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Collaborative Care: Multi-Agent Systems in Healthcare

David Power *,[1]
*ASSERT Centre, College of Medicine and Health, University College Cork, Ireland.

ABSTRACT Everyday thousands of IoT devices are added to networks globally. Medical IoT (IoMT) is a subdomain, which has had much success over recent years and is expanding rapidly. However, interoperability is poor with IoMT devices, and even the sharing of basic patient data is generally poor between healthcare systems. There is considerable waste and unnecessary duplication of data across devices, which grows exponentially across healthcare systems. Multi-agent systems have the potential to reduce waste and expenditure while improving efficiency and personalizing patient care and may offer the potential to realize both organizational and patient care benefits.

KEYWORDS
Healthcare
Collaborative care
IoT
IoMT

INTRODUCTION

The advent of the internet as we know it today began in 1991, changing the world almost immeasurably. In 1991, there were 1 million worldwide users of the internet, and today in 2023, this number has risen to over 5.16 billion users, with users steadily increasing daily. This figure is representative of 64.4% of global inhabitants who interact with the internet daily (Petrosyan 2023). All these users are generating massive amounts of data through their connected devices. By the year 2019, there were 8.6 billion internet-of-things (IoT) devices connected to the internet. By the end of this year, 2023, there is expected to be 15.14 billion, and by the year 2030, it is forecast that almost 30 billion IoT devices will be connected to the internet (Vailshery 2023). Every second, 127 new IoT devices are connected to the internet.

IoT devices are networked over the internet and allow monitoring and the exchange of data without human intervention. All these devices are generating massive amounts of data. Collecting and storing such volumes of heterogeneous data creates all kinds of challenges. One subtype of IoT is in the healthcare domain, often referred to as the Internet-of-Medical-Things (IoMT). IoMT devices connect and communicate with healthcare IT systems over the internet, or with other IoMT devices, either through IoT or Machine-to-Machine (M2M) technologies. M2M technology describes when two or more machines are connected together to capture and share data, with the ability to respond without human intervention. M2M is usually for monitoring and control purposes. IoT builds on and expands this idea, by connecting disparate wireless technologies to create a more fully connected environment that encompasses people, devices, and applications (Monteiro *et al.* 2023).

The IoMT is a massive growth market with a value of USD 41.17 billion in 2020, with a CAGR of 29.5%. Estimated growth by 2028 is USD 187.60 billion. Similar forces that are driving IoT are driving IoMT, such as lower costs of storage, memory, computing power, and sensors, in addition to massive amounts of data, hugely improved network speeds, and the availability of cloud computing resources. Furthermore, IoMT has the potential to drive down healthcare costs, improve patient monitoring, treatment, and services. It is estimated that 40% of all IoT devices will be health-related in the future (Sudarmani *et al.* 2022). However, most IoMT devices currently work as standalone devices or as part of a small network of connected similar devices. Interoperability is poor with IoMT devices, and even the sharing of basic patient data is generally poor between healthcare systems. Improving interoperability of devices and the sharing of health data allows for devices and health systems to improve patient monitoring and the delivery of healthcare services (Aledhari *et al.* 2022).

BACKGROUND

It would seem that this environment would be ideal for the use of multi-agent systems. An agent can be described as a computer system capable of autonomous action to meet certain design objectives within its working environment (Wooldridge 2002). The agent may be a physical or virtual entity. The agent's environment may be accessible, that is one which the agent can use its sensors to detect the complete environment state. The environment may be deterministic, which means that the next state within the environment is completely determined by the current state and the agents current action. The environment may be episodic which is

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[1]d.power@ucc.ie (**Corresponding author**).

to say that the environment is non-sequential and independent of other episodes. A dynamic environment describes one in which it changes while the agent is receiving inputs and/or performing actions (Fig. 1). A static environment does not change. A discrete environment refers to one which an agent can perform a finite number of actions, otherwise it is a continuous environment (Gupta *et al.* 2022).

The agent performs actions to solve goals, and these actions can be either discrete or continuous. Discrete actions are a limited response and number of actions to sensed information, while continuous refers to unconstrained actions. The purpose of the agent is to solve a task within its environment, therefore it must learn parameters and information about its environment. Using this knowledge and past experiences from previous actions the agent performance should improve at solving its task. Agents operate have autonomy of control over their own internal states and actions. Agents have the ability to sense changes and react to changes within their environment (Wooldridge 2002; Gupta *et al.* 2022). Agents display pro-active goal-directed behaviour. Agents have the ability to interact with other agents.

Agents may be simple reflex agents which make decisions based only on the current precept and react only on to predefined rules, or they may be model-based agents where actions are based on both the current and historical precepts. Goal-based agents use search and planning to achieve future goals and this directs its currents actions. Utility-based agents use performance metric such as a utility function to optimise its actions, calculating different paths and performance metrics to reach its goal. Learning agents can be any of the above types of agent that interacts with its environment and learns from its experience, adapts its behaviour and improves its performance (Goonatilleke and Hettige 2022). Multi-agent systems can be referred to as multiple interacting intelligent agents which can communicate with each other and their environment, and work towards solving a common goal. These systems interact by sharing data and information and must coordinate, collaborate, cooperate, negotiate and conflict resolution between agents to successfully meet their design objectives (Gupta *et al.* 2022).

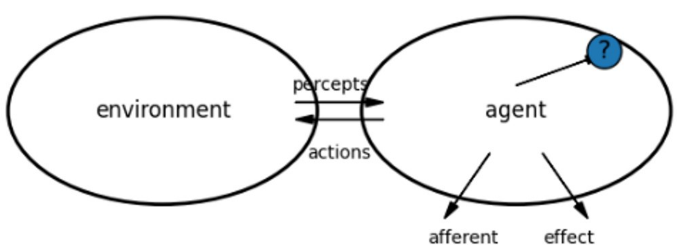

Figure 1 Agent interacting with environment

Multi-agent systems differ significantly from non-agent systems in their structure, behaviour, and capabilities. Multi-agent systems operate in a decentralized environment where each agent independently makes decisions based on its local knowledge and design goals. This decentralized nature allows for greater flexibility and adaptability as agents can respond dynamically to changes within their environment. By contrast, non-agent systems rely on centralized decision-making and control, making them less responsive to dynamic and unpredictable conditions. One of the defining features of multi-agent systems is their emergent behaviour, which arises from complex interactions between agents and their environment. Unlike non-agent systems, where behaviours are explicitly programmed, multi-agent systems exhibit behaviours that are not directly coded but emerge as a result of these interactions. While this emergent behaviour can lead to unpredictability and challenges in system control and verification, it also opens opportunities for novel and unexpected outcomes that can prove beneficial. For instance, emergent behaviours enable multi-agent systems to discover innovative solutions to problems, enhancing system efficiency and adaptability in dynamic and uncertain scenarios.

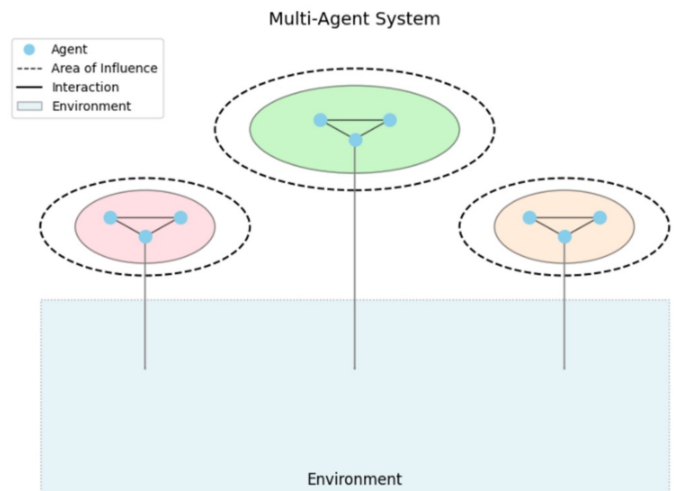

Figure 2 Multi-agent system interacting with environment

Agents within multi-agent systems demonstrate adaptability by learning from their experiences and evolving with changing conditions, leading to improved individual and collective performance over time. This capacity for adaptation distinguishes multi-agent systems from non-agent systems, which can only react within the constraints of their pre-programmed rules. Furthermore, multi-agent systems tend to be more robust and fault tolerant. In the event of an agent's failure, the system can continue to function as the overall behaviour emerges from the interactions of other agents rather than depending on a single component. In contrast, non-agent systems are more vulnerable to single points of failure, where the breakdown of a device or module may result in system-wide collapse. Scalability is another advantage of multi-agent systems.

Adding more agents allows the system to scale and handle larger, more complex tasks without requiring significant architectural changes. Non-agent systems, on the other hand, often require extensive redesign to accommodate greater complexity or workload. These advantages make multi-agent systems particularly well-suited for dynamic and decentralized applications such as swarm robotics, traffic management, and disaster response, and indeed the complex, dynamic and distributed environment of healthcare. However, fully realizing the potential of multi-agent systems requires addressing the inherent challenges of emergent behaviour, including unpredictability, coordination bottlenecks, and the computational complexity of validation and control. Ongoing research into advanced tools for modelling and controlling emergent behaviour, as well as interdisciplinary approaches, will be of the utmost importance for the continued development of multi-agent systems, especially in safety critical domains such as healthcare (Wooldridge 2002; Gupta *et al.* 2022; Goonatilleke and Hettige 2022).

DISCUSSION

Potentially multi-agent systems can solve more complex problems because multiple agents can divide the workload and work together to break the problem down and then solve different parts of the problem (Table 1). Multi-agent systems may be more flexible, adaptable, and resilient than non-agent systems, but they may also be more complex and difficult to design and manage. There is also a significant communication overhead and complexity to consider as each agent must interact and communicate with each other and the environment, which may affect the performance of the overall system. There is also the potential for conflicts to arise between agents if interpretations of a problem vary or there is conflicting goals, leading to system problems (Wooldridge 2002; Gupta *et al.* 2022; Goonatilleke and Hettige 2022).

Healthcare may benefit from a multi-agent system approach to the distribution of complex learning and decision-making problems. Within this system each agent contributes with its own knowledge and capabilities, sharing information, contributing to the decision-making process and coordinating behaviour with other agents towards an overall goal, within the multi-agent system. These agents may consist of a combination of software agents and hardware agents from patient monitoring devices, electronic patient records, and therapy devices working together for shared goals. A multi-agent approach to remote monitoring and intervention of the elderly is proposed by researchers utilising 5G technology and collaborative approaches. The system measured several vital signs and diabetic markers and alerted both patients and healthcare providers with alarms and when to take necessary interventions, with initial results outperforming existing mHealth technology (Humayun *et al.* 2022). Such multi-agent systems have been demonstrated to be highly accurate such as the activity-aware vital signs patient monitoring system proposed by researchers which demonstrated adaptability across various monitoring signals via disparate sensors in response to adapting physical activities ensuring accurate health assessments and timely alerts to patients and healthcare providers (Ivascu and Negru 2021). This distributed approach can improve the overall performance, especially when used in conjunction with machine learning approaches to enable the agents to learn from experiences and adapt to their environments more efficiently. Reinforcement learning can provide the agents with feedback based on the outcomes of their actions, therefore leading to improved performance and decision-making over time (Lim *et al.* 2022; Hassanien *et al.* 2021).

Multi-agent systems have demonstrated effectiveness managing complex manufacturing tasks in industrial applications with enhanced flexibility, robustness and reconfigurability in manufacturing processes (Pereira *et al.* 2012). In supply chain management multi-agent systems have been used to improve decision-making and coordination of complex logistics and supply chains (Lee and Kim 2007). Multi-agent systems are employed successfully to coordinate multiple robots for tasks such as assembly and material handling (Luo and Xue 2010).

The industrial application of multi-agent systems to manage complex, dynamic and distributed systems, makes for a compelling case for their adoption in healthcare to improve patient monitoring, resource management, and decision support systems. Multi-agent systems are well-known for their use in improving in information retrieval systems (Luo and Xue 2010). Their use in improving search results for medical purposes and improving security is a recent application of multi-agent systems in healthcare (Evtimova-Gardair 2019). Multi-agent systems have also been applied to improving the performance of medical chat-bots and medical decision support tools (Kumar 2022; Frikha *et al.* 2023).

The idea is that machines can either make better decisions in some situations than humans or can assist humans in making better decisions (Luo and Xue 2010). Multi-agent systems have also been proposed for use in healthcare wireless sensor networks. Wireless sensor networks are a large collection of homogenous nodes which work together within a cooperative network. Each node can sense, process and communicate data (Sreedevi *et al.* 2022). Another area of proposed use of multi-agent systems within healthcare is with body area sensor networks, which are IoT devices which collect, process and analyse data on or, from within the human body. These agents are typically heterogeneous. Typically, these IoT devices do not share information or interact in a cooperative manner (Gupta *et al.* 2022; Humayun *et al.* 2022; Lim *et al.* 2022).

A key driver to the huge investment in IoMT is concerns regarding a worldwide aging population. Chronic diseases will inflate healthcare expenses as those over 65 will number 1.5 billion by the year 2050 (Lim *et al.* 2022). Furthermore, there is significant shift in focus from treating disease to prevention-orientated healthcare, where health-surveillance via IoMT can play a key role (Shakahuki and Reid 2015). There have been some notable successes in IoMT with monitoring electrocardiogram (ECG), where the ECG is monitored, stored and notifications sent to healthcare workers using sensors and fog computing (Ivascu and Negru 2021). Alzheimer's disease is a chronic disease that deteriorates memory and judgement, sensors have been successfully embedded in clothing to track and monitor patient's behaviour and movements. Fall detection using a camera, fall sensor and Amazon Echo device has been successfully reported for aged adults (Ivascu and Negru 2021; Shakahuki and Reid 2015).

Medication monitoring can track the distribution and dosing of medication, and medicine boxes linked by IoMT will be able to monitor specific patient patterns and compliance. There is even research ongoing into using IoMT sensors for biomedical tracing of secretions from potential cancers given a patient's risk factors. There has been the development of a washable T-shirt with multiple IoMT sensors, such as ECG, temperature, respiratory rate and patient activity classification and monitoring (Gupta *et al.* 2022; Goonatilleke and Hettige 2022; Ivascu and Negru 2021; Shakahuki and Reid 2015; Humayun *et al.* 2022). Other successful applications have been described measuring glucose levels, oxygen saturation, blood pressure (Aledhari *et al.* 2022). During the Covid-19 pandemic IoMT came to the fore, with connected diagnostics such as blood gas analyzers and biological services, imaging such as CT, MRI and X-ray, smart instruments, smart patient beds and smart facilities (Somani *et al.* 2022).

Multi-agent systems are a group of autonomous agents that cooperate with each other, share information, reason together and coordinate their activities, collectively solving problems that would be impossible to solve alone (Aledhari *et al.* 2022). The environment of monitoring patients remotely would seem to benefit greatly from a multi-agent system approach, which differs from the current situation where devices collect and send information, but rarely work collectively or take action. Sharing information and working towards common goals while using historic data to gather patient patterns and real-time data between intelligent nodes could reduce healthcare workload by monitoring patients closely and increase patient safety by sending alerts in emergencies (Alshamrani 2022). Likewise, using a multi-agent systems approach to in-patients has several benefits also, and builds on the idea of the smart hospital.

Table 1 Comparison of multi-agent systems and centralized control systems

Aspect	Multi-Agent Systems	Centralized Control Systems
Flexibility	High flexibility due to decentralized decision-making and adaptability.	Low flexibility as decisions are made centrally and require reprogramming.
Scalability	Easily scalable by adding more agents.	Difficult to scale as system architecture needs significant redesign.
Fault Tolerance	High fault tolerance; failure of one agent doesn't affect the entire system.	Low fault tolerance; single point of failure can disrupt the entire system.
Emergent Behaviour	Exhibits emergent, unpredictable behaviour, which can lead to novel solutions.	No emergent behaviour; all outcomes are predefined and deterministic.
Complexity of Control	Complex to predict and control due to decentralized interactions.	Easier to control and predict due to centralized decision-making.
Resource Utilization	Efficient utilization by distributing tasks among agents.	Less efficient resource utilization as tasks are centrally allocated.
Communication Overhead	High communication overhead for coordination between agents.	Minimal communication overhead due to centralized control.
Adaptability	Learns and adapts to changing environments dynamically.	Limited adaptability; only reacts to predefined conditions.
Development Complexity	More complex to design, implement, and debug.	Easier to design, implement, and debug due to simpler architecture.
Cost	Potentially higher initial development and deployment costs.	Lower initial cost but higher cost to scale and adapt.

The concept of the smart hospital can find its origins from Korea in the early 2000's with the notion of the digital hospital. At the time Korea pioneered digitalisation of hospital workflow with the concept of the 4-lesses, which is filmless, chartless, slipless and paperless operations with the introduction of complete electronic medical record system. By the end of that decade radiofrequency identification systems were widespread throughout the USA, Korea and Japan, allowing the real-time tracking and tracing of patients, medicines, equipment and other assets around the health system. More recently the introduction of 5G and Wi-Fi 6, have overcome network bottlenecks, and introduction of IoMT devices to the network working with AI and intelligent building technologies have the potential to drive efficiencies up and cost down in the era of the smart hospital (Kwon *et al.* 2022).

CONCLUSION

As mentioned earlier in most instances IoMT devices have poor interoperability, this would lead to unnecessary duplication of data, and significant waste in processing, transfer and storage of data. Also, a significant concern with IoMT devices is minimising power consumption (Sharma and Tripathi 2022). By introducing a multi-agent systems approach to the smart hospital concept may help alleviate some of these issues as each IoMT device will work as a node within the larger multi-agent system, sharing data, responding to changing stimuli in the environment, updating and sharing this information with other nodes, reasoning together and making decisions together to reduce duplicate data, improve efficiencies and performance of the overall system. Most likely, for a system like this to preform efficiently it will have to learn through reinforcement learning (Ivascu and Negru 2021).

Reinforcement learning is where agents learn through trial and error and receive feedback in the form of rewards or punishments. Reinforcement learning has been successfully used to personalise patient treatment plans, optimise healthcare facility operations and allocate healthcare resources. However, reinforcement learning is not without challenges especially in the healthcare setting where there are more stringent ethical and regulatory concerns to protect patients from harm. These models can be complex and difficult to interpret. Therefore, significant simulations would first have to be developed before such systems could ever be used in real-world (Gupta *et al.* 2022; Goonatilleke and Hettige 2022; Ivascu and Negru 2021). The future is likely to be one where the smart hospital is common-place, multi-agent systems and reinforcement learning have the potential if used appropriately and safely to bring increased efficiencies to healthcare systems, and reduce expenditure while optimising patient care and personalising healthcare.

Availability of data and material

Not applicable.

Conflicts of interest

The author declares that there is no conflict of interest regarding the publication of this paper.

Ethical standard

The author has no relevant financial or non-financial interests to disclose.

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