Integrating Sensing and Communication for IoT Systems: Task-Oriented Control Perspective

Dongxuan He, Huazhou Hou, Rongkun Jiang, Xinghuo Yu, Zhongyuan Zhao, Yuanqiu Mo, Yongming Huang, Wenwu Yu, and Tony Q. S. Quek

Abstract

The Internet of Things (IoT) is widely acknowledged as an innovative paradigm that engenders profound alterations along with society's development due to its inevitability and universality. To effectively control IoT systems for specific tasks, it is important to tackle their emerging challenges, such as information transmission and sensing for the environment or specific task. Integrating sensing and communication (ISAC), which achieves the communication and sensing functionalities over one hardware platform, has significant advantages over dedicated sensing and communication, and has been regarded as a key technique for IoT ecosystems with the upcoming 6G communication revolution. Bearing this in mind, we provide an overview of ISAC-enabled IoT systems in terms of their framework and key technologies. In particular, we first give a basic introduction to control systems, which guides the design of our considered system structure. Then, ISAC and other enabling technologies are illustrated to facilitate our proposed system. Benefiting from the communication and sensing functionalities, our proposed ISAC-enabled IoT systems enable task-oriented control. Future challenges and directions for more efficient task-oriented IoT are also discussed.

Introduction

The Internet of Things (IoT) keeps a rapid growing trend with promising potential for future implementations, which is poised to be a pivotal element in the upcoming sixth generation communication technology (6G) and industry 4.0 revolution [1]. To be more specific, IoT authorizes cyber-physical interactions by facilitating interactions between numerous devices to complete substantial tasks, thus possesses the ability to meet increasingly diverse application needs in different scenarios. Therefore, the IoT is seen as a paradigm shift in different application areas, including smart cities, industry, transportation, agriculture, environmental services, etc., which significantly changes the landscape of key infrastructure applications [2].

Given its task-oriented property, IoT can deliver exceptional quality of experience (QoE) and quality of service (QoS) to the users autonomously, which provides unprecedented automation and efficiency levels. Nonetheless, such applications of IoT introduce new capability demands in terms of data collection, signal transmission, information integration, and processing [3]. Since the essence of IoT is to drive devices to collaborate to complete specific tasks, it is essential to regulate the equipment effectively. Therefore, sensing and communication capabilities are the cornerstone of promoting task-oriented IoT systems and the fundamental driving factors for implementing task-oriented IoT [4].

By introducing a dual-functional design for both communication and sensing, integrating sensing and communication (ISAC) has shown great potential in machine communications, which has been verified by pioneering works [5]. ISAC is an emerging technology which combines sensing and communication in one hardware platforms, to increase the efficiency of the wireless spectrum resources, and utilize their potential benefits. The fundamental of ISAC is that radio signal could transmit communication information from the transmitter to the receiver, along with the environment information simultaneously, which can be used to infer the physical world. Therefore, compared with the dedicated communication and sensing, ISAC provides two main advantages. Firstly, congested resources can be utilized with integrated efficiency manner. Secondly, by shared using of spectral and hardware resources, ISAC can be realized through a synergistic design to pursue integration gain, which ensures that the communication and sensing functionalities can be performed simultaneously. Regarding the aforementioned properties, ISAC has been regarded as a promising candidate that satisfies the requirements of IoT system, especially when faced with device control requirements [6, 7]. However, task-oriented IoT systems, with their requirements for holistic perception, reliable transmission, and intelligent processing, pose numerous challenges

Dongxuan He and Rongkun Jiang are with Beijing Institute of Technology (BIT), China; Huazhou Hou (corresponding author) is with Purple Mountain Laboratories (PML), China; Xinghuo Yu is with Royal Melbourne Institute of Technology (RMIT), Australia; Zhongyuan Zhao is with Beijing University of Posts and Telecommunications (BUPT), China; Yuanqiu Mo, Yongming Huang, Wenwu Yu are with Southeast University (SEU), China; Tony Q.S. Quek is with Singapore University of Technology and Design (SUTD), Singapore.

Digital Object Identifier: 10.1109/IOTM.001.2300210

for ISAC research in the IoT context.

In light of the above, we mainly focus on the ISAC-enabled IoT from the perspective of task-oriented control in this article, which are summarized as follows. Commencing from a basic introduction to control systems, we lay out the basic concept of the task-oriented control for IoT system. Then, we present the conceptual framework of the ISAC-enabled IoT system from a task-oriented control perspective. To obtain more intuitive insights about our considered ISAC-enabled IoT, the enabling technologies are detailed. Furthermore, a range of open issues are discussed to clarify the future research directions of ISAC-enabled task-oriented IoT before concluding this article.

Control In IoT Systems

IoT system refers to an interconnected system consisting of physical devices, vehicles, appliances, and other physical objectives, embedded with sensors, network connectivity, software and control center that allows them to collect and share data, then make informed control decisions. Control plays a significant role in managing and regulating the behavior of IoT machines and devices. To develop future intelligent IoT systems, control under network environment tends to be the primary concern in accomplishing specific and sophisticated tasks. More specifically, operational machines and devices need to be properly controlled according to the desired task objective, where control center relying on cloud or edge computing infrastructures will respond to task and generate associated command. Accordingly, the IoT system can work resilience, adaptability, and efficiency.

Introduction to Control System

Control system, interconnected by different components, is a system that will provide a desired system response by applying control signals [8]. Control refers to the process of strongly influencing or regulating the behavior or action of a system or process to achieve a desired objective. From the perspective of controller, the control process involves a series of steps, which can be detailed as follows:

1. Observe the system status and environment information,
2. Compute the control strategy corresponding to desired response,
3. Deliver the control strategy to executor,
4. Update the system status and repeat the aforementioned steps.

Obviously, to facilitate efficient control, it is important to aggregate the system status, which provides information about the relevant variables or parameters that need to be controlled. However, the full system status of a distributed IoT is hard to obtain, thus requiring the ISAC to sense the status. Then, based on the system status and control algorithm, the appropriate control strategy can be operated to achieve the intended task.

According to the existence of feedback loop in the control system, the control can be classified as two categories, i. e., open-loop control and closed-loop control [8], the illustration blocks are shown in Fig. 1.

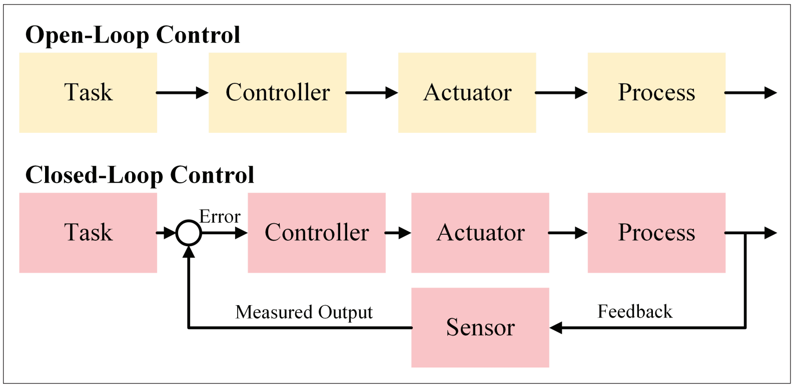

FIGURE 1. The comparison of open-loop control and closed-loop control. An open-loop control system employs an actuator to control the process without using output measurement, while a closed-loop control system uses feedback of system output to minimize the error between the output and the desired reference signal.

- **Open-loop control**, also known as non-feedback control, is a control system in which the response of controlled device is only determined by the input signal. In other words, the output in the open-loop system is neither measured nor fed back for comparison with the reference signal to adjust the control action. Typically, open-loop control is simple and cost-effective, but it is less reliable and less accurate since the disturbances or changes in the system are not considered.
- **Closed-loop control** is a control system that uses feedback information sensed from the output or the process under current control to adjust control actions and maintain desired set-points. Compared to open-loop control, the control process is continuously adjusted according to the difference between the reference signal and the actual output to reduce the error and bring the output of the system to a desired value. Closed-loop control offers better accuracy, stability, and robustness to disturbances and uncertainties. For high-value mission-critical tasks, closed-loop control is necessary, which can provide accurate and reliable control.

Control Performance Metric

To evaluate the effectiveness of a control system, the following performance metrics are typically considered [8].

- **Accuracy** refers to the degree of accuracy and correctness with which a control system is able to achieve and maintain a desired target value, which measures how well a control system is able to regulate a system or process to meet its intended objective.
- **Robustness** is the ability of a control system to maintain stable and satisfactory performance despite variations, uncertainties, perturbations, or changes in the dynamics or operating conditions of the system. Robust control is particularly important in real-world applications where the environment and system conditions may not be perfectly known or predictable.
- **Adaptability** refers to the ability of a control system to adjust, modify, or change its behavior in response to varying conditions, uncertainties, or changes in the system or environment, which is particularly important in dynamic and uncertain environments.
- **Stability** refers to the property of a control system that the output or behavior of the

To complete the task control, the controller first begins with specifying the task or objective that needs to be achieved.

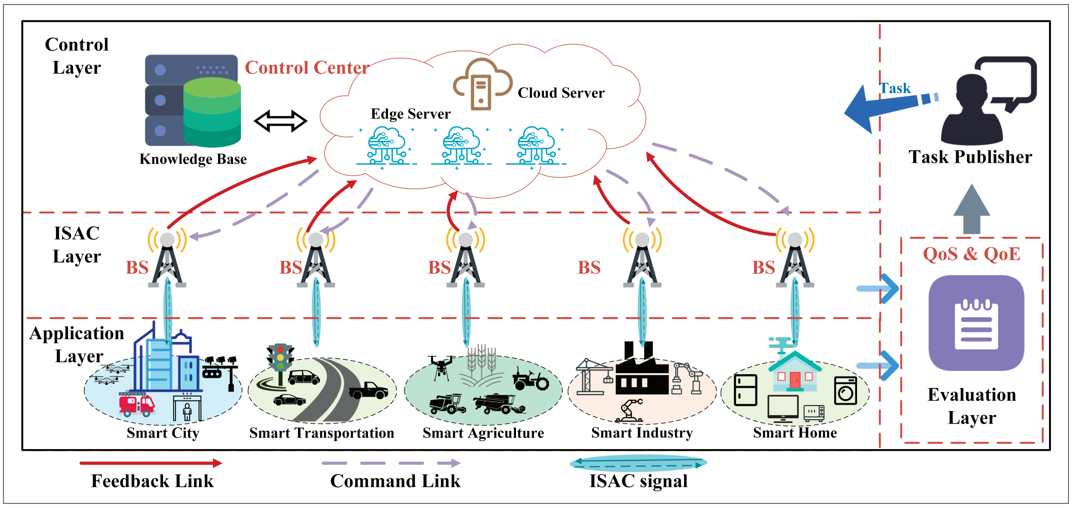

FIGURE 2. System framework of ISAC-enabled task-oriented IoT.

system remains bounded over time, even in the presence of perturbations, uncertainties, or changes in the system. Typically, stability is a fundamental requirement for the successful operation of any control system, ensuring that the controlled process remains under control and doesn't lead to unpredictable or undesirable outcomes

Besides, there are many other performance metrics for control system, such as design complexity, timing requirement, etc. Here we don't give detailed explanation.

Task-Oriented Control

Task-oriented control [9] is a control approach that focuses primarily on achieving a specific task or goal. In task-oriented control, control systems are designed to achieve desired task-relevant responses in a more intuitive and high-level manner, often leveraging higher-level commands or specifications.

More specifically, due to the abstract nature of the task, the control is designed according to the task or objective rather than directly manipulating the underlying control variables. Therein, the control system is provided with task specifications, objectives, or goals that need to be achieved, which could be in the form of high-level commands, trajectories, or constraints. To complete the task control, the controller first begins with specifying the task or objective that needs to be achieved. The task is then decomposed into smaller subtasks, where each subtask represents a specific step toward the task objective. Finally, task-oriented control system will use high-level control command to guide the system operates toward the desired task.

Therefore, in the IoT systems, the occurrence of task-oriented control increases the autonomy level at the system level, and enables the solution to the high level goals control problem. The control system requires stronger information gather abilities from the scheduled tasks and external environment, to perform the desired task.

Since the task of the IoT systems varies due to the different scenarios and physical devices, which relies on the different requirements on the communication and transmission network to ensure the reliable transmission of both sensed data and control command, based on the communication types, e.g., 6G, 5G, 4G long term evolution (LTE), near field communication (NFC), radio frequency identification (RFID), Bluetooth, narrow band-IoT (NB-IoT), LoRaWAN, and wireless utility networks(Wi-SUN), the task-oriented control of IoT systems can also be classified into time-sensitive control and delay tolerant control.

- **Time-sensitive control** refers to control systems or processes that require real-time or near-real-time responses, where precise time, computing, and communication with bounded latencies are strictly required. In such systems, the control actions must be executed within strict time constraints to achieve desired performance or ensure safety. In particular, the performance of closed-loop control, which include accuracy, robustness, adaptability, and stability, are heavily determined by the delay of command. For example, the control of power grids, control of autonomous vehicles. To satisfy the requirements time-sensitive control, low-latency transmission schemes exemplified by ultra-reliable low latency communications (URLLC) are required in distributed IoT system.
- **Delay-tolerant control** refers to control systems that can tolerate certain delays in control actions without significant adverse effects on system performance or stability. In such systems, the response time is less critical and occasional delays may be acceptable. For a stand-alone control system with a simple control algorithm and no processing exceptions, the delay tends to be low-impact. The chemical process control or bio-reactor control is typical delay-tolerant control.

ISAC-Enabled Task-Oriented IoT System

ISAC is indispensable in the design and implementation of task-oriented IoT, where both communication and sensing are important to control the ubiquitous IoT devices. Therefore, the advantage of ISAC has instigated the research inquiries into the realm of designing the ISAC-enabled IoT system. To enable the system to work effectively and efficiently, a task-oriented IoT system framework is proposed,

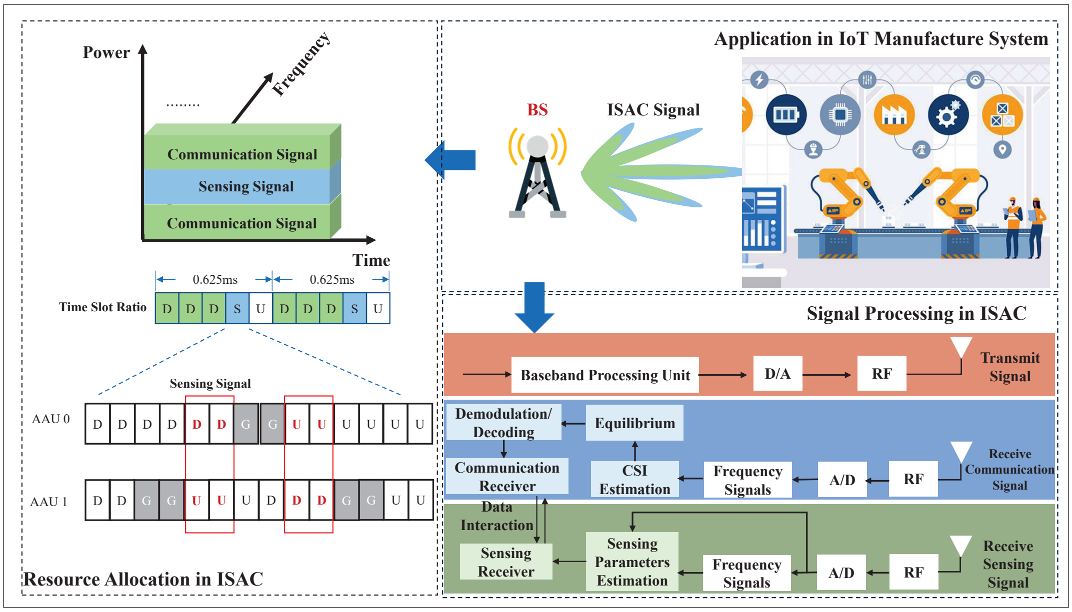

FIGURE 3. Detailed illustration of ISAC layer, signal processing in ISAC is presented and the feature of ISAC is shown as well.

Compared with separated communication and sensing systems, the utilization of ISAC can reduce costs and overcome the inter-layer constraints, thus facilitating faster deployment.

which is illustrated in Fig. 2. The proposed framework consists of four layers, namely control layer, ISAC layer, application layer, and evaluation layer.

Control Layer. Aiming to achieve a desired task, the control center first receives a specific task from the task publisher, such as a factory manager, a householder, etc., and then specifies the task as a specific step towards the objective. Next, based on the analysis of status data feedback from ISAC layer and the task objectives, the control center makes decisions and formulates its control strategies, which heavily relies on the computing power of the cloud server or edge server. In particular, the data from the ISAC layer provides sufficient status information about the device to be controlled, such as its location, attitude, motion, etc., which facilitates device control. Moreover, since IoT devices suffer from natural conditions or anthropogenic factors, their status will be adversely affected, which influences the control stability. Therefore, the control center continuously receives device status information and updates control commands to adjust the operating status of the device during the task. To improve the work efficiency of control center, a knowledge base can be used to store useful control strategies, which can avoid repeated calculations.

ISAC Layer. Benefiting from its capabilities in sensing and communication, the ISAC layer, which can realize status acquisition and information transmission, connects the control and application layers. More specifically, based on its information transmission capability, the ISAC layer, which is deployed on the base station (BS), can collect data for the control center and send control commands to the IoT devices. In addition, the ISAC layer can also monitor the IoT devices and the relevant environment, which provides useful information to make a correct control decision. Compared with separated communication and sensing systems, the utilization of ISAC can reduce costs and overcome the inter-layer constraints, thus facilitating faster deployment. Moreover, the joint signaling strategies are provably able to and enable optimal co-design and operation, where the communications and sensing functionalities can mutually assist each other. For example, the sensing functionality aids in facilitating more reliable communication between the BS and the device by providing accurate location of the device, which enables more accurate beamforming. At the same time, communication functionality, which can provide prior information about the detection target, can support more effective detection by avoiding blind searches. Moreover, to guarantee the communication between two IoT devices, the open system interconnection (OSI) reference model should be implemented to support the information delivery in ISAC layer. As such, the communication process can be defined by physical layer, data link layer, network layer, transmission layer. For better illustration, the features and processes of ISAC for IoT is shown in Fig. 3. The resource is allocated based on the specific requirement of sensing and communication over same hardware platform, the general signal processing in ISAC is also shown.

Application Layer. The application layer is primarily responsible for executing specific tasks, where IoT devices distributed in different scenarios will work regularly according to the commands from the control center. For example, centralized controller in smart transportation system can regulate traffic signals, manage traffic flow, and optimize the utilization rate of road networks, which enable the vehicles run efficiently and safely. The control-driven smart industry can manage and synchronize various machines and processes to optimize production and achieve specific production goals, thus realizing industrial automation. In smart home, the home appliances will work orderly to accomplish specific tasks, thus providing householders with peace of mind and comfort.

Evaluation Layer. The evaluation layer assesses the effectiveness of the task-oriented IoT system in terms of QoS and QoE. Note that the evaluation layer can appraise both the ISAC process and the control results, where the information from both the ISAC layer and application layer

> By integrating sensing and communications, control-driven systems can adapt to time-varying conditions or unforeseen events, thus enabling coordinated actions to efficiently achieve task objectives.

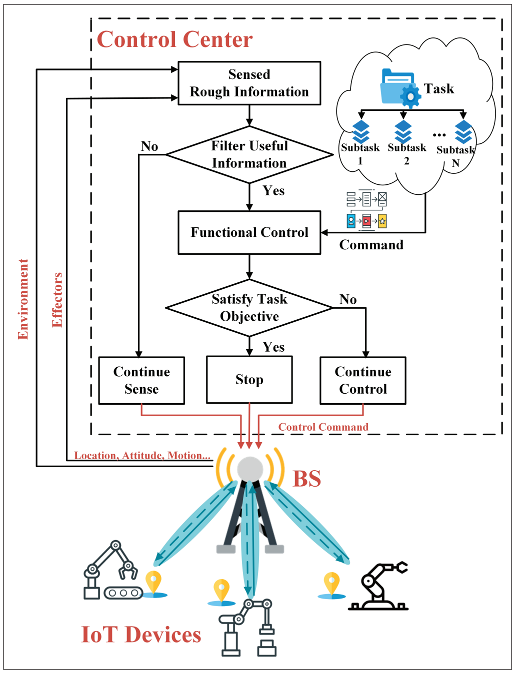

FIGURE 4. Illustration of ISAC-enabled task-oriented control, where the control center utilizes both environment and effector information to further determine control commands. Once the sensing fails to provide sufficient useful information, the BS is asked to further sense more information. Otherwise, control commands are issued based on the level of task completion.

will be fed to the evaluation layer. In particular, QoS emphasizes technical objective metrics such as throughput, transmission delay, packet loss rate, detection probability, false alarm rate, etc., which are helpful for evaluating the ISAC layer. At the same time, the QoE can be used to describe the satisfaction and perception of the user when interacting with a particular control task, which is more appropriate to evaluate whether the control results at the application layer satisfy the task publisher's requirements. To understand the requirements from the task publisher from the perspective of QoE, the user demand modeling can be considered [10]. The evaluation results are then sent to the control layer, which allows for the adjustment of control commands, thereby ensuring optimal control performance.

Why Need ISAC Layer?

Compared to the conventional IoT system, the ISAC layer is believed to be the crucial to satisfy the implementation requirements of task-oriented control system, the introduction of ISAC and some significances of the ISAC to the task-oriented IoT systems are introduced in the follows.

Integrating Sensing and Communication

As the basis of the considered task-oriented IoT system, ISAC takes responsibility of status acquisition and information transmission, which enables automatic and intelligent control of IoT devices. Typically, ISAC refers to the integration of sensing and communication systems to efficiently share the same resources, where the transmitted signal is separated for respective purpose or for both purposes. To obtain a acceptable performance of both sensing and communication, appropriate tradeoffs between the two functionalities are required, as well as advanced waveform design and processing to the ISAC signals [11].

On the one hand, the ISAC enables connectivity and networking between the BS and distributed IoT devices, thus guaranteeing reliable command delivery. Note that, the requirements for communications can vary significantly depending on the target applications, which range from ultra-high rate transmission for cluster control to URLLC for smart factories and remote robots control. As such, the communication scheme should be adaptively adjusted according to the intended device and specific task.

On the other hand, ISAC also provides sensing capabilities to monitor IoT devices, which facilitates continuous observation and analysis of various connected devices, thus ensuring proper functioning and making informed decisions.

Importance of ISAC to Task-Oriented IoT

Reliable Control for Specific Task: To successfully complete the task, the control center needs to first obtain the status of the IoT devices, such as their location, attitude, motion, etc., where intelligent identification, location, tracking, monitoring and management are required. Then, based on the analysis of the sensing information and the task objectives, the control center can make informed decisions and develop control strategies. Moreover, IoT plays an important role in connecting everything together and enabling information exchange and communication through specific protocols. By integrating sensing and communications, control-driven systems can adapt to time-varying conditions or unforeseen events, thus enabling coordinated actions to efficiently achieve task objectives. By continuously monitoring the device and environment, the IoT system can adjust actions to optimize performance and achieve its goals even in dynamic environments. In summary, with the help of ISAC, the task-oriented IoT can successfully complete the specific tasks regardless of the environmental change, thus guaranteeing the effectiveness of task-oriented control in IoT systems.

Cooperative Control for Distributed Devices: Based on the ISAC layer, the status of the distributed IoT devices can be collected together, and then the IoT devices can be controlled collaboratively. To this end, multiple devices can collaborate to achieve a specific task, thus improving fault tolerance and system reliability. As shown in Fig. 4, the task can be divided into several subtasks, where the control center generates control commands and sends them to the corresponding devices through the ISAC layer. Accordingly, devices in such cooperative control system with task division and specialization can be assigned specific tasks based on their capabilities and expertise, resulting in improved overall system performance. In addition, cooperative control enables intelligent decision-making on resource allocation, thereby leading to more efficient utilization of time, energy, and other resources [12].

Efficient Control with Integrated Resources: Integrating sensing and communication provides a more efficient solution, where wireless sensing functionality is integrated into commercial communication devices with the same hardware, spectrum and even signaling resources, thus leading to cost-efficient implementation in terms of infrastructure deployment and maintenance. Besides, through the shared use of these resources between communication and sensing, ISAC can be realized by a collaborative design to undertake the integration gain, where integrating communication and sensing can lead to innovative applications that leverage the strengths of both functions, such as location-based communication or a priori known sensing. Moreover, when the resources are shared, they can be dynamically allocated based on the specific task. For example, when performing open-loop control with complex processes, more resources can be allocated to support communication requirements. Conversely, when closed-loop control with simple commands is required, resources can be diverted to enhance sensing capabilities. Therefore, the integrated resources can be adaptively allocated to support different functionalities, thus enabling efficient control.

Other Enabling Technologies

In addition to ISAC, there are several other enabling technologies that enable effective task-oriented IoT systems.

Cloud and Edge Computing

The control layer, which processes and analyzes the data received from the ISAC layer and generates appropriate control commands, is too sophisticated for resource-limited devices. Moreover, highly responsive task computing, adaptive networking, and efficient resource management are also imperative for the implementation of task-oriented IoT, which further increase the computing burden. To this end, cloud and edge servers are important to the task-oriented IoT, which provide sufficient storage and computing capabilities [13].

Cloud computing refers to the delivery of computing resources such as computing power, storage, databases, networking, software and other services over the Internet. Instead of owning and maintaining physical hardware and software, users can access and use these resources on-demand from remote data centers provided by cloud servers. Unlike cloud computing, edge computing is a decentralized computing architecture that brings computation and data storage closer to where it is needed, often at the edge of the network, rather than relying on centralized data centers or cloud environments. For edge computing, data processing and analysis occur locally on geographically distributed devices or servers, thus reducing the need to transmit data back and forth to remote data centers.

Relying on cloud and edge computing, the control center can generate suitable control strategy, which guarantees the efficient work of the task-oriented IoT system. In addition to cloud and edge computing, leveraging state-of-the-art technologies such as blockchain and artificial intelligence can also facilitate data analysis and control commands.

Artificial Intelligence

Artificial intelligence (AI), which enables learning, reasoning, problem solving and interaction with the environment, also plays a crucial role in enhancing the capabilities and effectiveness of the IoT ecosystem, thus undoubtedly bringing significant advantages and opportunities for various industries and applications.

For example, AI techniques exemplified by machine learning and deep learning can enable efficient analysis of collected information to extract valuable insights, patterns, and trends that can drive informed control decision-making. Benefiting from its strong calculation ability, AI allows for immediate and automated decision-making, which is crucial for time-sensitive control such as autonomous vehicles, industrial automation, etc. Moreover, AI-powered IoT systems are able to predict future events and outcomes based on historical data, enabling proactive maintenance that improves the stability of adaptive control especially in dynamic environment.

Moreover, AI can also significantly improve the ISAC performance of our considered task-oriented IoT systems. For instance, the appropriate trade-off between sensing and communication capabilities can be adaptively tuned by AI, which facilitates a more efficient implementation of ISAC-enabled IoT systems. With the help of reinforcement learning (RL), AI enables intelligent data collection, where the ISAC transmitters can properly control the quality and/or the amount of sensing data based on the task requirements as well as the communication and computation capabilities of the system. Furthermore, AI is helpful to **fuse** the information data of the communications and networking environment, which dynamically adjust protocols without human interactions, thus leading to superior communication performance [14].

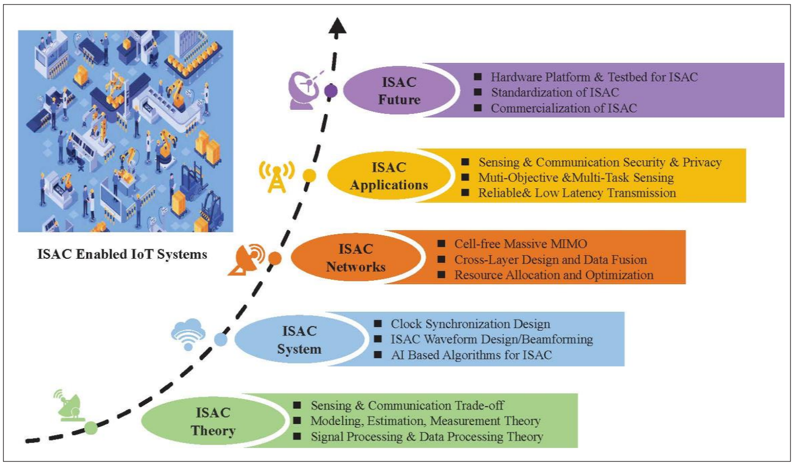

FIGURE 5. Open issues in ISAC.

Open Issues

Some insights on the potential ISAC-enabled IoT system from the perspective of task-oriented control have been shed. However, as a systematic implementation, there are still many open issues needed to be studied and resolved, which are illustrated in Fig. 5. In particular, some typical research directions are expected to be considered as follows.

Coordinated Frequency Resource

To facilitate task-specific sensing and communication with high flexibility, ISAC-enabled IoT should be a full-spectrum system with coordination in low, medium and high frequency bands. More specifi-

To facilitate task-specific sensing and communication with high flexibility, ISAC-enabled IoT should be a full-spectrum system with coordination in low, medium and high frequency bands.

cally, benefiting from its low path loss, the low-frequency band will provide wide area coverage and long range detection. Meanwhile, the medium-frequency band will be used for continuous coverage, Gbps-level transmission, and wide area sensing with meter-level accuracy. High-frequency bands exemplified by mmWave and Terahertz will provide high-speed communication and sub-meter resolution sensing. Obviously, the total system performance, flexibility and expansibility of the considered system can be improved prospectively by introducing coordinated frequency resource, which can meet the distinguishing requirements of personalized tasks. Therefore, further research on coordinated frequency resource management or allocation is urgently required for task-oriented control in the ISAC-enabled IoT system.

High-Efficiency Command Transmission

Complicated control commands are not appropriate for the IoT systems relying on wireless links, which impose stringent requirements on transmission bandwidth and latency. As a revolutionary transmission paradigm capable of incorporating control and task information, semantic communication, which focuses on the meaning and significance of the transmitted information rather than just the raw data, seems to be a promising solution for future task-oriented IoT from a control perspective. In particular, semantic communication can enable cross-system, cross-protocol, and cross-network compatibility, resulting in intelligent connectivity between control centers and IoT devices [15]. To realize such goal, a background knowledge base is required at the control center to generate comprehensible commands for the devices, which guarantees command information can be accurately restored and properly executed. Therefore, to realize high-efficiency command transmission, semantic communication seems to be a potential research direction for our considered task-oriented IoT system.

Security/Privacy Communication and Sensing

With the evolution of 6G communication technologies, the privacy and security problems are emerging challenges in ISAC enabled IoT systems since the common usage of the spectrum, and the naturally broadcast characteristics of wireless communication. Two different aspects can be discussed in this scenario, the first one is sensing-assisted physical layer security, which means that in secure ISAC IoT systems, communication transmission is protected by physical layer security approaches, both the radar and communication are working at the same time which is energy consumption, to increase the energy efficiency, it is desired that sensing and communication are working collaboratively, which motivates the sensing-assisted techniques to protect the communication, i.e., active sensing functionality to recognize the eavesdropper's direction. On the other hand, In the radar-communication coexistence scenario, radar parameters are transmitted to the communication system which leads to the radar privacy problem, which means by employing some machine-learning based approaches, the parameters of radar can be inferred. This risk motivates the research on how to exchange parameters between radar and communication in ISAC enabled IoT systems taking the privacy risk of each unit into consideration.

Conclusion

In this article, we present our understanding and conception of ISAC-enabled IoT system from a task-oriented control perspective. To this end, we first illustrate the fundamentals of the control process, followed by our proposed control-oriented IoT system framework consisting of three layers, namely control layer, ISAC layer, and application layer. As a connection between control and application layers, the ISAC layer shows great importance for our considered task-oriented IoT systems in providing reliable control for specific tasks, cooperative control for distributed devices, and efficient control with integrated resources. Then, the enabling technologies to guarantee the effectiveness of our considered system are provided. Finally, some potential issues along with possible solutions have also been further discussed.

Acknowledgment

D. He was supported by the National Natural Science Foundation of China under Grant No. 62101306, and the National Key Research and Development Program of China under Grant No. 2020YFB1807900, H. Hou was supported by the National Natural Science Foundation of China under Grant No. 62203109, the Natural Science Foundation of Jiangsu Province under Grant No. BK20220812, and China Postdoctoral Science Foundation No. 2023M742671. X. Yu was partially funded by the Australian Research Council under Discovery Program DP230101107, Y. Mo was supported by the National Natural Science Foundation of China under Grant No. 62303112, and Natural Science Foundation of Jiangsu Province under Grant No. BK20230826. Y. Huang was supported in part by the National Natural Science Foundation of China under Grant No. 62225107, the Fundamental Research Funds for the Central Universities 2242022k60002. W. Yu was supported by the National Key R&D Program of China under Grant No. 2022ZD0120001, the National Natural Science Foundation of China under Grants Nos. 62233004 and 62073076. T. Q.S. Quek was supported in part by the National Research Foundation, Singapore and Infocomm Media Development Authority under its Future Communications Research & Development Programme.

References

[1] F. Guo *et al.*, "Enabling Massive IoT toward 6G: A Comprehensive Survey," *IEEE Internet Things J.*, vol. 8, no. 15, 2021, pp. 11,891–915.
[2] A. Hakiri *et al.*, "Publish/subscribe-Enabled Software Defined Networking for Efficient and Scalable IoT Communications," *IEEE Commun. Mag.*, vol. 53, no. 9, 2015, pp. 48–54.
[3] L. Zhang *et al.*, "Information Fusion Based Smart Home Control System and its Application," *IEEE Trans. Consumer Electronics*, vol. 54, no. 3, 2008, pp. 1157–65.
[4] Y. Cui *et al.*, "Integrating Sensing and Communications for Ubiquitous IoT: Applications, Trends, and Challenges," *IEEE Network*, vol.~35, no. 5, 2021, pp. 158–67.
[5] W. Yuan *et al.*, "Integrated Sensing and Communication-Assisted Orthogonal Time Frequency Space Transmission for Vehicular Networks," *IEEE J. Sel. Topics Signal Process.*, vol. 15, no. 6, Nov. 2021, pp. 1515–28.
[6] X. Li *et al.*, "Over-the-Air Integrated Sensing, Communication, and Computation in IoT Networks," *IEEE Wireless Commun.*, vol. 30, no. 1, pp. 32–38, 2023.
[7] M. Zheng *et al.*, "A Flexible Retransmission Scheme for Reliable and Real-time Transmissions in Industrial Wireless Networks for Factory Automation," *IEEE Trans. Vec. Tech.*, vol.

72, no. 8, 2023, pp. 10,867–78.
[8] R. Bishop, and R. Dorf, "Modern Control Systems," Eleventh Edition, 2011, Prentice Hall, New York.
[9] M. Anthony, and C. A. Klein. "Obstacle Avoidance for Kinematically Redundant Manipulators in Dynamically Varying Environments," *The Int'l. J. Robotics Research,* 4.3, 1985, pp. 109–17.
[10] Y. Fu *et al.*. "A Distributed Microservice-aware Paradigm for 6G: Challenges, Principles, and Research Opportunities," *IEEE Network*, Early Access, 2023.
[11] X. Cheng *et al.*, "Integrated Sensing and Communications (ISAC) for Vehicular Communication Networks (VCN)," *IEEE Internet Things J.*, vol. 9, no. 23, 2022, pp. 23,441–51.
[12] M. Zheng, L. Zhang, and W. Liang, "Control-Aware Resource Scheduling Method for Wireless Networked Control Systems," *IEEE Sensors J.*, vol. 23, no. 18, 2023, pp. 21,946–55.
[13] J. Lin *et al.*, "A Survey on Internet of Things: Architecture, Enabling Technologies, Security and Privacy, and Applications," *IEEE Internet Things J.*, vol. 4, no. 5, 2017, pp. 1125–42.
[14] P. Chemouil *et al.*, "Special Issue on Artificial Intelligence and Machine Learning for Networking and Communications," *IEEE JSAC*, vol. 37, no. 6, 2019, pp. 1185–91.
[15] X. Luo, H. -H. Chen, and Q. Guo, "Semantic Communications: Overview, Open Issues, and Future Research Directions," *IEEE Wireless Commun.*, vol. 29, no. 1, 2022, pp. 210–19.

Biographies

Dongxuan He (dongxuan_he@bit.edu.cn) received the B.S. degree in automation and the Ph.D. degree in information and communication systems from the Beijing Institute of Technology (BIT) in 2013 and 2019, respectively. From 2017 to 2018, he was a Visiting Student at the Singapore University of Technology and Design (SUTD). From 2019 to 2022, he was a Post-Doctoral Researcher at the Department of Electronic Engineering, Tsinghua University. He is currently an Assistant Professor with the School of Information and Electronics, BIT. His current research interests include terahertz communication, AI empowered wireless communications, etc. He was also an Exemplary Reviewer of *IEEE Wireless Communications Letters*.

Huazhou Hou (houhuazhou@pmlabs.com.cn) received the B.S. degree from Beijing Institute of Technology (BIT) in 2013, the M. S. degree and the Ph.D. degree from Northeast University (NEU) in 2015 and 2020, respectively. From 2017 to 2019, he was a Joint Ph. D. student at RMIT university, Melbourne, Australia. From 2020 to 2023, he was a Post-Doctoral at Southeast University (SEU). He is currently an Associate Professor with the Purple Mountain Laborites (PML), Nanjing, China. His research interests include AI-Native Wireless Communication, Integrated Sensing and Communication (ISAC) and Signal Processing.

Rongkun Jiang (jiangrongkun@bit.edu.cn) received the Ph.D. degree from Beijing Institute of Technology (BIT), Beijing, China, in 2020, where he was a Postdoctoral Researcher from 2020 to 2023. He is currently a research assistant in the School of Integrated Circuits and Electronics, BIT, Beijing, China. His research interests include wireless communications, reconfigurable intelligent surface (RIS), integrated sensing and communications (ISAC), and deep learning-based solutions on signal processing. He was a recipient of the ELEX Best Paper Award from IEICE, Japan, in 2020.

Xinghuo Yu [F'08] (x.yu@rmit.edu.au) received the B.Eng. and M.Eng. degrees in electrical and electronic engineering from the University of Science and Technology of China, Hefei, China, in 1982 and 1984, respectively, and the Ph.D. degree in control science and engineering from Southeast University, Nanjing, China, in 1988. He is a Distinguished Professor and a ViceChancellor Professorial Fellow with the Royal Melbourne Institute of Technology (RMIT University), Melbourne, VIC, Australia. His research interests include control systems, complex and intelligent systems, and future energy systems. He was the President of the IEEE Industrial Electronics Society in 2018 and 2019. He is a Fellow of the Australian Academy of Science, an Honorary Fellow of Engineers Australia, and a fellow of several other professional associations.

Zhongyuan Zhao [M'14] (zyzhao@bupt.edu.cn) received the B.S. degree in applied mathematics and the Ph.D. degree in communication and information systems from Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2009 and 2014, respectively. He is currently an associate professor with BUPT. His research interests include fog/edge computing, content caching, and edge intelligence in wireless networks. He served as an editor of *IEEE Communications Letters* (2016–2022), and received Exemplary Editors Award twice (2017 and 2018). He was the recipient of the Best Paper Awards at the IEEE CIT 2014 and WASA 2015.

Yuanqiu Mo (moyuanqiu@gmail.com) received the Ph.D. degree in electrical and computer engineering at the University of Iowa, in 2019. He is currently an associate researcher with the Southeast University. His research interests include distributed algorithm design and stability theory. He has been awarded the 2018 CDC Outstanding Student Paper Award. He was also a finalist of the Young Author Award in the IFAC World Congress 2020.

Yongming Huang (huangym@seu.edu.cn) received the B.S. and M.S. degrees from Nanjing University, Nanjing, China, in 2000 and 2003, respectively, and the Ph.D. degree in electrical engineering from Southeast University, Nanjing, China, in 2007. Since March 2007, he has been a Faculty with the School of Information Science and Engineering, Southeast University, where he is currently a Full Professor. His research interests include intelligent 5G/6G mobile communications and millimeter wave wireless communications. He submitted around 20 technical contributions to IEEE standards, and was awarded a certificate of appreciation for outstanding contribution to the development of IEEE standard 802.11aj.

Wenwu Yu (wwyu@seu.edu.cn) received the B.Sc. degree and the M.Sc. degree from the Department of Mathematics, Southeast University, Nanjing, China, in 2004 and 2007, respectively, and the Ph.D. degree from the Department of Electronic Engineering, City University of Hong Kong, Hong Kong, in 2010. His research interests include multi-agent systems, complex networks and systems, disturbance control, distributed optimization, machine learning, game theory, cyberspace security, smart grids, intelligent transportation systems, and big-data analysis. He was listed by Clarivate Analytics/Thomson Reuters Highly Cited Researchers in Engineering from 2014 to 2020. He was a recipient of the Second Prize of the State Natural Science Award of China in 2016.

Tony Q. S. Quek [S'98, M'08, SM'12, F'18] (tonyquek@sutd.edu.sg) received the B.E. and M.E. degrees in electrical and electronics engineering from the Tokyo Institute of Technology in 1998 and 2000, respectively, and the Ph.D. degree in electrical engineering and computer science from the Massachusetts Institute of Technology in 2008. Currently, he is the Cheng Tsang Man Chair Professor, ST Engineering Distinguished Professor, and Head of ISTD Pillar with Singapore University of Technology and Design as well as the Director of Future Communications R&D Programme. He is a Fellow of IEEE and a Fellow of the Academy of Engineering Singapore.