Self-Awareness for Autonomous Systems

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Autonomous systems are able to make decisions and potentially take actions without direct human intervention, which requires some knowledge about the system and its environment as well as goal-oriented reasoning. In computer systems, one can derive such behavior from the concept of a rational agent with autonomy ("control over its own actions"), reactivity ("react to events from the environment"), proactivity ("act on its own initiative"), and sociality ("interact with other agents") as fundamental properties [1]. Autonomous systems will undoubtedly pervade into our everyday lives, and we will find them in a variety of domains and applications including robotics, transportation, health care, communications, and entertainment to name a few.

The articles in this month's special issue cover concepts and fundamentals, architectures and techniques, and applications and case studies in the exciting area of self-awareness in autonomous systems.

Self-awareness is a broad concept borrowed from cognitive science and psychology that describes the property of a system, which has knowledge of "itself," based on its own senses and internal models. This knowledge may take different forms, is based on perceptions of both internal and external phenomena, and is essential for being able to anticipate and adapt to unknown situations. Computational self-awareness methods comprise a new promising field that enables an autonomous agent to detect nonstationary conditions, to learn internal models of its environment, and to autonomously adapt its behavior and structure to the contextual tasks. Roughly speaking, a self-aware autonomous system has the following key capabilities: 1) create and learn models from sensor inputs; 2) infer its state and the environment's state based on the models; 3) detect discrepancies between observed and inferred behavior; and 4) explore tradeoffs and act in accordance with high-level goals. Although the level and complexity of these capabilities may vary, they serve as the basis towards achieving truly autonomous behaviors.

Over the last decades, researchers from different disciplines have proposed and investigated computing systems with various levels of autonomy in order to manage ever increasing levels of complexity and uncertainty. Self-awareness in a computational context is founded on advanced methods and algorithms from different disciplines, including signal processing, control engineering, communications, machine learning, and artificial intelligence [2]–[4]. As a consequence, research on self-awareness in autonomous systems is fragmented over several fields and lacks a common terminology. To foster collaboration and advance research, this special issue aims to bridge this gap by providing a comprehensive collection of recent research in this diverse field covering fundamentals, methods, and applications.

Not only due to this diversity of disciplines, self-awareness may also be considered a fundamental principle with the potential of becoming an enabling technology for a variety of applications in autonomous systems. However,

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there are still important topics not comprehensively covered in this special issue. We briefly discuss some topics as examples where we believe further investigation would be fruitful.

1) Exploiting models derived from sensor data often may result in emergent behavior of the autonomous agent but it is challenging to design the agent such that a particular behavior will eventually emerge. Even worse, the deployment of autonomous systems often requires to guarantee that a projected behavior will be achieved—or avoided. Such guarantees can only be derived by some specifications of models and behaviors which somehow contradicts the concept of self-awareness.
2) Self-awareness can not only be considered in the context of a single individual but also in collective systems, where there is no central point at which such global knowledge is located. The fundamental challenge is how the individual agents should (inter-)act given only local and incomplete knowledge such that the global objective can be achieved.
3) For engineering a self-aware computing system, one must be able to estimate, or at least to provide bounds on, the system's performance and properties such as resource usage, reliability, and safety. Moreover, self-awareness incurs overheads and the corresponding tradeoffs between these overheads and the system capabilities need to be explored and quantified.
4) The complexity of self-awareness models may vary depending on the type and dimensionality of information carried by sensors as well as on the actions performed by an agent in a given environment. This will require new methods and techniques to be explored in domains like multimodal signal processing, information fusion, and machine learning to allow self-awareness of an autonomous agent to be expanded and maintained to required levels.
5) Finally, autonomous systems may soon participate in our society in many ways. We must design them to understand and follow social norms, including morality, ethics, and convention, sometimes encoded and enforced as laws, sometimes as expectations with less formal enforcement, and to earn the trust of others in society [5].

We hope this special issue inspires further exploration and research to address the many open challenges for self-awareness in autonomous systems. Advancing computational self-awareness and enabling its integration into autonomous systems presents steep challenges while promising many benefits for humanity.

I. OVERVIEW OF THE SPECIAL ISSUE

The 11 articles of this special issue cover a wide variety of topics of self-awareness in autonomous systems and are organized along three categories. The first group of articles covers concepts and fundamentals from neurobiology, bio-inspired, and signal-based modeling to symbolic and agent-based verification. The second group of articles discusses architectures and techniques of self-awareness, including hardware architectures and embodiments, forecasting, and software engineering. The last group presents examples of applications and case studies in the area of self-aware audio processing, networking, and autonomous navigation.

A. Concepts and Fundamentals

Invited Paper:
Neurobiologically Inspired Self-Monitoring Systems
by A. A. Chiba and J. L. Krichmar

Self-awareness principles have deep roots in neurobiology and cognitive sciences. Chiba and Krichmar's article relates the fundamental neurobiological principles underlying a living organism's health and performance, to how these principles could be applied to achieve self-awareness in engineered systems. The authors draw parallels between neurobiological systems and engineered systems at multiple abstraction levels: lowest (sensory and motor); intermediate (homeostatis and allostasis); and highest (cognitive control). Using adaptive, self-monitoring robots as an example of an engineered system, the authors relate specific neurobiological principles to how these could be applied to self-monitoring cognitive robots that combine engineering techniques from machine learning, AI, and classical robotics. This article concludes with a discussion of self-monitoring (to achieve autonomy of engineered agents) and self-awareness (that can enable socialization between groups of agents).

Invited Paper:
Multisensorial Generative and Descriptive Self-Awareness Models for Autonomous Systems
by C. S. Regazzoni, L. Marcenaro, D. Campo, and B. Rinner

The authors discuss a multisensor signal processing framework to allow an agent to incrementally learn emergent self-awareness models from perception of itself and of the surrounding environment. Bio-inspired theories of self-awareness connected with computational approaches are presented and critically analyzed. The authors show how state-of-the-art theories provide complementary aspects that provide a basis for the design of a self-supervised computational framework within which an agent can incrementally organize perceptions of its own dynamic experiences into self-awareness models. Uncertainty management and interaction representation within generative and descriptive models are shown to be key aspects of existing models that drive a proposed novel hierarchical Bayesian representation paradigm that is capable of

learning self-awareness models from either proprioceptive or exteroceptive sensorial sequences. The authors show how descriptions of abnormalities produced by models can allow the agent to incrementally increase its own self-awareness capabilities. The presented techniques are discussed within the framework of cognitive dynamic Bayesian networks and generalized filtering paradigms, and a mobile autonomous system case study is presented to show example applications.

Invited Paper:
Verifiable Self-Aware Agent-Based Autonomous Systems
by L. A. Dennis and M. Fisher

This article provides an overview not only of how self-aware autonomous systems can be constructed, but also how a verifiable self-aware behavior can be potentially achieved. The authors follow a modular agent-based approach and present formal verification techniques that allow them to assess key system properties. In this modular autonomous system architecture, agents transparently capture important decision-making processes, that is, intentional and rational agents, which allow them to apply strong (formal) agent verification techniques to these systems. They further discuss self-awareness capabilities and system aspects from ethics or self-certification to self-reconfigurability and explainability.

B. Architectures and Techniques

Invited Paper:
Embodied Self-Aware Computing Systems
by H. Hoffmann, A. Jantsch, and N. D. Dutt

This article presents the notion of embodied self-aware computing systems, where self-awareness principles are applied to a computing system that is situated (or embodied) in a physical or external environment, requiring sensing of environmental inputs, and self-aware strategies for actuation in the external physical environment. The authors present a conceptual framework for reasoning about embodied self-awareness through a self-model and the faculties of self-inspection, self-assessment, goal management, decision making, and action control. Using several case studies in health-monitoring, systems-on-chip, control systems, and industrial production systems, the authors demonstrate how computational embodiment combined with computational self-awareness can result in systems that are adaptive to environmental changes, while managing dynamic goals for efficient computational system execution. This article concludes with a discussion of open challenges in formalisms, automated runtime abstraction, and dynamic learning to support self-aware embodiment in emerging computing platforms.

Invited Paper:
Self-Aware Neural Network Systems: A Survey and New Perspective
by Z. Du, Q. Guo, Y. Zhao, T. Zhi, Y. Chen, and Z. Xu

The authors present a self-aware approach to improving the performance and energy characteristics of NNs through continuous sensing of the inputs, and dynamic reaction and adaptation of the NN computations and topology. This article begins with a brief review of NN algorithms, hardware accelerators, system software, and applications. The authors then review the current state of the art in self-aware NN and present a comparative analysis of key self-awareness properties exhibited by these systems across the dimensions of goal management, self-monitoring, decision making, and policy execution. This article then presents a case study of the self-aware MinMaxNN system, demonstrating its adaptability for run-time performance and energy tradeoffs through leveraging self-awareness principles at higher levels of system abstraction.

Invited Paper:
Time Series Forecasting for Self-Aware Systems
by A. Bauer, M. Züfle, N. Herbst, A. Zehe, A. Hotho, and S. Kounev

The authors focus on time-series forecasting as an essential pillar for decision making in self-aware systems. Given historical data, forecasting is concerned with learning suitable models that allow one to predict how a system will evolve. In their article, they present the basics of time-series analysis and survey state-of-the-art forecasting methods and feature engineering techniques. The numerous and widely applied methods can be categorized into statistical and ML-based approaches. In the context of self-awareness, they support inference, anomaly detection, and memorization as key capabilities. They conclude with benchmark results of a forecasting method competition to guide in selecting and appropriately using existing forecasting methods.

Invited Paper:
Synergizing Domain Expertise With Self-Awareness in Software Systems: A Patternized Architecture Guideline
by T. Chen, R. Bahsoon, and X. Yao

Self-awareness means different things by different people in different contexts. This article highlights five levels of self-awareness in software systems, that is, stimulus awareness, time awareness, interaction awareness, goal awareness, and meta-self-awareness. These five levels of self-awareness have been studied by researchers in the past few years. In particular, the barriers to construct and engineer software systems with such capabilities have been lowered with the advent of self-aware architectural patterns. The authors take the above research work yet another step forward. Not only do they consider architectural patterns in designing self-aware and self-adaptive software systems, but also human expertise. They incorporate human design expertise into self-aware architectural patterns to provide a better and unified methodology, called DBASES, for engineering self-aware and self-adaptive software systems. A number of key issues are studied in depth in this article,

including the representation of human expertise, different synergies that can be achieved between human expertise and self-aware architectural design patterns, a practical step-by-step methodology that assists the engineers in selecting the possible ways of synergies, and three case studies that demonstrate the potential benefits and difficulties one might encounter in developing self-aware software systems using the DBASES methodology.

C. Applications and Case Studies

Invited Paper:
Acoustic Self-Awareness of Autonomous Systems in a World of Sounds
by A. Schmidt, H. W. Löllmann, and W. Kellermann

This article considers acoustic sensory modality as the reference information source of an agent with acoustic perception and actuators capable of generating sounds. Acoustic self-awareness is analyzed with an in-depth overview of the state of the art that discusses how autonomous agents can benefit from acoustic signal processing techniques oriented to dynamically separate and analyze signals that they themselves generate from environmental acoustic sources. Techniques are discussed for signal modeling, source localization, signal extraction, and enhancement, as well as detection and classification that are at the basis of acoustic awareness. The authors show how ego-noise, that is, noise produced by the agent and perceived by its own sensor can be an important source from which an agent can obtain new dynamic information about its own state and the state of the surrounding environment. Using acoustic self-awareness based on ego noise analysis as an example, the authors describe how an agent can reach more robust adaptive dynamic stability with the surrounding environment. This article concludes with how information fusion between acoustic and heterogeneous sensorial modalities oriented to observe the control modules of the agent (e.g., a robot's motor commands) can be a future line of research to develop more complex self-awareness models.

Invited Paper:
Self-Aware Networks That Optimize Security, QoS, and Energy
by E. Gelenbe, J. Domanska, P. Fröhlich, M. P. Nowak, and S. Nowak

This article presents self-awareness techniques in networking. Networking plays a key role in connecting multiple autonomous devices in an IoT context, as well as to enable communication between humans and autonomous IoT systems. The authors outline the role of self-aware functionality in networking of these systems. After an initial analysis of existing self-awareness methods in networking, they discuss the benefits from deploying self-awareness with respect to quality of service, energy, and security. Solutions are presented and discussed to highlight methods and issues that can allow data-driven and machine learning methods to be used with other techniques to implement self-awareness functionalities to a different degree. The authors argue that distributed self-awareness within different nodes is a key issue in forthcoming networks to provide secure and efficient communications.

Contributed Paper:
Self-Aware Swarm Navigation in Autonomous Exploration Missions
by S. Zhang, R. Pöhlmann, T. Wiedemann, A. Dammann, H. Wymeersch, and P. A. Hoeher

Unlike other articles in this special issue, this article investigates self-awareness in a swarm, rather than in a single agent. The authors study the problem of localization by a swarm of autonomous robots in an uncertain environment. In addition to considering the classical localization algorithm, such as an EKF or a particle filter, and considering the estimation uncertainty, they introduce self-awareness into a traditional navigation system by considering the causality between robot's position and the localization uncertainty explicitly. This equips the navigation system with the capabilities of time-awareness and interaction-awareness and leads to a better and more adaptive system. A case study is presented in this article to illustrate the methodology used to develop a swarm of autonomous robots for gas exploration on Mars.

Invited Paper:
Achieving Resiliency and Behavior Assurance in Autonomous Navigation: An Industry Perspective
by S. Baruah, P. Lee, P. Sarathy, and M. Wolf

This article presents an industrial state of the art for deployment of self-aware autonomous navigation systems that need to guarantee correct operation through resilience against both dynamic environments and adversarial attacks. The authors begin by outlining the essential characteristics for achieving resilience in autonomous systems and survey advances in resilience management for several autonomous system domains, including air, ground, marine, underwater, and space systems. Each domain is distinguished by unique characteristics pertaining to variability in: operating conditions; communication and networking; and heterogeneity in sensing modalities. For each domain, the authors survey mission capabilities, decision making methods for resilience, and outline limitations. The authors then discuss safety assurance for autonomous systems, and survey industry standards for multidomain operation and behavioral assurance. This article concludes with perspectives on emerging challenges relating to system security in the face of malicious cyber-attacks, and the need to guarantee resilience while managing multiple, possibly conflicting design constraints such as real-time performance, power/energy, and thermal constraints. ■

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