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# Next Generation of Multi-Agent Driven Smart City Applications and Research Paradigms

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**ABSTRACT** Smart cities have seen a growing interest among governments, researchers, and industries. Smart cities use digital technologies to enhance the quality of life for residents while promoting sustainability and efficient resource management. By integrating various technologies such as Information and Communication Technologies (ICT), Artificial Intelligence (AI), and Internet of Things (IoT), smart cities can improve the delivery of public services, optimize transportation systems, reduce energy consumption, and enhance public safety, among other benefits. Smart cities focus on automating different disciplines, including smart environment, smart home, smart economy, smart mobility, and smart governance. As a result, multi-agent driven smart cities have received tremendous attention from the research community for obtaining intelligent solutions to complex problems in different disciplines by subdividing responsibilities into multiple agents and empowering agents through AI. In this regard, it is vital to explore the usage of multi-agent systems in different critical application areas of smart cities. In this paper, a detailed description of the multi-agent process for smart city application areas is provided, along with resources and future research directions. Four different application areas: smart home, smart governance, smart environment, and smart mobility are discussed in detail.

**INDEX TERMS** Smart city, multi-agent system, smart home, smart governance, smart environment, smart mobility, artificial intelligence, IoT, big data.

## I. INTRODUCTION

TO BUILD an intelligent urban ecosystem, smart city approaches need to be emphasized toward sustainable and holistic design for all critical applications. Smart cities are becoming a trend in all parts of the world [1]. for example, the NEOM project of Saudi Arabia aims to incorporate smart city technologies to develop a city of a million residents stretching across a length of 170 km, which will preserve 95% of the surrounding nature with zero carbon emissions [2], [3], [4]. The Ministry of Housing and Urban Affairs, Government of India has initiated a mission, Transform-Nation-Smart City, to drive economic growth and to uplift the quality of life of citizens. Another major effort to build/transform smart cities is from the European Union (EU) which is devising strategies for embedding smart city concepts for urban area growth [5]. These efforts are aimed at eliminating the negative impacts that unplanned urbanization can have on the environment and society, including depletion of natural resources, increased pollution, and overcrowding [6]. Unplanned urbanization can also put additional

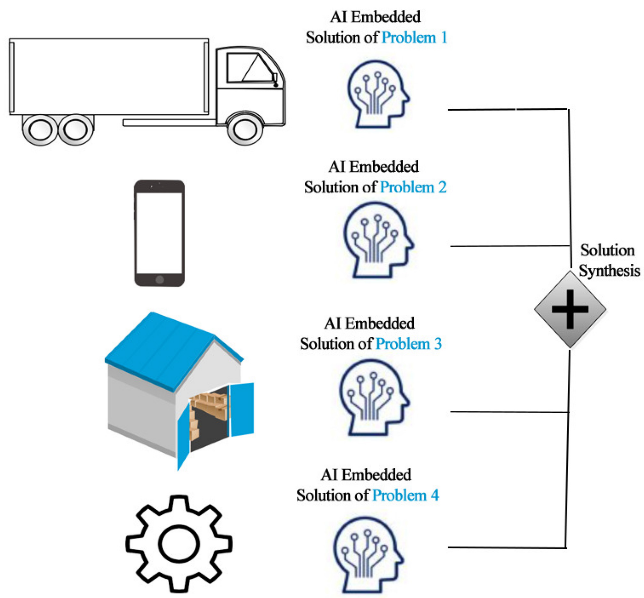


FIGURE 1. Parallel AI: Low level of flexibility.

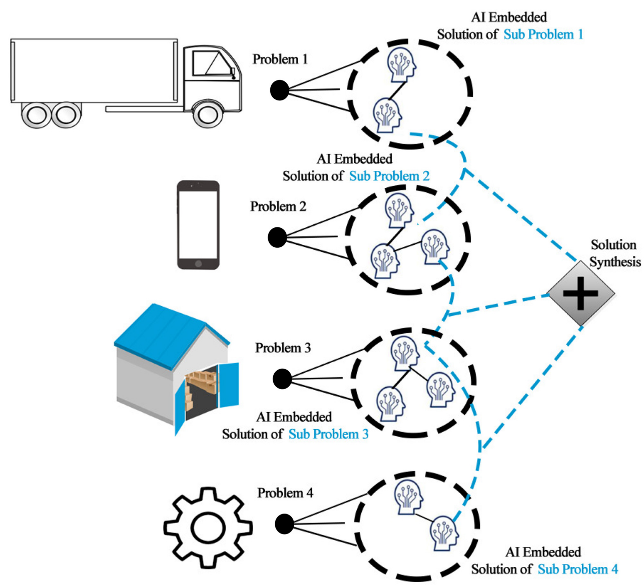


FIGURE 2. Distributed problem solving: Better flexibility compared to parallel AI.

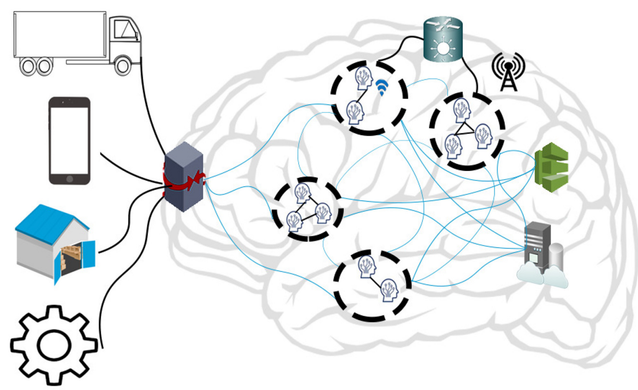

FIGURE 3. Multi agent system: High level of flexibility.

pressure on public services, such as transportation and waste management [7], [8].

Usually, all smart city problems require a learning process that can find out the solution by automated reasoning. Information and Communication Technology (ICT) integration acts as an enabling technology for automated reasoning and autonomous learning process for solving varying smart city problems. Smart cities utilize various information and communication technologies: cloud and fog computing [9], machine learning (ML) [10], Internet of Things (IoT) [11], blockchain [12], artificial intelligence (AI) [13] etc., to build an intelligent ecosystem [14]. One promising and prognosticating approach is distributed artificial intelligence (DAI) whose wide spectrum of multiple applications for smart cities is explored in detail in this paper. Many smart city applications need an approach to handle complex learning, planning, and decision-making problems [15]. For that, DAI is the only viable solution that can solve smart city problems intelligently. Robustness, optimized resource utilization, and flexibility can also be incorporated into the smart city system with the support of DAI [16], [17], [18]. Smart city research work has been performed in the following three AI paradigms [19], [20]:

- *Parallel AI (PAI) Systems:* In parallel AI, parallel algorithms, architectures, and languages are developed. The systems are developed using parallel AI and carry flexibility, but at a low level. Figure 1 represents the parallel AI-driven smart city sample application process.
- *Distributed Problem Solving (DPS) System:* DPS divides tasks into sub-tasks that are assigned to computing entities (considered as nodes in the system). These computing entities share resources and knowledge as and when required, based on a predefined communication setup [21]. This process enhances the flexibility factor in multi-agent systems but within limits. Distributed problem-solving driven process of a sample smart city application is shown in Figure 2. Solid lines in Figure 2 show actual data transfer and the dashed lines reflect data to knowledge formation and knowledge synthesis using artificial intelligence process.
- *Multi Agent System (MAS):* A MAS represents autonomous entities that learn context and actions in coordination with neighboring agents and the environment. Finally, each agent uses its own AI knowledge base to decide and perform the most appropriate action according to the situation. AI and learning incorporate a high level of flexibility in the system for performing tasks [22]. Figure 3 depicts a multi-agent/distributed AI-driven system with a high level of flexibility. Solid and dashed lines in Figure 3 show actual data and knowledge formation, and knowledge synthesis using the AI process, respectively.

The difference between the working of parallel AI, distributed problem solving, and multi-agent systems is clearly visible in the pictorial depiction [23], [24]. The transition from parallel AI to MAS significantly enhances the flexibility in coordination, analytics, decision-making, and resource sharing within intelligent systems. Out of the three systems discussed above, MAS is considered as a subdivision of DAI and is experiencing rapid growth due to its ability to address complex computing problems intelligently. DAI enables AI algorithms in the MAS system to autonomously and intelligently process data across multiple systems, domains, or devices on the edge. In a MAS, the agent is an entity placed in an environment that senses different factors and performs actions to build an encapsulated, autonomous, and goal-oriented decision-making system [25]. The agent performs a specific action based on the decision. Agents/autonomous entities perform appropriate actions using multiple inputs such as the history of actions, interaction with neighboring agents, and goals of agents. Recent surveys relevant to MAS are enlisted in Table 1; these papers cover numerous perspectives of MAS such as agent-based programming, deep reinforcement learning, intrusion detection, and logic-based technologies for solving smart city application problems [26].

A comprehensive explanation of agents, multi-agent systems, MAS applications, evaluation, communication, and research challenges of multi-agent systems has been explored by Dorri et al. [19]. Overview of multi-agent programming is provided by Cardoso and Ferrando [32], MAS deep reinforcement learning methods by Du and Ream [33], and additional papers are listed in Table 1. These recent publications show the importance of MAS to address recent research problems in designing effective and intelligent smart city applications [42]. This paper aims to provide a comprehensive and integrated literature overview of MAS solutions for smart cities domains. Additionally, research problems associated with four sub-domains of smart cities, along with datasets and multi-agent solutions are explored and presented schematically. The research contributions of this paper are as follows:

- A schematic and generic diagrammatic overview of distributed AI process of multi-agent technologies for smart city problems is presented.
- Detailed study of four prime sub-domains: smart home, smart governance, smart environment, and smart mobility is presented.
- A generic conceptual multi-agent process and recent research overview for smart home, smart governance, smart environment, and smart mobility are presented from the future research viewpoint.
- Dataset resources for considered sub-domains are explored.
- Future research directions along with reference points are enlisted.

In this paper, Section II discusses the framework and ICT technological support required for multi-agent smart city research problems. Four critical research areas: smart home, smart governance, smart environment, and smart mobility are explored in Sections III, Section IV, Section V, and Section VI, respectively. The conceptual framework, datasets, and research directions for these smart city domains are

TABLE 1. Recent MAS survey papers.

| Year | Author | Author Contributions |
|---|---|---|
| **2018** | Dorri *et al.* [19] | A comprehensive discussion of all aspects of MAS. |
| **2018** | Ruhlandt*et al.* [27] | Study reveals contextual factors, measurement techniques, outcomes among concepts of smart city governance. |
| **2020** | Gjikopulli *et al.* [28] | Discuss diverse aspects of MAS starting with definition of agents and their features. |
| **2020** | Sharma *et al.* [29] | AI and effective governance: A review, critique and research agenda. |
| **2021** | Bougueroua *et al.* [30] | Insight past, current, future solutions for collaborative intrusion detection. |
| **2021** | Calegari *et al.* [31] | Comprehensive view of logic-based technologies for MAS. |
| **2021** | Cardoso *et al.* [32] | A systematic review of agent programming for MAS. Provides a review of literature on agent-based programming for multi-agent systems. |
| **2021** | Du *et al.* [33] | A detailed and systematic overview of multi-agent deep reinforcement learning methods. |
| **2021** | Herrera *et al.* [34] | Review of MAS and Complex network to address system engineering and management issues. |
| **2021** | Mahela *et al.* [35] | Overview of MAS system that is used for the control of smart grids. |
| **2021** | Zhang *et al.* [36] | A survey on fault estimation, detection, diagnosis, fault tolerant control, cyber attack detection, and secure control of MAS. |
| **2022** | Singh *et al.* [37] | Discusses an architecture for a smart city that consists of several layers, including Sensing, Transportation, Data Management, and Application Layers. |
| **2022** | band *et al.* [38] | Comprehensive review focuses on a number of machine learning methods in the context of smart cities. |
| **2022** | Gohari *et al.* [39] | Systematic review to examine the use of surveillance drones in the context of smart cities. |
| **2023** | Pandya *et al.* [40] | Presents an overview of Federated Learning (FL) in the context of smart cities. FL is a machine-learning approach that allows multiple devices or nodes to collaboratively train a shared model while keeping the data local. |
| **2023** | Wang *et al.* [41] | Reviews the application of Digital Twin technology in the context of smart cities. It explores how it can be used to manage data and information gathered from various physical objects in a city in real time. |

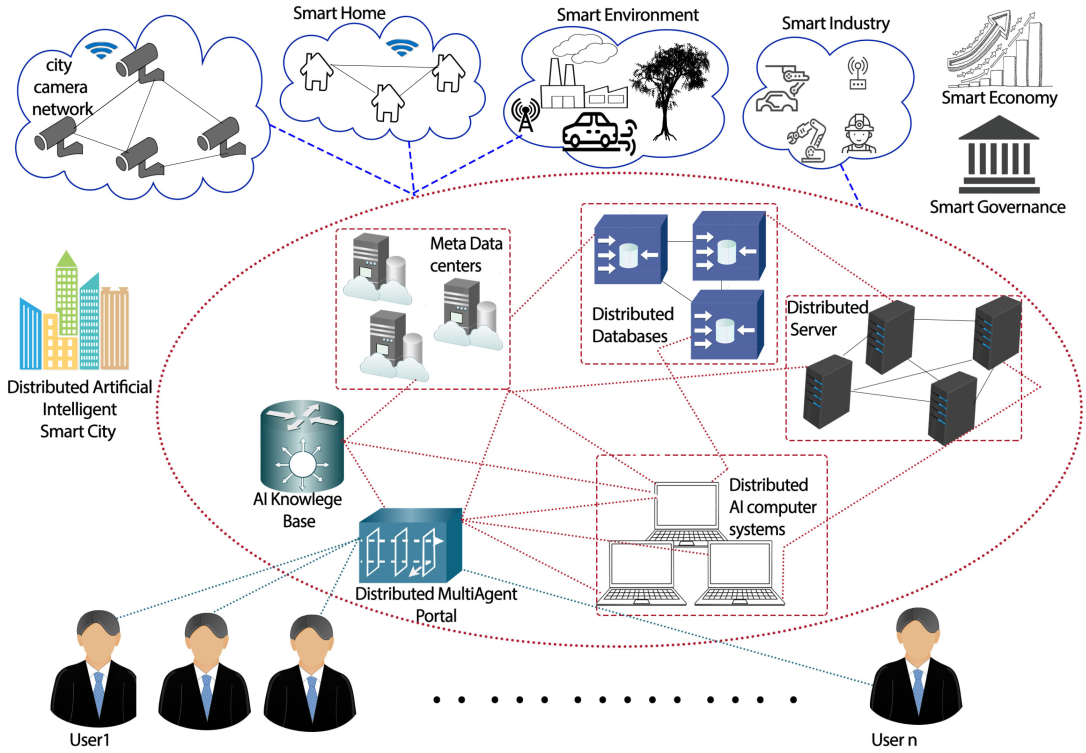


**FIGURE 4.** Schematic diagram of a distributed AI system for various application areas of a smart city.

discussed in detail in these sections. Finally, concluding remarks are presented in Section VII.

## II. MULTI-AGENT SYSTEM DRIVEN INTELLIGENT SMART CITY

A smart city refers to a place or territory that contains a planned usage of human and natural resources to upgrade the quality of life with the help of integration of advanced technological factors. A smart city is defined as a multi-dimensional approach that is merged, coordinated, and integrated with the help of AI techniques to address the social, economic, and environmental problems of a city. Dimensions could be human (engineers, skilled labor, workers, etc.), infrastructural facilities (WiFi zones), social (information exchange), and entrepreneurship (business decisions and activities) [27], [43]. Basically, the MAS system for a smart city is an amalgam of multi-actor, multi-sector, and multi-level perspectives [44] to provide a versatile environment, decision-making capability, and coordination in the social-technical system. The multi-agent system process is pictorially represented in Figure 4 which shows the smart city core application domains: smart home, smart environment, smart industry [45], smart economy [46], and smart governance in the blue color clouds.

ICT technologies include metadata centers, distributed databases, distributed servers, AI knowledge bases (for decision-making), distributed multi-agent portals, etc. These are requisite based on the scope of work and are depicted in the elliptical red color boundary. The variety of technical approaches is decided based on the objective/goal of the smart city application. Intervention arrangements, security, and privacy arrangement are also part of the designed MAS system. To emulate human behavior, AI systems are incorporated to exhibit human intelligence in smart city systems and make it successful at all levels. Traditional city structures operate with a minimum level of interaction between each other, which affects the quality of life, sustainability of the city infrastructure, as well as the environment. Whereas, the development and integration of the Internet of Things (IoT), Internet of Services (IoS), online learning, and social networks in city settings have a persistent, decisive, and positive impact on city services such as transportation, energy, healthcare, security, safety, water distribution, economy, and governance.

Smart city systems are complex multi-agent driven systems for making decisions based on multi-agent behavior using minimized resources and optimal infrastructure which is controlled by novel algorithms [47]. A variety of agents are involved in smart city applications according to their defined roles. A categorical division of agents for a smart city is shown in Figure 5 where the agent is a flexible autonomous entity placed in an environment. The role of an agent is to sense the varying parameters for decision-making based on the defined goal of the entity and further perform specific actions based on the taken decisions. Some more agents are as follows:

- **Active Agents:** Proactively take actions in its environment to achieve its goals;
- **Passive Agents:** Respond to incoming stimuli or requests from its environment;

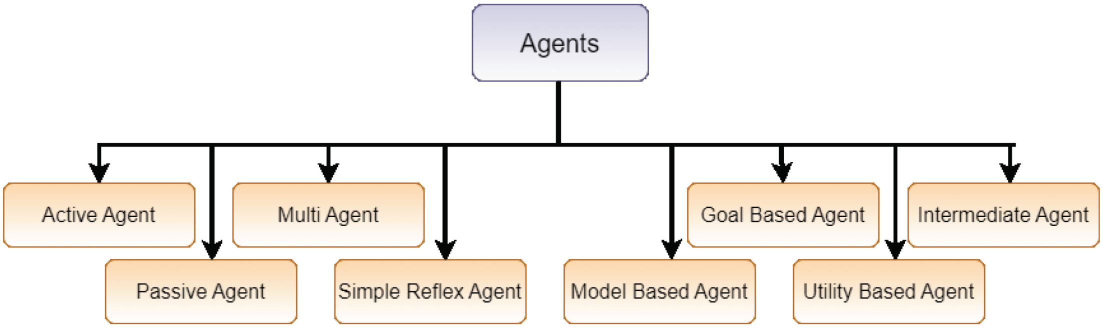


**FIGURE 5.** Agent categories in a multi-agent system.

- **Multi-Agents:** Interact with each other to achieve a shared goal. In a MAS, agents have their own capabilities;
- **Simple Reflex Agents:** Take input from the environment and produce an action in response to that particular input, based on a set of pre-defined rules;
- **Cognitive Agents:** Agents that can reason, learn, and make decisions based on their knowledge and understanding of the world, unlike those based on pre-defined rules in the reflex agent;
- **Model-Based Agents:** Maintain an internal model or representation of the environment in which it operates;
- **Goal-Based Agents:** Operate by first determining a set of goals that they wish to achieve and then taking actions to reach those goals;
- **Utility-Based Agents:** Make decisions based on the expected utility or value of different actions;
- **Intermediate Agents:** Operate in a MAS and act as intermediaries between other agents in the system.

Factors associated with the stated agents are:

1) *Entity* is the type of agents, for example, software, hardware, and a combination of both;
2) *Environment* is the place where an agent is located;
3) *Parameters* are the variety of data that agents accept from the environment;
4) *Action* is the activity that automatically is performed by an agent that results in changes in the environment; and
5) *Constraints* are the additional factors corresponding to entity, environment, or action which need to be under consideration while developing a multi-agent system.

MAS research is essential for developing intelligent agents that can effectively control, manage, and coordinate multiple device data, specifically for critical smart city application areas. The next four sections discuss the critical application areas of smart cities which need significant MAS research to provide a stable smart city system. In MAS research, agents can collaborate to optimize data flow, coordinate scheduling, and facilitate the sharing of resources among different entities. These practices of MAS research remain the same for all smart city subdomains. Out of many, the four most prominent and popular subdomain details are discussed in this paper. The MAS challenges of these four subdomains are as follows:

1) Smart homes are equipped with various IoT devices and sensors that interact with each other to provide automated and intelligent services to residents. MAS research is essential for developing intelligent agents that can control and manage these devices. Agents can coordinate tasks such as temperature, lighting, security, and energy management within the home. MAS systems need to provide an optimized solution for enhancing residents' comfort and convenience.
2) Smart governance's objective is to improve public services, provide an effective decision-making process, and build an optimized solution to involve the public in decision-making for government policy. A MAS system is requisite to gather and analyze public opinion data collected through numerous resources and provide real-time insights to policymakers. Even interactive interfaces or apps need to be developed for monitoring city operations, citizen engagements, public participation, etc.
3) Smart environment focuses on monitoring, managing, and controlling environmental factors. Multi-agent smart environment systems have intelligent agents to collect sensor data and make intelligent decisions. MAS in the smart environment can help in the smart grid and smart energy management system to optimize energy generation, distribution, and consumption.
4) Smart mobility focuses on building an intelligent transportation system for pedestrians, public transportation, traffic management, and autonomous vehicles. By leveraging MAS services, multiple agents can collaborate to optimize traffic flow, coordinate public transportation schedules, and facilitate the sharing of resources among different modes of transport.

## III. SMART HOME

Smart home is an emergent area and attracts the synergy of several computational techniques. This section focuses on some specific exemplary smart home applications that are needed to increase the quality of human life. Multi-agent systems are computationally intelligent systems having the

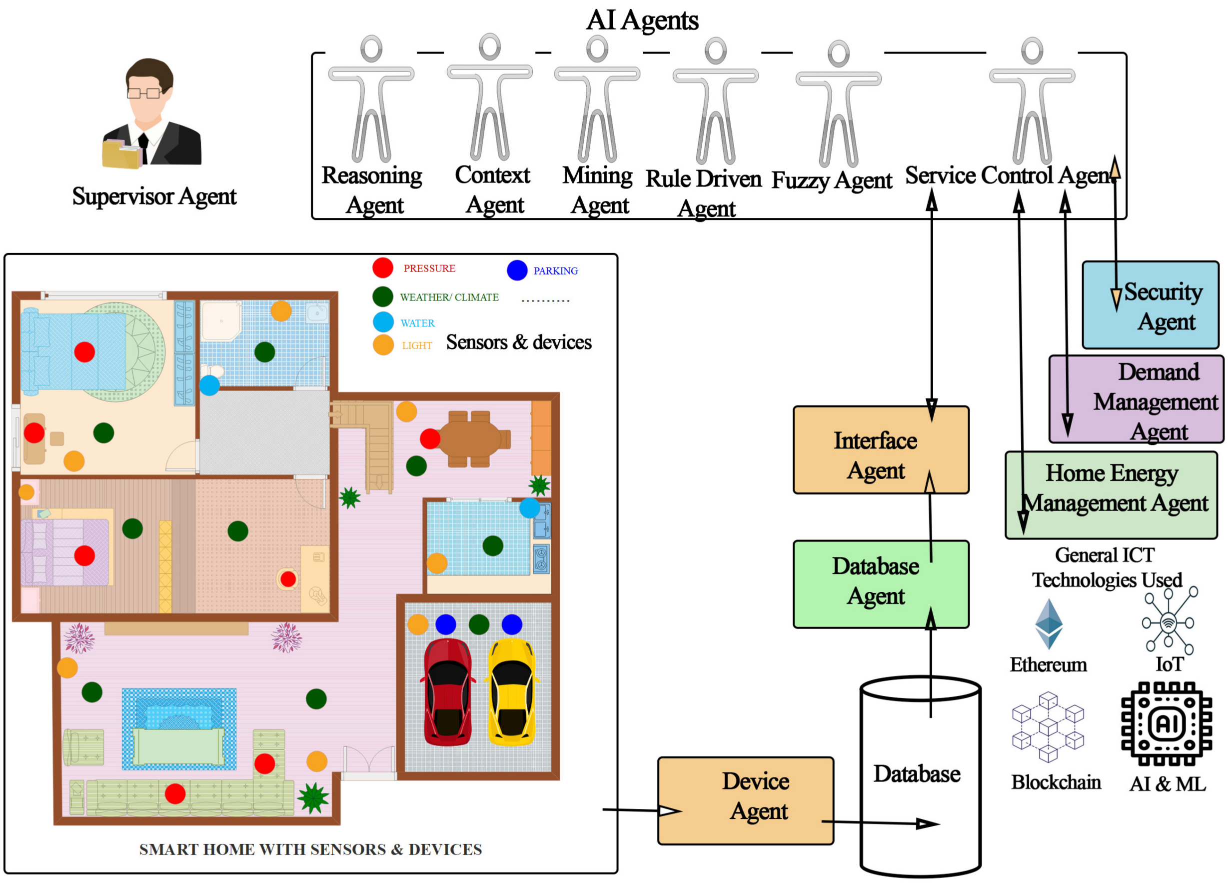


**FIGURE 6.** Generic multi-agent framework for smart home applications.

potential to implement multiple interactive intelligent agents in an environment to build a smart home application. Several initiatives exist where a realistic and ICT-enabled technical and commercial architecture for smart home has been designed [48]. Generic and usual practices are the development of individual intelligent smart home applications, i.e., agent driven intelligent smart home applications [49]. Whereas, multi-agent driven distributed intelligent smart home application is the only feasible and effective solution for a high-level proactive and AI-based end solution of smart home projects. The goals of the MavHome smart home project [50] at the University of Texas at Arlington can predict mobility patterns and device usage of the inhabitants. The authors have demonstrated that multi-agent is an effective approach to controlling smart environment problems. Although an individual agent is sufficient to handle a specific set of problems, but to coordinate the activities of multiple agents, a multi-agent solution is requisite.

### A. GENERIC FRAMEWORK OF SMART HOME

The most recent work done in this direction presents a multi-agent system using probabilistic logic programming for the smart home environment. The authors have introduced probabilistic reasoning techniques which help agents to take a decision under uncertainty and enhance the decision-making process by exchanging information about missing and unidentified factors [51] [52]. Mekuria et al. [53] have introduced a multi-agent system in which device agent, service agent, reasoner agent, and negotiator agent are formed for different scenarios for the smart home environment. Another multi-agent system for developing a self-adaptive IoT system to take appropriate decisions in an unexpected situation is introduced by Ayala et al. [54]. In this work, a combination of goal-oriented and software product line approaches are introduced to drive the evolution of multi-agent systems. Based on existing literature, a generic multi-agent framework specifically for the smart home application is presented in Figure 6. The figure shows a generic conceptual diagram which at the first and initial stage has several sensors fixed in a smart home. The device agent controls and intelligently handles all states of sensors in the smart home. Information on all the sensors is stored in the database and is handled by the database agent. The interface agent works as an interface to check out artificially intelligent behavior on the sensor data to provide different AI-enabled services such as energy management, smart home control, security, and elderly care. The framework in the figure may need changes in agents and services provided/handled by agents according to the research goal.

### B. DATA RESOURCES

In a smart home, data is collected by sensors from a number of different professionals (healthcare, e-commerce portals, caregivers, family, and service providers) who may have an interest in the data. For smart home applications, temporal data is needed which is either in the form of a sequence or a time series. This temporal data is collected using sensors positioned in the smart homes to capture human activities of daily living and contain enormous valuable information. Systematic literature survey in this area is published in [51], [52], [53]. The authors have quoted that research work for the smart home area is mainly done in three directions: energy management, home automation, and patient-elderly care [53]. Therefore, data is also explored in the same direction and is detailed herewith.

Smart home automation data collection is done via some fixed methods. The most common and popular method for data collection is fixing sensors at various places in the home and recording time-series data for a certain period. A few datasets that are collected through this are enlisted in Table 2. Chimamiwa et al. [55] have provided an unlabelled dataset collected continuously from sensors over a period of six months. Several sensors (infrared sensor, force sensing resistor, reed switch, light sensors, temperature sensors, humidity sensors, etc.) are used to fetch data from the users' interaction with the environment such as movement of people, water usage, and pressure on mattresses. The dataset consists of six unique sensors: light, pressure, motion, humidity, force, and temperature. These six sensors are fixed at varying places, so in total 23 sensors' data is collected and stored in a SQL database for six continuous months. Some alternate data collection methods have been used by researchers such as smartphones and camera feeds. Smartphones are used to collect activities of daily living and authors have used accelerometers and gyroscopes for the same [56], [57], [58].

Camera feed to trace human activities is another approach that is used by Pirsiavash and Ramanan [67] where data is captured using a wearable camera device. Some more datasets for specific smart home environments are available on GitHub, Mendeley, and Kaggle such as weather information, smart home device scheduling dataset [68] [69], and health smart home dataset [70]. A detailed list of smart home datasets is given in Table 2.

### C. RESEARCH DIRECTIONS

The smart home research community has considered many interesting research directions. In existing literature, there are three main sectors in the smart home research domain [48], [71]:

1) Energy management,
2) Home automation,
3) Elderly care.

Potential for considerable future research remains in these three sectors due to the evolution of high-end, complex, and unique functionality sensors. These new sensors can be used to provide previously unseen facilities to users which makes research under this domain perceptive and responsive. Visualization of smart home designs can transform into effective smart home and accelerate their development. Other

**TABLE 2.** Dataset sources and relevant research papers for smart home.

| References | Sensors | Url |
|---|---|---|
| **Chimamiwa et al., 2021 [55]** | 23 sensors of 6 types- infrared, force sensing resistor, reed switch, light, temperature, humidity | https://data.mendeley.com/datasets/t9n68ykfk3/1 |
| **Alshammari et al., 2018 [59]** | Dataset generated using Open Smart Home Simulator | http://datasets.openshs.org/ |
| **Lago et al., 2017 [60]** | interaction sensors (water, power, current, pressure, contact, smart electric device, switch, thermostat), context sensor (microphone, infrared, luminosity, weather, music, indoor position) | https://hal.archives-ouvertes.fr/hal-01551418 |
| **Alemdar et al., 2013 [61]** | 20 sensors (force sensitive, pressure mats, contact, proximity, sonar distance, photocells, temperature, infrared receivers) | http://www.cmpe.boun.edu.tr/aras/ |
| **Ordóñez et al., 2013 [62]** | 12-23 sensors (passive infrared, reed switches, float sensors) | on-demand from author |
| **Cook et al., 2013 [63]; Cook et al., 2009 [64]** | 20-86 sensors (motion, door, light, water, burner, etc.) | https://ailab.wsu.edu/casas |
| **Kasteren et al., 2011 [65]** | 14-23 sensors (reed switches, mercury contacts, passive infrared, float sensors) | http://sites.google.com/site/tim0306/ |
| **Skubic et al., 2009 [66]** | Multiple sensors for motion, video, stove, bed activities | www.eldertech.missouri/ |

than these three areas, one open research area is privacy and security. Privacy in smart homes is mandatory and ensures that data should be accessible on a need-to-know basis, i.e.,

- What data is required?
- Who needs that data?
- Why is data needed?

The security goal for multi-agent systems is the need for a stable system. Another research direction is multi-sensor dataset formation for multi-agent smart home systems and coordination of these multi-agent resource data. There is enormous potential of future research in the area of learning models. Nevertheless, the immediate future work likely be focusing on the exploration of memory-based neural models, reinforcement learning models, and deep learning models for sensor-collected time series/sequence data.

For energy management systems, energy storage on rooftop solar photo-voltaic deployments, future energy demand, and supply prediction need to be considered [71]. Appliance load balancing is an important application in energy-efficient load balancing. An effective intrusive load monitoring system is proposed in [72] to develop an activity recognition system for data captured through IoT sensors. Three machine-learning classifier models: feed forward neural network, long short-term memory (LSTM), and support vector machine are used to validate the outcome. Agents are also involved in activities such as collecting and storing historical data regarding power consumption. By applying artificial intelligence, the system can understand user habits as well as support to reduce CO2 emissions. Another research direction is context-Aware smart home design which is in its inception stage in both research and development and has lots of research scope with varying contextual factors.

A few research papers on similar topics are listed in Table 3 where applications, associated authors, and ICT technologies are detailed for various research directions in the smart home domain.

**TABLE 3.** **Research directions for smart home applications (MAS: multi-agent system, SCADA: supervisory control and data acquisition; AI: artificial intelligence, IoT: Internet of Things, ANN: artificial neural network, CA-MAS: context-aware multi-agent system, OWL: Web ontology language; BDI: beliefs, desires, and intentions; AR: augmented reality, RL: reinforcement learning).**

| Authors | Applications | ICT Technologies |
|---|---|---|
| Padmanaban *et al.*, 2023 [73] | Describe application areas affected due to technological advancement such as IoT, Web of things | Machine learning, AI, IoT, Cloud Computing |
| Omran *et al.*, 2022 [74] | Surveillance and control home conditions via Blynk app for both Android or IOS | Raspberry Pi 3 Model B+ and Arduino Mega 2560 |
| Xu *et al.*, 2020 [71] | Home energy management | MAS, ANN, RL, Q-Learning |
| Sun *et al.*, 2020 [75] | Indoor intelligent lighting control | MAS, AI, Sensors |
| Mostafa *et al.*, 2020 [76] | Elderly smart home simulation | MAS, IoT, Sensors |
| Jiménez-Bravo *et al.*, 2020 [77] | Central heating installation in buildings | MAS, AI, IoT |
| Sabir *et al.*, 2020 [78] | Secure mobile agent | MAS, IoT, AI, Security, Blockchain |
| Rafferty *et al.*, 2018 [79] | Smart home IoT security | MAS, Security, IoT, BDI Architecture |
| Zouai *et al.*, 2017 [80] | Smart home simulation | MAS, IoT, Sensors |
| Singh *et al.*, 2017 [81] | Activity recognition in smart home | CNN, RNN |
| Li *et al.*, 2016 [82] | Demand side management strategy integrated into home energy management system | MAS, SCADA |
| Li *et al.*, 2015 [48] | Energy management in smart home | MAS, AI, SCADA |
| Muñoz *et al.*, 2011 [83] | Ambient intelligent assisted living system for elderly people | AI, Semantic OWL, MAS |
| Lim *et al.*, 2009 [84] | Context-aware smart home: trace movement and actions of occupants and predict events engaged by them | MAS, Sensors, IoT, Web of Thing |
| Uhm *et al.*, 2007 [85] | Context aware MAS for intelligent building | CA-MAS, OWL, Sensors, IoT |

## IV. SMART GOVERNANCE

The smart governance paradigm is aimed at supporting decision-making in smart cities to define well-designed policies. Also, it refers to the usage of ICT in innovative ways to exchange information, communicate, and collaborate with stakeholders to improvise the delivery of government services. Multi-agent systems are used to enable communication among stakeholders of various services, especially citizens. MAS also investigates decision-making methods to overcome the communication gaps between citizens and government service providers. Although a considerable number of works have been published for decision-making in smart cities, out of all, AI-based methods for urban decision-making require special attention due to less exploration [77]. In 2019, Hoang et al. [86] mentioned in their review work that only a few pieces of research detailed agent-based methods in terms of artificial intelligence in order to provide robust and automated decision support systems. Khansari et al. [87] have explored and developed prototypes to evaluate agent-based models for census, energy reports, Delaware Valley Regional Planning Commission (DVRPC) region surveys, GIS modeling, and social science theories of

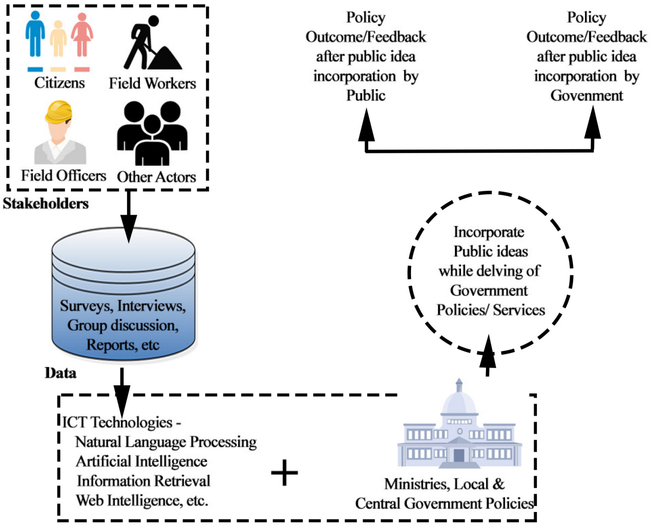


**FIGURE 7.** Generic smart governance conceptual framework.

human behavior. Another interesting work in this direction is done by Ligtenberg et al. [88] in which the focus is on MAS systems for developing planning support systems by taking human action and human decision in consideration for spatial changes. The various actor factors such as government officials, field workers, citizens, etc. are used.

### A. GENERIC FRAMEWORK FOR SMART GOVERNANCE

A generic smart governance conceptual framework is introduced and depicted in Figure 7 where the first bounding box presents stakeholders who are beneficiaries of policies, i.e., public (citizens) or officials who are performing groundwork and understand public demand/views for a particular policy [89]. This information is collected in various forms (surveys, interviews, group discussions, etc.) and stored in a structured database. Further, in the case of smart governance, ministries, local governments, policy-specific departments, and central service providers would apply different ICT technologies to extract insights from the previous boundary interaction. The final outcome of these ICT activities for policy-making or upgradation is to incorporate public ideas while delving into government policies/services for the well-being of its citizens. In the end, the outcome in terms of feedback on new smart governance-designed policies is collected from the public and government officials.

The presented generic conceptual model can be explored and used to build several prototypes of smart governance policies to evaluate the role of agent-based modeling. For example, in the case of urban development, the model can be used to extrapolate the population in an urban scenario in the future, collect public views corresponding to raised issues, and design tools to measure transportation demand, energy demand, economic demand, and environmental footprint demand. Further, an appropriate policy in all these aspects should be designed by taking care of all environmental factors [87]. Rausser et al. [90] have worked on the characteristics of a smart government and the core principles of sound policy analyses. This work is done to explain the disjointedness of observed agriculture and resource policies due to a lack of interaction. The conceptual framework can be applied to a number of policy-making areas by the government to reduce reluctance among citizens and the government. Subsequent subsections provide details of resources for smart governance research work in the future in terms of open government datasets (Section IV-B) and research directions (Section IV-C) for advancement using ICT technologies.

### B. DATASET RESOURCES

Government organizations have started to share open data to help public organizations to get insights from stakeholders' interaction data in the smart city context. Pereira et al. [91] have proposed a conceptual model to analyze the enhancement in public values acquired by smart city projects that disclose open data. In October 2015, the International Open Data Charter set principles and best practices for the release of government data which was initially adopted by 17 countries and gained by 74 national and local government signatories as of 2020. Out of many, some open data repositories of various countries are enlisted in Table 4 in the context of smart governance.

Various data-related activities in the context of smart governance have been attempted in recent years of research such as data collection, data processing, data structuring, data access, data analysis, and real-time data for analyzing city life. However, preparing data for designing policies according to the defined viewpoint of stakeholders is itself a challenging task as data collected is generally unstructured and semi-structured, which needs refinement.

### C. RESEARCH DIRECTIONS

Smart governance is a way to help public organizations to become more open and improve interaction with stakeholders to identify the decisions based on their views shared in various forms such as social media, blogs, public discussion forums, word of mouth, surveys, etc. Researchers have a wide spectrum of research directions and a large amount of work has been initiated in this area for the welfare of society using technologies. The work is done as a flexible autonomous entity, i.e., an agent, but the accumulation of these agents in the form of a multi-agent system is an under-explored area. Hence, research work specific to multi-agent systems concerning smart governance is explained here. In a multi-agent system, each agent performs a proper action using multiple inputs and then interacts with neighboring agents, and the environment is set up for coordination and learning new contexts and actions which incorporate extreme flexibility into the system. In multi-agent systems, new artificial intelligence based approached have emerged to model complex decision-making systems. As the challenge of modeling complex multi-agent smart governance systems is gaining leverage, the research community has started to

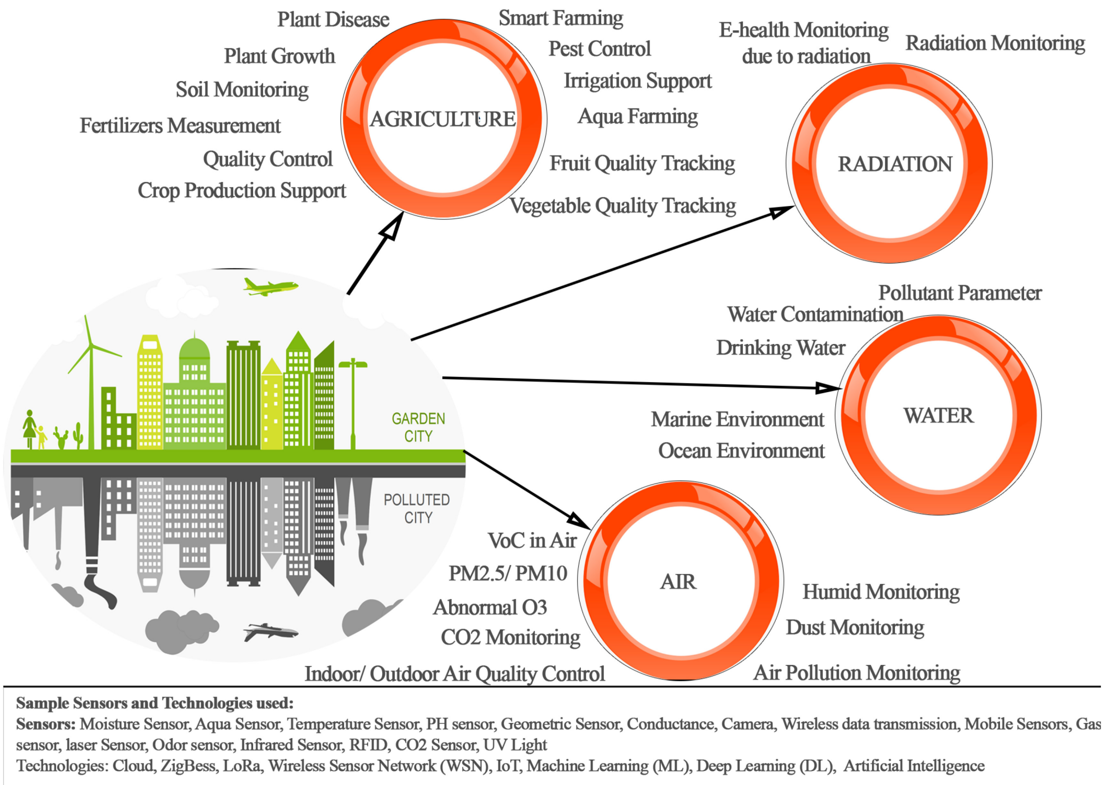


**FIGURE 8.** Research directions in the area of smart environment.

apply various computational models to define the bounds and goals of this wide research spectrum.

A smart and intelligent administration promotes the digital dignity of citizens by incorporating public values and technological advancement into policy-making [92]. Distributed AI needs to be implemented by the government in public service, decision-making, and policy-designing process to handle the ever-changing environment and provide a sustainable solution [93]. Several interesting applications are listed in Table 5 related to AI which could be base studies to propose multi-agent/distributed AI systems for smart governance applications. The table shows the work done for the advancement of smart governance along with computational technologies used to achieve the defined goal. However, a number of research gaps exist for future research in the smart governance area concerning MAS for the smart city domain.

## V. SMART ENVIRONMENT

One of the main objectives of a smart city is to enrich the quality of life by providing accurate and timely information and services to citizens with the help of ICT, while addressing the concern of reducing the environmental footprints of the cities. Owing to this, government bodies have integrated smart environment as one main areas for research and innovation in smart city projects. Sustainable environment of the city and quality of life are the predominant objectives of a smart city.

### A. SMART ENVIRONMENT RESEARCH DIMENSIONS AND TECHNOLOGICAL SUPPORT

To monitor environment footprints, ad-hoc sensors are required to be deployed in the smart city. IoT evolution has made sensors feasible due to low cost but numerous other factors such as large installation areas and regular maintenance/replacement issues have increased costs rapidly. Thus, an intelligent solution is needed to achieve a feasible and cost-effective system. Research in this direction has focused on the hybrid IoT framework [103] and dimension selection [104] for designing an intelligent and cost-effective smart environment system. The smart environment system research dimensions are spread out from enriching the quality of life to minimizing the devastating impact of natural and man-made catastrophes [105]. The impact of smart environmental systems would positively improve the quality of life for urban citizens. For example, a big decrease in carbon dioxide emissions would be helpful in adding value to everyone's life.

It is evident that sensing technologies and computational processing are the prominent factors to facilitate smart environments. Smart environment standalone solutions are in existence but beginning to gain more adoption as a complete solution for multi-agent smart city solutions. A review of work on smart environment monitoring systems using sensors and IoT is presented by Ullo and Sinha [106] to get a detailed knowledge of smart environment research work. An interesting work to demonstrate the blockchain perspective for IoT-based agriculture is by Vangala et al. [107].

**TABLE 4. Government provided data repositories of some countries.**

| Dataset URL | Description | Data Availability |
|---|---|---|
| https://www.data.gov/ | U.S. Government Open Data | Industry, water, and sanitation, power and energy, agriculture, health & family welfare, transport, etc. |
| https://data.europa.eu/e | Europe Data Portal | Agriculture, economy, education, culture, sport, energy, environment, government and public sector, health, etc. |
| https://data.gov.uk/ | U.K. Data | Health, society, defense, education, environment, crime, justice, transport, business, town, and cities, etc. |
| https://opendata.swiss/en/ | Switzerland Open Data | Administration, agriculture, forestry, construction, crime, culture, media, education, energy, finance, health, etc. |
| https://www.govdata.de/ | Germany Open Data | Pollution, society, education, culture, sport, energy, international issues, agriculture, fishing, forestry, environment, traffic, etc. |
| https://u.ae/en/information-and-services/g2g-services/open-government-data | UAE Open Government Data | Health, education, human resource and employment, social affairs, labor, and private sector establishment, financial matters, environment, etc. |
| https://data.gov.in/ | India Government | Agriculture, climate, energy, local government, maritime, ocean, older adult health, etc. |

**TABLE 5. Research directions of smart governance (MAS: multi-agent system, AI: artificial intelligence, IR: information retrieval, IoT: Internet of Things, ANN: artificial neural network, AR: augmented reality, SCRUM: systematic customer resolution unravelling meeting).**

| Authors | Applications | Computational Technologies |
|---|---|---|
| Ruijer*et al.*, 2023 [94] | Discussed numerous tools to help public professionals in dealing with smart governance | Toolkit Citizen Sensing, SCOPE-Smart Nation, CITYkeys, etc. |
| Zhang *et al.*, 2022 [95] | Adaptation behavior of citizens is explored to develop strategies to engage people for one-stop governance app | Data Analysis, Data Mining |
| Abraham *et al.*, 2020 [96] | Smart toll transaction | Blockchain, IoT, MAS, AI |
| Gonzalez *et al.*, 2020 [97] | Traffic flow, transportation system of Bogotá city located in Colombia | IoT, ANN, Matlab, Data Visualization |
| Varghese, 2020 [98] | Urban policy knowledge for smart governance using Tweets | Android Studio, Kotlin Programming Language, AI |
| Grayson, 2020 [99] | Sustainable urbanism | IoT, Big Data, AI |
| Alruwaili, 2020 [100] | Distributed ledger system for better privacy and security of electronic healthcare records | Blockchain, MAS, AI |
| Khansari *et al.*, 2017 [87] | Urban climate, transportation, energy consumption, environment at residence location | MAS, AI, Data Visualization, Simulation |
| Nissan *et al.*, 2017 [101] | Lawyering, judging, policing and law enforcement | IR, Text Mining, ECHO- ANN Tol Araucaria, ArguMed-Visualization Tool, AR |
| Khan *et al.*, 2017 [102] | Citizen participation for social innovation and co-creating urban regeneration | SCRUM, JavaScript |
| Ligtenberg *et al.*, 2009 [88] | Multi-actor interactive spatial-planning process | MAS |

The authors proposed a generalized blockchain-based secure and smart architecture with a detailed cost analysis. Also, state-of-art schemes and literature overview on information security of IoT sensor data through blockchain technologies are discussed, particularly for smart agriculture. Figure 8 shows several research directions in the field of the smart environment. The intelligent environment is concerned with controlling and monitoring environmental factors such as pollution, waste, green development, irrigation, global warming factors analysis, etc. [108]. These various aspects of the intelligent environment along with other research directions

TABLE 6. A few smart environment datasets.

| Dataset URL | Description | Data Availability |
|---|---|---|
| IP102 [111] | insect pest recognition dataset | 75,000 images belonging to 102 categories. Out of which 19,000 images with bounding boxes for object detection |
| https://data.cnr.it/site/data [112] | Istat(National Institute of Statistics) Dataset | crop type, year, geographic area, crop production amounts, temperature, rainfall amount, phosphate and mineral amount, organic fertilizers, and organic compounds |
| Human Activity Recognition [113] | Activities of daily living (ADL) and instrumental activities of daily living (IADL) | activities inside the house using IoT sensors analyzing the air components |
| H2020 project CAPTOR dataset [114] https://zenodo.org/record/4570449 | 25 csv files of three testbeds in Spain, Italy and Austria | IoT sensor data for air pollution Monitoring |

are shown, which depicts some of research done in the domains of air, water, radiation, and agriculture. Several issues of each domain are mentioned such as in the agriculture domain, with respect to the environment, plant growth, soil monitoring, fertilizers measurement, etc. are study areas for both the research and development perspectives. The key ingredient sensors and technologies that are used for the work in this direction are also listed here. A few smart environment dataset resources are listed in Table 6.

### B. RESEARCH DIRECTIONS

Research work is at its inception stage and entering into a new era for smart environments in the context of multi-agent smart city problems. A smart environment consists of various services for pollution-driven factors such as air quality, waste management [109], water pollution, radiation pollution, agriculture system, ocean environment monitoring, etc. [106].

These systems need to be agent-driven for smart environment associated studies where ICT techniques such as machine learning, AI, big data management, IoT sensors, and actuators are beginning to gain widespread adoption and are useful in building intelligent MAS for maintaining the environment smartly. Machine learning and deep learning methods have started contributing to building intelligent smart environment models in different aspects of planning, prediction, clustering, classification, and uncertainty analysis of smart cities due to environmental factors [114]. Table 7 shows a few research directions for the smart environment research problem using MAS.

TABLE 7. Research directions associated with smart environment SAE: staked auto encoder; LSTM: long short-term memory, DL: deep learning; ML: machine learning; CNN: convolution neural network, MAS: multi-agent systems.

| Authors | Applications | Computational Technologies |
|---|---|---|
| Rito *et al.*, 2023 [121] | Build a platform on a large number of IoT devices that have communication, sensing, and computing of Aveiro Tech City Living Lab (ATCLL), Portugal | IoT, LiDAR |
| Liu *et al.*, 2021 [115] | Prediction of air quality in smart environment | ML, DL, SAE, LSTM |
| Baranwal *et al.*, 2021 [122]; Shinde *et al.*, 2018 [123]; Wang *et al.*, 2018 [109]; Chen *et al.*, 2013 [124] | Smart agriculture management, plant growth, and disease prediction, soil monitoring for farming, aqua farming | IoT, CNN, ML |
| Shaikh *et al.*, 2019 [125] | Oceanic environment monitoring | IoT, CMOS |
| Anagnostopoulos *et al.*, 2018 [126]; Rahmayanti *et al.*, 2018 [127] | Waste bins and trucks are enabled with IoT | MAS, IoT, Sensors |
| Dhas *et al.*, 2017 [46] | Air pollution monitoring system | Sensor with MQ3 Model, Rasberry Pi, IoT |

## VI. SMART MOBILITY

Smart mobility means the use of ICT to enhance transportation related services and functions such as traffic management [115], traffic estimation, autonomous transport system, handling freight and logistics [116], material finding in cargo, etc. Smart mobility is the combination of ICT and mobility, i.e., ICT usage for capturing various levels of mobility are explored and reconstructed under the smart mobility domain. A number of projects have been initiated under the smart mobility area to capture general public usage mobility patterns that people can track with their handheld devices. Smart mobility systems require multi-agent modeling due to their highly distributed structure to tackle complex real-time and spatiotemporal data problems.

### A. RESEARCH DIMENSIONS

Smart mobility contains a wide range of transport facilities including gas vehicles, electric vehicles, traditional vehicles, car/bike/scooter/bicycle tracking [117], and sharing services (e.g., Uber, Ola, Lyft), car pooling plans, rail lines, augmented learning and educating systems related to mobility. These services promise to facilitate and support citizens in their mobility needs and save time by notifying them of congestion and increasing safety which in turn has a positive impact on the economy. One recent publication by Teixeira et al. [118] proposes a proactive approach to prevent potential accidents between vehicles and vulnerable road users (VRUs), such as pedestrians and cyclists. By using a multi-sensing and communication approach, the system can predict potential collisions and notify both the vehicle driver and the VRUs about the danger before the accident occurs [118]. In 2020, Anagnostopoulos et al. [117] worked on Intelligent Transport Signaling (ITS) infrastructure to handle priorities between a group of cyclists and other traffic while reaching towards a traffic light signal. A MAS system was proposed by incorporating real GPS trace data for the city of Melbourne in Australia. A multi-agent system for bike sharing is developed in [119], where a multi-modal mobility model is connected to the real-world bike-sharing location in Hamburg in Germany. The model retrieves data from IoT sensors and incorporates it into the existing simulation model of Hamburg's traffic system. The critical technologies to perform these smart mobility experiments are IoT, cloud computing, big data management and analysis, and artificial intelligence. The proposed model, which is a combination of MAS and IoT, is a digital twin which shows enormous potential for city planning and other decision-making.

Bike-sharing systems have also played an important role in smart mobility applications to provide a convenient means of transport. These systems typically involve a fleet of bicycles that are available for short-term rental to individuals for a low fee.

### B. DATASET RESOURCES

In smart mobility applications, the dataset is collected through various sensors deployed at different places. The main research issue in smart mobility data collection is cross-connection among different data sources which is required to build an effective smart mobility application. This is the place where multi-agent systems place a key role in this particular domain. Smart mobility applications need MAS that learn context and action in coordination with different agents and the environment. Finally, the agent uses its artificially intelligent knowledge to decide and recommend the most appropriate action according to the scenario. For example, considering an effective carpooling system, the various required datasets are road navigation, people demographic information, office entry and exit times,

TABLE 8. Some smart mobility datasets.

| Dataset URL | Description | Data Availability |
|---|---|---|
| Hadi et al., 2013 [128] | Bike Sharing Dataset | Hourly and daily count of rental bikes in Capital bikeshare system with weather and seasonal information |
| https://citibikenyc.com/system-data | City bike trip Data | Ride start location, ride end location, time, distance, popular station, etc. information of city bikers' ride |
| https://ndgishub.nd.gov/ArcGIS/rest/services/ | Ambulance Service Locations | Ambulance navigation data and other emergency service data |
| https://dataspace.mobi/dataset/city-bus-bhubaneswar-electronic-ticketing-machine-etm/resource/a934ad10-481a-42b8-9cde-f06f15b101a6 | City Bus E-ticketing data | City Bus Electronic Ticketing Machine (ETM) in Bhubaneshwar City |
| https://dc.gov/ | Road Network | The dataset contains 14,458 road segmentation and 7846 intersections. |
| https://www.odaa.dk/ | Open Data Aarhus (ODAA) Denmark dataset | The data contains pollution, road traffic, weather, parking, as well as cultural and library event information. For smart mobility pollution and road traffic dataset can be used |
| https://data.gov/ | Car Pooling Dataset | large-scale carpool matching dataset generation is an open challenge with the help of candidates pool, social network, and road network [129] |
| https://paperswithcode.com/dataset/kitti | multimodal dataset | 3D object tracking tags for different objects such as cars, trucks, streetcars, pedestrians, and cyclists [130] |

and office and home location information. Therefore, for this application, cross-domain knowledge and matching is itself a challenging task. A sample dataset relevant to smart mobility is discussed in Table 8. Another open challenge for smart mobility in terms of the dataset is that of multimodal datasets, i.e., datasets collected using different types of sensors such as LiDAR, RADAR, GPS/IMU, and cameras which need to be stored within the same dataset.

### C. RESEARCH DIRECTIONS

Some broad objectives and directions for research in the smart mobility subdomain of smart city are: (1) enhancement in road safety; (2) improvement in city economy which is dependent on smart mobility to sustain the professional and daily life of citizens; (3) monitor and collect vehicle mobility information with the help of GPS, radar, and camera to communicate the real-time situation to drivers as an early warning system; (4) smart and secure toll transaction system [130]; (5) smart vehicle travel time reduction using routing algorithms [131]; (6) curb pollution and energy consumption using car polling and bike sharing system [132] [133]; (7) improve fuel economy in smart mobility systems. Out of all these areas, few highly cited recent work done by researchers in recent years are discussed in detail here. In 2020, Wu et al. discussed algorithmic solutions for re-balancing in bike sharing systems since the optimized solution is needed for the redistribution of bikes across stations to ensure an adequate supply and demand balance [134]. The bike-sharing system issues for four main components: system design, system prediction, system balancing, and trip advisor are considered in [134]. Another well-known smart mobility application is ride-hailing services that connect passengers with drivers through a mobile app. A number of challenges are addressed for effective ride-hailing service providers and some of these challenges are resolved using machine learning and deep learning approaches. An overview of machine-learning-based methodologies for on-demand ride-hailing services is presented in 2022 [135]. Its authors have described emerging deep learning techniques (convolution neural network (CNN), graph convolution neural network (GCN), recurrent neural network (RNN), etc.) used for spatio-temporal dynamics of traffic. The focus of the study was on two aspects of spatio-temporal traffic data to produce precise and timely recommendations for matching and assigning idle vehicles. In this same review paper, machine learning solutions to handle several other challenges for ride-hailing services are enlisted, such as individual mobility patterns, on-line ride-hailing services order matching, and vehicle dispatching [135].

Smart mobility applications have a wide research scope, and several existing discussions on future research directions for smart mobility are highlighted in [136]. The paper reviewed several smart mobility applications such as smart streets, smart parking, pedestrian management system, traffic management system, navigation system, etc. The smart toll transaction application has brought security and privacy into smart mobility applications where IoT, blockchain, and artificial intelligence work as key accelerators. Abraham et al. [96], [130] have introduced an AI based system that enables a multi-agent system and real-time smart contracts between cars and tolls. Their system secures the economic transaction privacy of users using blockchain, acting as an interface between an economic transaction layer and governance layer. Effectively managing resources is another big challenge in mobility. In general, existing architectures in the literature consider prior positions of mobile nodes which is a constraint corresponding to the real scenario. Hence, Fazio et al. proposed an approach for adaptively sampling mobility patterns based on intrinsic features of human behavior, and spectral content is taken into consideration in mobility samples [137]. This work reflects some important and novel aspects which could help future researchers to determine the sampling period in a smart IoT mobile environment, paying particular attention to energy issues.

## VII. CONCLUSION

In this paper, we presented an overview of Distributed AI along with the role of multi-agent systems in smart cities. Smart city schematic diagram and details for distributed artificial intelligence, i.e., multi-agent systems are detailed. We have covered the role of multi-agent systems in critical application areas of smart cities. A generic conceptual framework, dataset resources, and research directions of all the considered critical application areas are presented. The critical application areas that are detailed in the paper are: smart home, smart governance, smart environment, and smart mobility. The research directions originating from the state-of-art work have also been discussed. This research is expected to serve as a valuable resource for smart city enhancement for all countries, governments, research agencies, and industries.

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