Recent Advances in Autonomous Systems for Inspection and Predictive Maintenance of Infrastructures: An Overview of the Special Session

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***Abstract*—Autonomous systems are artificial systems capable of performing a variety of tasks with a high degree of autonomy. Cognitive Dynamic Systems (CDSs) are one of the possible approaches that allow us to face the challenges of autonomous systems design. CDSs aim to develop rules of behavior over time through learning from continuous experiential interactions with the surroundings. By exploiting these rules, CDSs can deal with environmental dynamics and uncertainties, and have therefore leveraged the automation of tasks with complex perception-action cycles including surveillance, inspection, predictive maintenance, cognitive radio, traffic control, and robot-mediated industrial and domestic applications. This paper presents an overview of this Special Session, featuring works in the fields of inspection and predictive maintenance of infrastructures, that address challenges associated with autonomy, including perception, decision-making, and adaptation.**

***Index Terms*—Autonomous Systems, Artificial Intelligence, Cognitive Dynamic Systems, Inspection, Predictive Maintenance**

I. Introduction

The rapid advancements in autonomous systems and artificial intelligence have paved the way for significant innovations in the field of infrastructure inspection and maintenance. The global infrastructure landscape is aging, with many critical structures such as bridges, pipelines, railways, ports, and power plants nearing or surpassing their intended lifespans. Ensuring the safety, reliability, and efficiency of these infrastructures is paramount, yet traditional inspection and maintenance methods are often labor-intensive, time-consuming, costly, and sometimes hazardous. As a result, there is a need for innovative solutions that can enhance the effectiveness and efficiency of these processes. Some of the works recently proposed in the literature are related to the adoption and integration of digital, robotic, and artificial intelligence technologies a) in construction sites and shipyards, to support the quality checks of building blocks, assemblies as well as the completed structure b) in container yards, to monitor container stacks after severe weather events, or to check for the leakage of dangerous material c) in major infrastructural projects, to periodically monitor the state of advancement of works.

Examples of the adoption of advanced autonomous systems in this field can be related to the definition and implementation of innovative monitoring system based on the use of Unmanned Aerial Vehicle (UAVs) as mobile sensors for the collection of multispectral images and video streams, and the consequent processing of these streams using Artificial Intelligence (AI) approaches (e.g., neural networks) for automatic and real-time detection of potential danger scenarios [1]–[3]. Optionally, other types of sensors can be installed on the drone to collect heterogeneous data, which can be processed and correlated with the information obtained using video technology [4], [5].

Focusing on naval scenarios, recent advancements in integrating drones with machine learning and deep learning algorithms have significantly enhanced maritime applications. In [6], for instance, the authors describe a UAV equipped with various sensors that is able to detect and classify maritime targets in real time. Their system relies on visible, infrared, and hyperspectral imaging data and additional information coming from an Inertial Navigation System (INS) and an Automatic Identification System (AIS) receiver. Some key issues, such as dense distribution, multi-scale objects, and occlusion of UAV images in maritime environments, are then tackled in [7], where a lightweight deep learning-based object detection algorithm (called AB2D-YOLO) is proposed. A different object detection algorithm, also based on a variant of the YOLO approach, but optimized for drones operating in wide-area maritime settings, is presented in [8]. The performance results show that the system performs well, maintaining a balance between detection accuracy and computational efficiency.

Cognitive Dynamic Systems (CDSs) represent a promising approach that allows us to address some of the challenges that autonomous systems need to handle. Unlike traditional static systems, CDSs continuously adapt and evolve over time by learning from the interactions with their surroundings. Through this learning process, they are able to develop behavioral rules that allow them to respond effectively to different and unpredictable conditions. By leveraging these

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rules, CDSs enhance automation capabilities. Therefore, the ability of CDSs to autonomously adjust their behavior based on the feedback coming from the environment makes them particularly well-suited for applications where adaptability and real-time decision-making are crucial.

Various research works based on CDS principles have been recently presented in the literature, in the context of autonomous systems, for inspection and predictive maintenance of infrastructures. Authors in [9] present a data-driven dynamic predictive maintenance scheduling framework that employs a deep learning ensemble model. More specifically, data are collected from multiple sensors and processed using a combination of a deep autoencoder and a bidirectional long short-term memory network. The system dynamically predicts maintenance decisions based on real-time monitoring information, and this aligns with cognitive dynamic principles. Research in [10] introduces Hierarchical Temporal Memory (HTM), a model inspired by the human neocortex, for real-time anomaly detection in manufacturing systems. HTMs continuously evolve and adjust while remaining resilient to noise, and mimic biological cognition, making them suitable for predictive maintenance applications where systems need to adapt to evolving conditions. The authors demonstrate the effectiveness in detecting bearing failures and simulated 3D printer failures. Dynamic Bayesian networks are instead used in [11], combining them with partially observable Markov decision processes, to develop optimal inspection and maintenance strategies for degrading structures. This approach enables the system to propagate and update the uncertainty associated with a deterioration process and make informed decisions under uncertain conditions, thus embodying cognitive dynamic principles in this context. Finally, an integrated framework that combines Transformer-based neural networks with deep reinforcement learning to optimize maintenance actions is presented in [12].

Considering artificial agents, the concept of awareness refers to the knowledge an agent possesses about its external environment. On the other hand, self-awareness relates to the agent's ability to recognize and understand its own internal state. The concept of self-awareness, which originates in neuroscience, has been explored for autonomous systems in [13]. A self-aware system can thus be described as a system that not only focuses on the external environment but monitors and adapts to the evolution of its own state. As a result, two types of sensors can be distinguished in this case: exteroceptive sensors to achieve awareness about the world, such as outdoor cameras and GPS, and proprioceptive sensors to gain self-awareness, such as a steering wheel sensor and a sensor on the pedal. Various works based on a self-awareness framework have been recently proposed, combining signals from both exteroceptive and proprioceptive sensors for anomaly detection [14] and localization purposes [15], [16].

II. Overview of the Special Session

The four articles of this Special Session cover various topics related to the application of autonomous systems in the context of the inspection and predictive maintenance of infrastructures. They thus address the challenges associated with autonomy, including perception, decision-making, and adaptation, providing novel insights and contributions to the development of autonomous systems (see also Table I).

A. *IPD: An Industrial Pipeline Dataset for anomaly detection and localization*

In this paper, the authors explore the complex challenge of visual inspection in industrial pipelines, where key difficulties include highly noisy and cluttered pipeline background, unknown damage types in advance, significant variability in the visual appearance of damage, and an imbalanced distribution of training samples. To address this, visual Anomaly Detection (AD) and Anomaly Localization (AL) emerge as effective and appropriate approaches. A dataset primarily collected from industrial facilities across Europe is introduced, specifically focusing on damages to insulated pipelines. Industry experts guided data collection and annotation to make sure that insulation damages are accurately identified. To establish a baseline for this inspection task, state-of-the-art AD and AL methods are analyzed. Their somewhat limited performance, both visually and empirically, highlights the inherent difficulty of the task. The paper contributes in two key ways: (i) IPD is, to the authors' knowledge, the first publicly available AD/AL dataset dedicated to the visual inspection of industrial pipeline insulation, and (ii) given the poor performance of modern AD/AL methods on IPD, the dataset serves as a crucial research benchmark.

B. *Generative Models for Incremental Learning to Advance Autonomous Agent Evolution: A 3D Perspective*

Unmanned Aerial Vehicles (UAVs) are playing a growing role in fields like inspection, surveillance, and autonomous navigation. Accurately mapping their trajectories still remains challenging due to sensor noise and dynamic environments. The work presented in this paper describes a method to improve UAV trajectory analysis by combining adaptive filtering with sequential clustering. The authors apply this approach to 3D synthetic trajectories, projecting them onto 2D planes to generate clusters that form a movement vocabulary. Since the 3D data are generated through known models, they follow 3D Gaussian distributions which, when projected, remain Gaussian in 2D. This allows the authors to compare data-driven clusters with model-derived (ground truth) clusters on each 2D plane. The study offers a way to analyze UAV trajectories when only 2D data are available and explore how well 2D projections capture 3D dynamics. Future developments will focus on combining clusters from different planes to reconstruct the full 3D trajectory and validate it against the original 3D model.

C. *Physics-informed Intelligent Motor Fault Detection*

Intelligent Fault Detection (IFD) has attracted considerable attention with advancements in AI-driven predictive maintenance. Research in this field focuses on detecting early

TABLE I
OVERVIEW OF THE PAPERS OF THIS SPECIAL SESSION CATEGORIZED BY TITLE, APPLICATION DOMAIN, AND METHOD TYPE

Paper title	**Application domain**	**Method type**
IPD: An Industrial Pipeline Dataset for anomaly detection and localization [17]	Industrial pipelines	Visual anomaly detection and localization with the introduction of a benchmark dataset
Generative Models for Incremental Learning to Advance Autonomous Agent Evolution: A 3D Perspective [18]	UAV trajectory analysis	Adaptive filtering and sequential clustering for 3D trajectory mapping
Physics-informed Intelligent Motor Fault Detection [19]	Industrial predictive maintenance	Physics-informed lightweight AI algorithms for edge-based fault detection
Proficiency-Driven Decision-Making for Networks of Autonomous Agent [20]	Autonomous agent networks	Self-assessed proficiency metric for adaptive decision-making

failures and preventing device breakdowns. However, a major challenge in implementing IFD models is their interpretability, as the underlying mechanisms are complex and difficult to integrate into data-driven models. In this work, the authors tackle critical challenges in automatic fault detection for industrial motors on the Edge, addressing three key constraints, namely limited availability of training data, lack of model interpretability, and the computational and storage restrictions of edge devices. To overcome these limitations, a suite of Physics-informed light weight AI algorithms designed to enable Edge IFD, while maintaining detection performance, is proposed. The methods are validated using both simulated and experimental data for Motor Fault detection. Additionally, the results obtained from implementing the proposed algorithm on an Edge device are discussed, highlighting its benefits and providing future research directions.

D. Proficiency-Driven Decision-Making for Networks of Autonomous Agent

This paper presents a proficiency-driven decision-making framework for autonomous agents, which are increasingly deployed in high-stakes domains such as emergency response and urban safety. These agents must operate independently in complex and dynamic environments, making the ability to assess their own performance a key component of effective autonomy. In this work, a Bayesian-based proficiency metric, inspired by the Cramér-Rao Lower Bound (CRLB), allows agents to evaluate the accuracy of their available observation models. This self-assessment capability is then used to dynamically select the most suitable observation model for real-time navigation and for estimating the position of a moving source. To further enhance system performance, a team-based coordination strategy is proposed, in which agents share information and collectively adopt a common observation model. By incorporating proficiency assessment, the approach enhances user navigation, ensuring that agents efficiently complete their assigned missions.

III. CONCLUSIONS AND FUTURE DIRECTIONS

The advancements presented in this Special Session highlight progress in autonomous systems that tackle perception, decision-making, and adaptation. Integrating CDS principles has enabled real-time learning, environmental adaptation, and informed decision-making. However, several challenges remain. Current self-awareness models are still limited and require prompt enhancement, especially when integrated with environmental awareness for better decision-making and anomaly detection. Although multimodal sensor fusion shows promise, optimizing it for complex environments remains a significant hurdle. Increasing system complexity also raises concerns about scalability and efficiency, necessitating lightweight algorithms and edge computing for real-time performance. Incremental learning approaches, such as those used for UAV trajectory analysis, should be extended to support continuous adaptation with minimal retraining. Lastly, although datasets like IPD aid progress, broader benchmarks are needed to evaluate system performance across various domains. Addressing these open issues will be essential to develop more reliable, efficient, and adaptable autonomous systems for diverse infrastructure applications.

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