Article

去中心化的動態協調機制在多代理系統中的設計與實現：基於發佈訂閱模型

Design and Implementation of Decentralized Dynamic Coordination in Multi-Agent Systems: Based on the Publish-Subscribe Model

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**Abstract:** This article delves into the deployment of Multi-Agent Systems (MAS) within the realm of distributed computing. It capitalizes on the flexibility afforded by the publish-subscribe architecture and employs the holonic agent structure to adeptly model complex systems. The study introduces a framework utilizing this architecture to address the critical challenges of message overhead and load balancing—key to the reliability of expansive systems. Drawing inspiration from the decentralized systems that underpin cryptocurrency technologies, it seeks to promote independent and scalable interactions among agents. The MAS framework is enriched by principles of Swarm Intelligence, Distributed Ledger Technology and Service-Oriented Architecture, emphasizing durable and efficient operations for intricate tasks. The article lays out the foundational design phase and sets the stage for subsequent experiments aimed at enhancing communication and operational efficacy within the system.

**Keywords:** Multi-Agent Systems, Distributed Artificial Intelligence, Publish-Subscribe Architecture, Decentralized Computing

1. Introduction

Advancements in artificial intelligence and computing hardware have catalyzed the extensive deployment of deep learning networks in cloud and edge computing. This evolution facilitates the synthesis of distributed intelligent nodes into cohesive services. Central to this integration is Multi-Agent Systems (MAS), a critical component of Distributed Artificial Intelligence (DAI) [1], which harnesses loosely coupled autonomous agents to accomplish shared objectives [2]. This paper introduces a practical framework tailored for distributed computing environments, utilizing the prevalent publish-subscribe communication architecture of MAS. Furthermore, we showcase an effective implementation of this framework within MAS, underscoring its utility in enhancing collaborative efforts among distributed intelligent agents.

Because of its parallel computation capability, robustness, scalability, low cost, and reusability, MAS technology is suitable for large systems [3]. In terms of the agent organization architecture, a holonic agent organization with a recursive structure [4] can easily model a complex system [5]. The publish-subscribe architecture, while contributing to the flexibility of MAS, also poses significant challenges, particularly in terms of message overhead and load balancing [nn]. Addressing these issues to ensure system reliability requires a nuanced design approach and may involve additional mechanisms such as message compression, Quality of Service (QoS) adjustments, and consensus algorithms.

The issue of message overhead typically arises in one-to-many communication scenarios, where a single agent serves multiple client agents. This occurs as server agents often publish responses using the same topic, and client agents must filter out messages not pertinent to them, leading to unnecessary message propagation. Additionally, load balancing becomes challenging in many-to-one scenarios, such as determining the executing agent within a cluster designed to enhance response efficiency and fault tolerance. We are attempting to address these issues through a dynamic decentralized approach at the framework level.

Decentralized mechanisms, exemplified by those used in cryptocurrencies, are highly effective in multi-agent systems by enabling autonomy, and scalability. This dynamic coordination allows for independent decision-making and seamless adaptation, akin to the decentralized consensus models that underpin cryptocurrencies, ensuring secure and transparent transactions without centralized authority. This dynamic coordination not only bolsters system robustness—making it resilient against failures—but also enhances efficiency and privacy through reduced communication overhead and localized data processing.

Initially, we will design a Multi-Agent Systems model that adheres to the Holonic Agent concept, and then, based on this model, develop decentralized solutions for one-to-many and many-to-one issues. The design phase will cover class diagrams, sequence diagrams, and algorithms. Experiments are planned to assess the feasibility of reducing message overhead and to evaluate the effectiveness of improvements in load balancing. Ultimately, we will integrate these algorithms to validate the framework's successful handling of many-to-many issues, specifically, accurately responding to numerous clients with a clustered agent service group within a decentralized Multi-Agent Systems model.

Swarm Intelligence guide the development of adaptable and resilient Multi-Agent Systems by modeling emergent and dynamic behaviors. Distributed Ledger Technology ensures secure, transparent inter-agent communication, eliminating the need for central oversight. Service-Oriented Architecture (SOA) enables modular, interoperable design, enhancing system scalability. Collectively, these concepts support the research by providing a theoretical foundation for creating a MAS framework that is robust, efficient, and capable of handling complex, distributed tasks through intelligent agent collaboration and communication.

The thesis is structured to methodically explore the integration of Multi-Agent Systems in distributed computing, beginning with an Introduction that sets the stage by outlining the research problem, objectives, and theoretical foundation. The Design section details the development of a MAS model, emphasizing the publish-subscribe architecture and holonic agent organization. In the Experiment section, we conduct rigorous testing to assess system performance, specifically focusing on message overhead and load balancing. The Discussion delves into the analysis of experimental outcomes, implications, and the challenges encountered. Finally, the Conclusion summarizes the study's findings, contributions, and potential directions for future research.

2. Design

This chapter delves into the intricate design of a decentralized framework for MAS, addressing the paramount challenges of communication within such systems. It systematically unfolds solutions for one-to-many, many-to-one, and many-to-many communication challenges, culminating in the integration of these solutions to fortify the collaborative efficacy of distributed intelligent agents. Through the exploration of decentralized mechanisms, inspired by the dynamic coordination and consensus models of cryptocurrencies, it aims to unveil a practical framework that enhances system reliability, efficiency, and privacy, thereby revolutionizing the way agents interact within the MAS paradigm.

2.1. Decentralized Framework Design for MAS

Physiology has a hierarchical structure, with cells serving as the fundamental unit. From the outside, tissues, organs, and systems are sequentially formed, resulting in a whole individual. From the inside, the cell itself is composed of organelles with different functions. Among these organelles, the nucleus, which contains lower-level entities such as nucleoli and chromosomes, is regarded as the most crucial internal organelle. The composition and shape of the units at each level confer unique functions to them [9]. For example, stereoscopic vision is possible because the eyes are formed in pairs. Hence, hierarchical structure and organizational style are regarded as the fundamental principles of physiological composition.

MASs can be used to solve specific problems involving computational entities [21]-[23]. In a MAS, each computational entity is referred to as an agent. A MAS is defined as a network of agents in which the agents communicate with each other and share resources to solve higher-order problems that are beyond the capacity of a single agent. MASs have numerous organizational structures [2], with holonic MAS being suitable for designing complex AI systems [24].

A holon is a stable and coherent structure that can be sub-structured by multiple holons as part of a larger framework. The concept of a holon was initially used to explain the social behavior of biological species [25]. However, the hierarchical structure of the holon and its interactions have been used to model the behavior of large-scale organizations in the manufacturing and commercial sectors [26-28]. In a MAS, an agent that appears to be a single entity may also be composed of numerous subagents.

Each holon has a head agent that can communicate with the environment or other agents, and this head agent has numerous resources and communication capabilities. In inhomogeneous MASs, the selection of head agents may be random, as illustrated by the rotation strategy used in distributed wireless sensor networks (WSNs) [29]. However, in a heterogeneous architecture, the agent capabilities determine such selection. Some holons can be further combined to form superholons depending on the requirements. Fig. 1 depicts a superholon composed of three holons. Agents H-21 and H-31 are head agents responsible for contacting agent H-1, and H-4 is an atomic agent with no subagents.



**Fig. 1 Example of a Holonic MAS**

Generally, the holonic MAS recursive continuous structure is similar to a physiological system and can be easily used to emulate biological tissues. In this study, a holonic MAS was used to implement the structural design of complex intelligent agents, resulting in an architecture capable of incorporating diverse perceptions and actions.

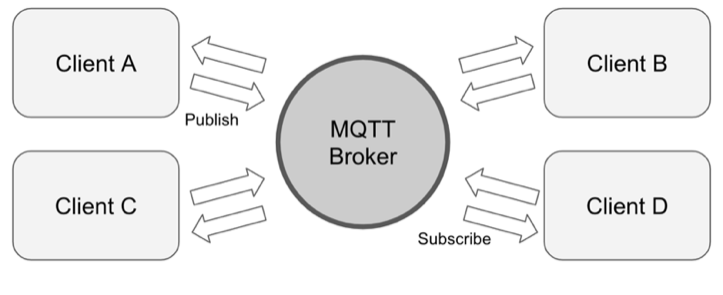
2.2. Solutions for One-to-Many Communication Challenges

In the human body, organs and tissues are coordinated by two major systems: the circulatory system and the nervous system. The circulatory system uses blood to transport substances required by the cells throughout the body and to remove metabolites. The nervous system communicates with various tissues and organs, receives external information, and transmits this information to the processing area. This study, to imitate the circulatory system to share global data, and to learn from the nervous system to process regional information.

2.2.1. Circulatory System and Global Coordination

The circulatory system transports life-sustaining substances throughout the body, such as oxygen, hormones, and antibodies. It uniformly delivers nutrients to all organs and tissues. The heart serves as the central generator of the circulatory system. Although the circulatory system is capable of global transmission, it is slow, and the substances that can be transmitted are limited in number and size.

MQTT uses a message broker as its centralized message routing core. As shown in Fig. 2, the delivery content of MQTT is highly streamlined. It is intended for Internet of Things (IoT) environments with limited computational resources and network bandwidth. The publisher of MQTT sends messages on a specific topic to the message broker, and the subscribers of the same topic on the client side receive the content transmitted by the broker. As a result of the decoupling design used, the publisher and subscriber are not required to share information such as their location.



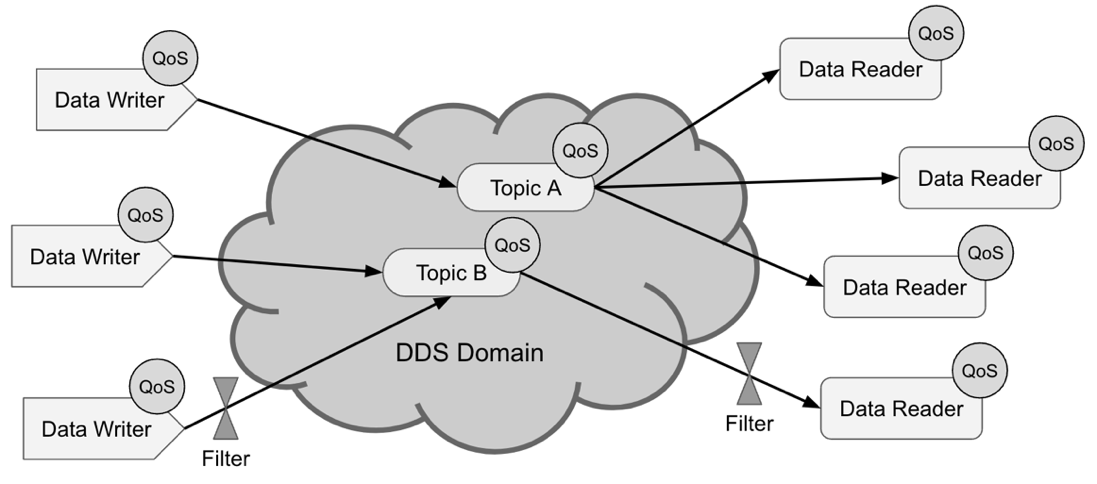
**Fig. 2 MQTT Architecture**

Because of the similarity between MQTT and the circulatory system, MQTT can serve as a global communication mechanism for complex artificial agents. It can also be used for system initialization, heartbeats, status notifications, or announcements, among other applications.

2.2.2. Nervous System and Regional Coordination

The nervous system coordinates various tissues and organs, receives external information, and transmits this information to relevant receptors, such as the brain or muscles. Different organs or tissues, such as the eyes, ears, and skin, produce distinct messages. This involves regional and specialized message transfer. The nervous system rapidly responds to a particular target by processing a large amount of information at an electronic speed. For instance, the visual cells in the retina continuously transmit large amounts of photosensitive data to the visual areas of the brain. The tactile cells on the skin respond to intermittent stimuli, starting from the peripheral nervous system and running to the somatosensory regions of the cerebral cortex.

As depicted in Fig. 3, OMG’s DDS is a relay protocol and an API standard used for data-centric connections [30]. It integrates system components and provides the low-latency data connections required by IoT systems. The DDS features a highly scalable architecture, high reliability, high speed, and point-to-point transmission. It has also been successfully implemented in wireless sensor network (WSN) systems [31]. Similar to MQTT, the DDS establishes information links by publishing and subscribing to topics. However, it is not limited by narrow frequencies or low power consumption, confirming its reliability and security.

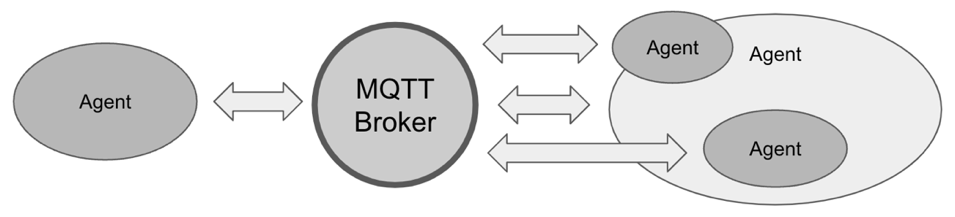


**Fig. 3 DDS Deployment Scenario**

Because the DDS protocol can securely and reliably transmit messages at a high speed, its point-to-point characteristics satisfy the requirements for regional transmission. Therefore, in this research, the DDS was used to study the nervous system as a message delivery system for sight, hearing, touch, or any perception or feedback.

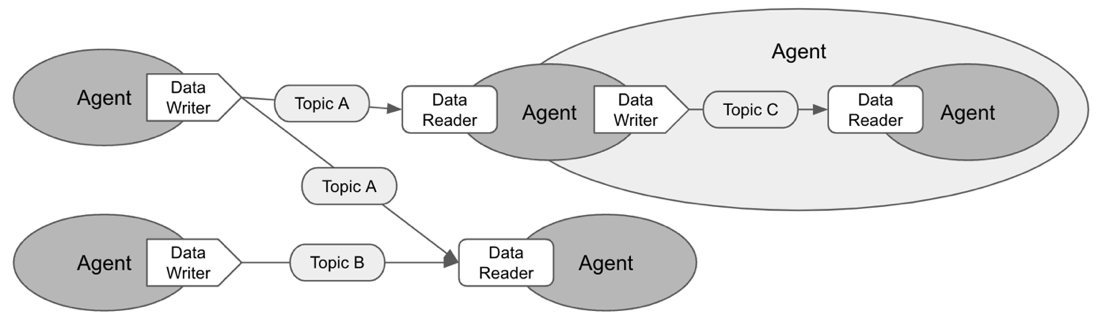
2.3. Solutions for Many-to-One Communication Challenges

Because of the lightweight nature of MQTT, all agents are designed as MQTT clients without burdening the whole system. Thus, all the agents in the system can gracefully obtain the system status, which is advantageous for overall control. Fig. 4 depicts the scenario of agent and MQTT integration.



**Fig. 4 Agent and MQTT Integration Scenario**

Agents publish or subscribe to related topics as required. Head agents often serve as message receivers and communicate with other agents within the same super-agent by using the same mechanism. Fig. 5 depicts the scenario of agent and DDS integration.

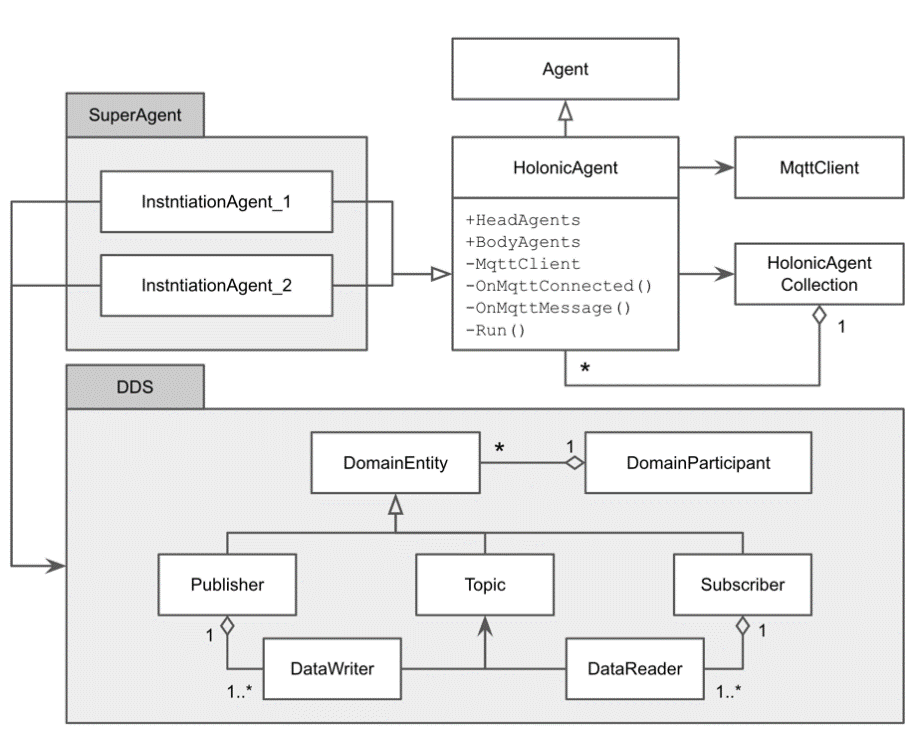


**Fig. 5 Agent and DDS Integration Scenario**

2.4. Integration for Many-to-Many Communication

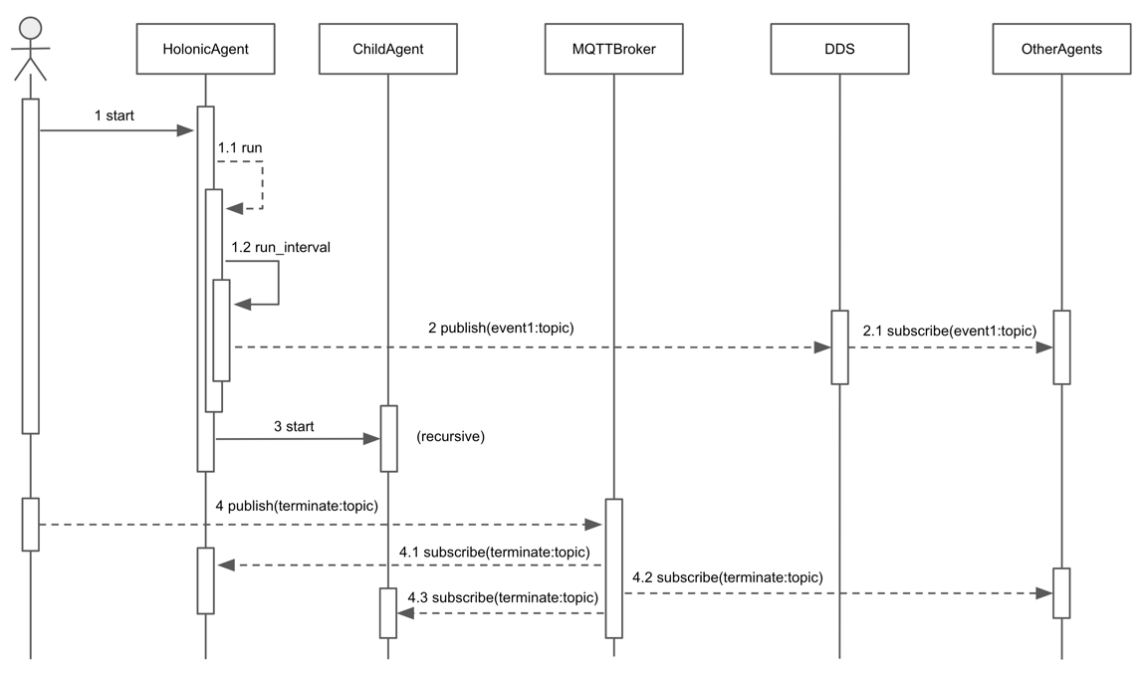
Fig. 6 depicts the class diagram of the integration of agents and coordination. HolonicAgent represents the core, and HeadAgents and BodyAgents represent the collection of head agents and subagents, respectively. MQTT is the fundamental communication protocol for agents in the global circulation system, and MqttClient is a private member of HolonicAgent, which allows the agent to have built-in MQTT connection and reception capabilities.

All agents inherit from HolonicAgent to form a hierarchical structure, and they use the DDS to achieve neural message transmission depending on their specific behavior. Each super-agent is a DDS domain that publishes or subscribes to related topics with the required QoS, such as the DEADLINE policy to confirm the date of the data or the TRANSPORT\_PRIORITY policy to define the transmission priority order [20], in order to achieve the purpose of a specific agent.



**Fig. 6 Class diagram of integration**

According to the sequence diagram depicted in Fig. 7, the DDS and MQTT serve to transmit messages for the agents. Action 1 entails generating an independent process immediately after the root agent is initialized. Action 2 entails subscribing to or publishing relevant topics within the QoS constraints. Action 3 entails recursively calling all the subagents to initiate the action. The agent main action is performed in a separate process of Action 2 until it is notified of its termination. Finally, Action 4 entails generating a global broadcast with MQTT, with a system termination notification serving as an example in this study.



**Fig. 7 Sequence Diagram of Integration**

The implementation of this architecture: <https://github.com/mfshiu/abdi.git>

3. Results

On the basis of the proposed complex artificial agent integration method, an experiment with a navigation system for the visually impaired was planned to verify the feasibility of the design and evaluate the results.

3.1. Experiment Design

Generally, developing a navigation system for visually impaired individuals can demonstrate the feasibility of a proposed architecture. This is a sufficiently complex agent system that must integrate numerous AI systems, including machine learning modules [32]. The completion of this system was expected to confirm the feasibility of the proposed architecture.

Because of their limited vision, visually impaired individuals experience numerous transportation inconveniences. Their primary limitations stem from the selection of routes, the avoidance of obstacles while walking, and the avoidance of obstacles on the road [33]. Therefore, in this study, a system was designed to assist visually impaired individuals in determining the optimal route to their destination and to inform them of the road conditions. This system must communicate in a multiturn dialogue and execute appropriate actions and responses [34].

The navigation system for the visually impaired consists of a visual system, a sound system, an auditory system, a navigation system, and a dialogue system. The navigation system includes a road subsystem, which can detect the surrounding environment, and a path planning subsystem. The visual system obtains images with depth values from a 3D camera and sends these images to the visual receiving area of the navigation system through image preprocessing. The images are then used as the source of environmental detection. The dialogue system receives speech from the auditory system, understands the language used, and generates instructions, such as providing a destination or interrupting navigation. After speech synthesis, the dialogue system creates a natural language response, which is then sent to the user by the vocal system. Finally, human–machine interaction is achieved.

Table 1 lists the general definitions of the agents, Table 2 lists the definitions of the global MQTT topics, and Table 3 lists the definitions and descriptions of the internal DDS topics. Fig. 8 depicts the overall system structure design, which conforms to the continuity structure of holonic MASs.

**Table 1. Agents IDs**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **ID** | **Agent** | **ID** | **Agent** | **ID** | **Agent** |
| 000 | Visually Impaired Navigation System |  |  |  |  |
| A00 | Navigation System | B00 | Dialogue System | D00 | Hearing System |
| A01 | Visual Reception | B01 | Voice Output | D01 | Microphone |
| A02 | Command Reception | B02 | Auditory Reception | D02 | Background Denoising |
| A03 | Path Planning | B03 | NLU | E00 | Sound System |
| A10 | Environment Detection | B04 | NLG | E01 | Speaker |
| A11 | Road Detection | C00 | Vision System | E02 | Voice Reception |
| A12 | Obstacle Detection | C01 | 3D Camera | E03 | Tone Processing |
| A13 | Signboard Detection | C02 | Image Preprocessing | F00 | Speech Synthesis |

**Table 2. MQTT Topics**

|  |  |  |  |
| --- | --- | --- | --- |
| **ID** | **Topic** | **Format** | **Content** |
| M1 | Startup | Text | System startup notification |
| M2 | Terminating | Text | System shutdown notification |
| M3 | Heartbeat | Text | System heartbeat |
| M4 | Status | Text | System Status |
| M5 | Information | Text | Global message |

**Table 3. DDS Topics**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **ID** | **Topic** | **Format** | **Concerned**  **Super-agents** | **Content** |
| 1 | Vision | Image | C | Video frame from 3D Camera |
| 2 | VisionProcessed | Image | AC | processed image |
| 3 | TextVoice | Text | AB | Text before speech synthesis |
| 4 | SynthesizedSpeech | Audio | E | voice after speech synthesis |
| 5 | InputVoice | Audio | BD | Audio phrase of hearing |
| 6 | InputSentence | Text | B | Text phrase of hearing |
| 7 | OutputSentence | Text | B | Sentences to be output |
| 8 | UserIntention | Text | B | User intent after understanding |
| 9 | UserCommand | Text | AB | The command of action |
| 10 | OutputContent | Text | B | Output of dialogue system |
| 11 | SoundProcessed | Audio | D | processed sound |
| 12 | Sound | Audio | D | sound phrase from Microphone |
| 13 | WalkCommand | Text | A | Commands required by the navigation |
| 14 | WalkTarget | Text | A | navigation destination |
| 15 | WalkRoute | Text | A | path to destination |
| 16 | StreetTarget | Text | A | The closest target currently in the path |
| 17 | StreetVision | Image | A | street view |
| 18 | SignInfo | Text | A | sign on the road |
| 19 | RoadInfo | Text | A | Road information while walking |
| 20 | OutputVoice | Audio | E | the sound that will be made |
| 21 | OutputVoiceProcessed | Audio | E | upcoming sound after pitch processing |



**Fig. 8 Structural Design of Navigation System for Visually Impaired**

Agents at all levels perform independent processes and communicate with other agents through MQTT and the DDS. This means that the physical environment of the system is unlimited. The agents can be separated from one another. For example, the environment detection agent may be located in another deep learning server, and natural language understanding [36] may utilize certain cloud services. Neither affects the overall system architecture.

3.2. Experiment Results

For the system to function, many messages with different topics are sent between the agents. The DDS stimulates the nervous system to transmit a variety of data while meeting the required QoS. MQTT is similar to the circulatory system in terms of systemic message notification. These actions occur in parallel. Table 4 illustrates working snippets representing speakers, words, and how sentences are formed inside the system.

**Table 4. System execution record**

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Speaker** | **Words** | **Agents with topics flow** |
| 1 |  | (System startup) | 000(M1) |
| 2 | User | Please take me to the MRT station. | D01(12) 🡪 D02(11) 🡪 D00(5) 🡪 B02(6) 🡪 B03 |
| 3 | Navigator | Okay, let me check, please wait. | B00(10) 🡪 B04(7) 🡪 B01(3) 🡪 F00(4) 🡪 E02(20) 🡪 E03(21) 🡪 E01 |
| 4 | Navigator | There is Zhongyi Station 300 meters nearby. May I take you there? | B00(9) 🡪 A02(13) 🡪 A03(15) 🡪 B00(10) 🡪 B04(7) 🡪 B01(3) 🡪 F00(4) 🡪 E02(20) 🡪 E03(21) 🡪 E01 |
| 5 | User | Yes, that’s right. | D01(12) 🡪 D02(11) 🡪 D00(5) 🡪 B02(6) 🡪 B03 |
| 6 | Navigator | Please walk straight along the sidewalk. | 1. B00(9) 🡪 A02(13) 🡪 A00(15) 2. C01(1) 🡪 C02(2) 🡪 A01(2) 🡪 A11 3. A11(19) 🡪 A10(3) 🡪 F00(4) 🡪 E02(20) 🡪 E03(21) 🡪 E01 |
| 7 | User | Hi, partner, I would like to take a break. | D01(12) 🡪 D02(11) 🡪 D00(5) 🡪 B02(6) 🡪 B03 |
| 8 | Navigator | Okay, I will suspend until you call me. | 1. B00(10) 🡪 B04(7) 🡪 B01(3) 🡪 F00(4) 🡪 E02(20) 🡪 E03(21) 🡪 E01 2. B00(M4: Suspend) |
| 9 |  | (System suspended) |  |
| 10 | User | Please take me to the MRT station. | D01(12) 🡪 D02(11) 🡪 D00(5) 🡪 B02(6) 🡪 B03 |
| 11 | Navigator | Okay, let’s go. | 1. B00(M4: Resume) 2. B00(10) 🡪 B04(7) 🡪 B01(3) 🡪 F00(4) 🡪 E02(20) 🡪 E03(21) 🡪 E01 |
| 12 | Navigator | We are passing 7-11 convenience store on the left. | 1. C01(1) 🡪 C02(2) 🡪 A01(2) 🡪 A13 2. A13(18) 🡪 A10(3) 🡪 F00(4) 🡪 E02(20) 🡪 E03(21) 🡪 E01 |
| 13 | Navigator | You have already arrived the MRT station. | A00(3) 🡪 F00(4) 🡪 E02(20) 🡪 E03(21) 🡪 E01 |
| 14 |  | (System terminate) | 000(M2) |

Note 1: The format of the content in the fourth column is as follows: source agent ID (publish topic ID) 🡪 target agent ID (publish topic ID).

Note 2: The sequential items in the fourth column represent parallelized processes, but the former affect the behavior of the latter.

During the experiment, the existence of the head agent was ambiguous. According to the design, the head agent served as a communication bridge for the super-agent. However, during the planning of the experiment, the super-agent sometimes directly addressed external communication, such as environmental detection (A10) or the auditory system (E00). Therefore, because the head agent served only as a message forwarder, it was omitted. To avoid the duplication of unnecessary information, the super-agent or internal body agents directly published the message. The head agent existed only when messages were converted or filtered.

Here, the holonic MAS aided in the design of structures. Publishing and subscribing to topics between agents also increased the flexibility of the system. The agents in the system were easily modified so as to gracefully update the system. Importantly, the system had a large number of repeated paths, for example, hearing and understanding (D01(12) 🡪 D02(11) 🡪 D00(5) 🡪 B02(6) 🡪 B03), vision and recognition (C01(1) 🡪 C02(2) 🡪 A01(2) 🡪 A11, A12, A13), and voice output (A00, B00(10) 🡪 B04(7) 🡪 B01(3) 🡪 F00(4) 🡪 E02(20) 🡪 E03(21) 🡪 E01). These paths were dynamic subsystems of the cross-agent service whose discovery aided in understanding and optimizing the system (e.g., in terms of pipelining).

The execution time of the dynamic subsystem was calculated as follows:

|  |  |
| --- | --- |
|  | (1) |
|  | (2) |

where is the ordered set of agents, is the specific agent, and is the function used to compute the execution time.

4. Discussion

According to physiology, distributed, hierarchical, regional, and global communication are essential mechanisms of complex intelligent agents. In this study, these insights were applied to the coordination of organizational structure and communication. A complex AI integration framework was also designed and experimentally validated.

The interior of complex intelligent agents is primarily heterogeneous, and entire systems can form a homogeneous connection through the interface between agents and topics. All modules and components at any level are agents, which is advantageous for constructing a fully autonomous system.

The participant discovery of the DDS [35] allows agents to dynamically participate in the system, thereby rendering the system scalable. For instance, adding Lidar’s distance sensing to a visual agent can improve the accuracy of road detection. The system can also be upgraded or repaired online.

As a more advanced protocol, OMG’s DDS is functionally a superset of MQTT and can cover the majority of its features. Because of its wide compatibility and simple implementation, MQTT is still used as a solution for global communication. Given its low frequency and power consumption, its lightweight centralized protocol meets the global communication requirements. Therefore, MQTT is regarded as an essential communication capability for agents.

Some studies have highlighted the benefits of continuous multiagent organization and autonomy [36]. The abstraction of the inner operations of holonic agents has allowed for great flexibility in behavioral decisions. However, predicting the final behavior of a holonic agent is difficult because of the lack of knowledge regarding the internal structure of holons [37].

5. Conclusions

The proposed complex framework for AI integration is a middle layer between the operating system and its applications. It helps organize the system and facilitates the sharing of information and parallelization of processes. This may allow developers to increase their productivity by working in parallel teams and focusing more on the developmental aspect. This study, however, did not investigate the synchronization of parallel processing between agents, which will be provided as a supplementary study in the future.

In addition to functional development, the decision-making of complex AI systems can be crucial at times. Decisions can be made through negotiation or competition among agents or through the application of game theory [38]. MAS-based structures can employ the theory of multiagent decision-making [39] to provide more intelligent decision-making.

System prototypes are great for rapid development, whether for early validation or for iterative development. This is the advantage of the iterative methodology and the essence of agile software development [40]. This complex AI integration framework allows developers to rapidly build verifiable systems.

The framework implements the belief–desire–intention (BDI) software model [41]. This architecture incorporates the concepts of belief and intention but omits desire. Therefore, integrating the desire concept may allow the system to provide more active services and bring it closer to an optimal autonomous system. Future research should focus on implementing the complete BDI methodology.

Among the future implementations of the proposed architecture in more complex AI systems are autonomous mobile robots, intelligent navigation robots, and manufacturing assistance systems for Industry 4.0.

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* **Code availability**

The source code generated during the current study is available from the corresponding author upon reasonable request.

* **Authors' contributions**

Ching Han Chen and Ming Fang Shiu conceived the presented idea. M.F.S. developed the theory and performed the computations. C.H.C. verified the analytical methods and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

**Additional declarations for articles in life science journals that report the results of studies involving humans and/or animals**

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