplify the creation, integration, and implementation of a distributed context model for autonomous systems.

The next step is to further validate the created design principles in real applications and expert interviews. In particular, this qualitative validation should prove the relevance and effectiveness of the design principles on the basis of instantiated distributed context models.

APPENDIX

Examination of the relevant literature and the contextual models used in each instance was an essential element of this research. Table 3 provides a summary and classification of the sources used to establish the design principles.

TABLE 3. Overview of the Considered Literature

Source	Author	Year	Application domain	Research field
A Survey of Context-Aware Mobile Computing Research A Survey of Context-Aware Mobile Computing Research	G. Chen and D. Kotz	2000	Context-aware computing	Software engineering
Modelling and Using Sensed Context Information in the Design of Interactive Applications	P. Gray and D. Salber	2001	Context-aware computing	Software engineering
A Survey of Semantics-Based Approaches for Context Reasoning in Ambient Intelligence	A. Bikakis et al.	2008	Context-aware computing	Context reasoning
Context Aware Computing in Wireless Sensor Networks	K. B. Balavalad, S. S. Manvi and A. V. Sutagundar	2009	Context-aware computing	Cognitive context awareness
A goal-based framework for contextual requirements modeling and analysis	R. Ali, F. Dalpiaz and P. Giorgini	2010	Context-aware computing	Requirements engineering
A Survey on Context Awareness	W. Liu, X. Li and D. Huang	2011	Context-aware computing	Software engineering
Context Aware Computing for the Internet of Things: A Survey	C. Perera, A. Zaslavsky, P. Christen and D. Georgakopoulos	2014	Context-aware computing	Internet-of-Things
Representing and Communicating Context in Multiagent Systems	S. Rode and R. M. Turner	2015	Autonomous robots	Context fusion
Towards an Ontological Framework for Environmental Survey Hazard Analysis of Autonomous Systems	C. Harper and P. Caleb-Solly	2016	Autonomous robots	Safety analysis
Context-awareness in industrial applications: definition, classification and use case	P. Rosenberger and D. Gerhard	2018	Industrial applications	Context implementation
Empowering UAV scene perception by semantic spatio-temporal features	D. Cavaliere et al.	2018	Autonomous robots	Context implementation
A multi-perspective aerial monitoring system for scenario detection	D. Cavaliere, S. Senatore and V. Loia	2018	Autonomous robots	Context implementation
A Knowledge Fusion Approach for Context Awareness in Vehicular Networks	M Ruta et al.	2018	Autonomous robots	Context fusion
Proactive UAVs for Cognitive Contextual Awareness	D. Cavaliere, S. Senatore and V. Loia	2019	Autonomous robots	Cognitive context awareness
Combining Probabilistic Contexts in Multi-Agent Systems	L. Predoiu	2019	Autonomous robots	Context fusion
Towards a layered agent-modeling of IoT devices to precision agriculture	D. Cavaliere, V. Loia and S. Senatore	2020	Industrial applications	Context implementation
A survey on context awareness in big data analytics for business applications	L. T. N, Dinh, G. Karmakar and J. Kamruzzaman	2020	Industrial applications	Big data
Collective Scenario Understanding in a Multivehicle System by Consensus Decision Making	D. Cavaliere et al.	2020	Autonomous robots	Context fusion
Operational Context-Based Design Method of Autonomous Vehicles Logical Architectures	Y. Damak, Y. Leroy, G. Trehard and M. Jankovic	2020	Autonomous robots	Systems engineering
Design, Implementation and Validation of a Multipurpose Localization Service for Cooperative Multi-UAV Systems	E. P. de Freitas et al.	2020	Autonomous robots	Context fusion
Environment Model Generation And Localisation Of Mobile Indoor Autonomous Robots	D. Maria et al.	2021	Autonomous robots	Context implementation
ARCog: An Aerial Robotics Cognitive Architecture	M. F. Pinto et al.	2021	Autonomous robots	Cognitive context awareness
Semantics-Native Communication with Contextual Reasoning	H. Deo, J. Park, M. Bennis and M. Debbah	2021	Autonomous robots	Context reasoning
SMMR-Explore: SubMap-based Multi-Robot Exploration System with Multi-robot Multi-target Potential Field Exploration Method	J. Yu et al.	2021	Autonomous robots	Context fusion
Architecture for ontology-supported multi-context reasoning systems	A. LeClair et al.	2022	Industrial applications	Context reasoning
Detecting Out-Of-Context Objects Using Graph Context Reasoning Network	M. Acharya et al.	2022	Autonomous robots	Computer vision
A Map Building and Sharing Framework for Multiple UAV Systems	A. Silva et al.	2022	Autonomous robots	Context fusion
Context modeling for cyber?physical systems	M. Daun and B. Tenbergen	2022	Autonomous robots	Systems engineering
An approach for semantic interoperability in autonomic distributed intelligent system	K. Yaghoobirafi and A. Farahani	2022	Context-aware computing	Context fusion
Reliable autonomous driving environment model with unified state-extended boundary	X. Jiao et al.	2022	Autonomous robots	Context implementation
A multi-layered bigraphical modelling approach for context-aware systems	A. T. E. DIB and R. Maamri	2022	Autonomous robots	Systems engineering
A Context Ontology-Based Model to Mitigate Root Causes of Uncertainty in Cyber-Physical Systems	M. N. Asmat et al.	2023	Autonomous robots	Context implementation
FBC-ANet: A Semantic Segmentation Model for UAV Forest Fire Images Combining Boundary Enhancement and Context Awareness	L. Zhang et al.	2023	Autonomous robots	Cognitive context awareness
Analyzing Factors Influencing Situation Awareness in Autonomous Vehicles - A Survey	H. A. Ignatious et al.	2023	Autonomous robots	Context implementation
Spatio-Temporal Domain Awareness for Multi-Agent Collaborative Perception	K. Yang et al.	2023	Autonomous robots	Cognitive context awareness

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