Advancing Sustainability: Research Initiatives at the Signals and Images Lab

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Abstract

In this paper, we aim to briefly survey the relations of the work conducted at the Signals and Images Lab of CNR-ISTI, Pisa, with the themes of sustainability. We explore both the broader implications and the application-specific aspects of our work, highlighting references to published research and collaborative projects undertaken with key stakeholders and industrial partners.

Keywords

Sustainability, Computer vision, Deep learning, Ensembling, Topological data analysis, Smart cameras, Precision agriculture, Hydrological modelling, Artificial Groundwater Recharge, Medical waste, Urban mobility, Environmental monitoring, Citizen science

1. Introduction

The relationship between Sustainability and Artificial Intelligence (AI) is multifaceted. On the one hand, Artificial Intelligence can aid in addressing the challenges of modernization that may potentially conflict with sustainability goals. However, on the other hand, energy-intensive methods employed in artificial intelligence applications may themselves pose sustainability concerns. In addition, many paradigms and models within artificial intelligence are difficult to manage and maintain in a sustainable bias-free way, particularly under the dynamic and non-stationary nature of societal and technological changes.

In this context, the association with the principles of explainability, trustworthiness, and accountability of AI models emerges as crucial, as these attributes are considered fundamental for ensuring the sustainability and acceptance of AI technologies.

Despite the recent concerns and regulatory initiatives of the European Community, AI holds immense potential to be harnessed for advancing the sustainable development goals outlined by the United Nations, surpassing established targets and identifying new challenges.

Given the significance of these themes, numerous facets of the research conducted at the Signals and Images Lab (SI Lab) of CNR-ISTI have been directed towards enhancing sustainability across various levels and encompassing a broad spectrum of globally relevant applications.

In particular, after describing efficient models based on a new ensembling strategy in Section 2.1, we report recent results concerning agriculture (Section 2.2), hydrodynamical modelling and access to water resources (Section 2.3), recycling and end-of-waste for medical waste (Section 2.4), urban mobility (Section 2.5), biodiversity (Section 2.6) and citizen science for maritime applications (Section 2.7).

To address such a wide group of applications, an arsenal of different methods was devised, tested and validated; they can be tracked back mainly to general machine learning theory, computer vision and pervasive computing, topological data analysis and reliability analysis of observed data.

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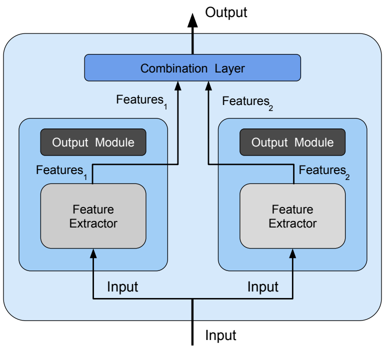

Figure 1: Proposed ensembling method

2. Research topics

2.1. Adapting ensembling for green AI

In the realm of greenAI, computer vision stands out as a field greatly benefiting from deep learning, continually advancing the state-of-the-art through the utilization of convolutional neural networks (CNNs) and visual transformers. Across various computer vision scenarios, in the last years, complexity has appeared to escalate exponentially, even for marginal enhancements, affecting both the number of parameters and Floating Point Operations (FLOPs). Among various machine learning methodologies, ensembling emerges as a technique that fuses multiple models, termed weak learners, to produce a model with superior performance than any individual weak learner. Typically, this amalgamation involves aggregating the weak learners' outputs, often through voting or averaging for classification or regression tasks, respectively. Factors such as ensemble size (i.e., the number of weak learners) and ensemble techniques (e.g., bagging, boosting, stacking) play crucial roles in achieving satisfactory results. However, ensembling necessitates training several models, rendering the overall validation process more resource-intensive, with model complexity growing at least linearly relative to the ensemble size. Additionally, ensembling is time-consuming, thus posing a significant barrier to its widespread adoption, particularly in computer vision applications.

Contrary to these challenges, in [1] we introduced a technique aimed at reversing the prevailing trend in image classification, characterized by marginal performance gains accompanied by substantial increases in complexity. Specifically, our approach involves a reimagined form of ensembling designed to surpass the state-of-the-art while maintaining constrained complexity in terms of both parameter count and FLOPs. We demonstrated the feasibility of this approach by implementing bagging on two distinct subsets of data, employing two EfficientNet-b0 weak learners trained to overfit on their respective subsets. In the study, we explored the limits of ensemble size by utilizing only two weak learners. We found that this adaptive ensemble strategy remains efficient, even when extended to include up to five weak learners. Additionally, we identified potential avenues for further improvements, such as implementing various bagging strategies (e.g., training weak learners on subsets categorized by class dimensionality, clustering, or different colour space mappings of inputs). The basic idea of the method is depicted in Figure 1; in particular, ensembling is accomplished by an innovative strategy of performing bagging at the deep feature level. Namely, only the convolutional layers of each trained weak model are kept, while the final decisional layers are neglected; in this way, each weak model is turned into an extractor of deep features. The deep features of each weak model are then concatenated and fed to a trainable final decision layer.

These findings lay the groundwork for exploring similar strategies in various domains, such as Object Detection (by performing the ensemble at the feature extraction backbone level) and Segmentation (by conducting the ensemble on the encoding within typical encoder-decoder architectures).

2.2. AI and sustainable agriculture

The early detection of plant stress stands as a pivotal practice in agriculture. Plant stress can be categorized into biotic stress, caused by living organisms such as viruses, bacteria, fungi, nematodes, insects, arachnids, and weeds, and abiotic stress, resulting from environmental factors like drought, heat, cold, strong winds, flooding, and nutrient deficiencies. Both forms of stress significantly impact crop yield and quality, leading to substantial economic losses when stress thresholds are surpassed. Despite advancements in genetics providing cultivars increasingly resistant to various stresses, yield and quality losses remain critical globally, particularly with the concurrent occurrence of abiotic and biotic stresses due to climate change. Presently, most plant inspections rely on manual methods involving direct visual analysis, which may not always facilitate accurately identifying diseases and stress types, especially in underdeveloped areas of the world. Farmers typically rely on naked-eye inspections, necessitating constant observation, high levels of skill, and experience. While some farmers may utilize guidelines containing basic concepts and visual aids (such as pictures or notes) to distinguish between biotic and abiotic injuries and determine appropriate solutions, others may require technical assistance for formal and comprehensive diagnoses. However, these methodologies are often time-consuming and expensive, posing challenges for large farms or those with limited resources. Furthermore, identifying weed types, whether broadleaf or grassy, during their early stages (from germination to the development of the first four/six leaves) presents significant difficulties, precisely when intervention would be most effective. Consequently, there is a growing need for automated infection recognition methods to enhance accuracy and efficiency. The increasing public concern for environmental conservation and the imperative for more efficient agriculture to accommodate population growth amidst shrinking arable land underscores the importance of developing cost-effective and sustainable solutions to support farmers. In this context, machine learning techniques can potentially revolutionize the timely suppression of harmful plant organisms, thereby maintaining chemical treatment and other interventions at economically and ecologically justified levels. In the research activities at the lab, the methods detailed in Section 2.1 have been applied to the agricultural domain. Initially, state-of-the-art results were attained on the PlantVillage dataset [2]. Subsequently, these methods were leveraged to form the intelligent core of the mobile application Granoscan, developed within the Agrosat project and made available by Barilla on popular iOS and Android platforms. Additionally, outstanding outcomes, coupled with a new dataset for weed classification, were documented in [3]. Furthermore, an application targeting Olive tree diseases, a vital sector in Italy's agricultural production, was presented in [4].

2.3. Hydrological modelling for resilience and equitable access to water

Many basins in the Mediterranean and the MENA region (Middle-East North Africa) are currently facing recurring droughts and periods of water scarcity, often exacerbated by intermittent extreme events. Consequently, urgent action is required to implement effective measures for the sustainable management of water resources, with a particular emphasis on groundwater. In this context, Artificial Groundwater Recharge (AGR) has emerged as a viable solution for addressing water scarcity challenges. By capturing and storing surplus water during periods of intense precipitation or increased surface water availability, artificial recharge can replenish depleted aquifers and serve as a dependable water source during drought periods. In this context, considerable efforts have been directed towards enhancing the accuracy of hydrological models and reducing uncertainty. This has involved incorporating various remote sensing-based Actual Evapotranspiration (AET) products and assessing their effectiveness in improving the simulation of hydrological responses, both in single and multi-variable scenarios [5]. Similarly, the Soil and Water Assessment Tool (SWAT) model and remotely sensed products have been incorporated to characterize the dynamics of streamflow and snow in the High Atlas watershed [6]. Furthermore, investigations have been conducted to infer how excess irrigation water from rice cultivation can mitigate saltwater intrusion and potentially contribute to recharging the north of the Nile Delta Aquifer [7]. The findings indicate that strategically placing rice cultivation and utilizing natural recharge methods can significantly reduce aquifer vulnerability.

2.4. Computer vision for medical waste

Medical waste (MW) poses a significant challenge as healthcare facilities generate considerable quantities of hazardous waste daily. Proper handling and treatment are essential, necessitating specialized management practices. Typically, medical waste is deposited into designated containers at the point of origin, which are subsequently sealed and require prompt disposal. Disposal methods, primarily through incineration or waste-to-energy processes, take place in specialized treatment facilities often situated at a considerable distance from the point of waste generation. Moreover, due to the potential biological hazards, manual handling of the waste post-disposal is prohibited, with human intervention limited to critical situations and requiring specialized personal protective equipment. Recent years have seen a rise in medical waste production attributed to factors such as the expansion of the healthcare sector and increased utilization of disposable medical equipment. The emergence of COVID-19 further exacerbated this trend, resulting in surges in the production of potentially hazardous and infectious waste. Consequently, there is a pressing need for scalable and sustainable methods to manage medical waste. Notably, medical devices are often composed of high-quality virgin materials, predominantly polymers, alongside significant proportions of glass, textiles, and metals. Therefore, sorting medical waste for recycling presents an opportunity for more sustainable waste management practices. However, primary sorting is essential as manual intervention at later stages is impractical due to the associated hazards. Secondary sorting may only occur after the infectious and hazardous nature of the medical waste has been neutralized, typically through sterilization. Manual primary sorting of medical waste is laborious and time-intensive, potentially overburdening healthcare facility operators and increasing the risk of human error. Thus, there is a need for systems to assist specialized staff during sorting, streamlining the process and minimizing errors. To address this need, in the framework of the project Medical Waste Treating 4.0, in cooperation with industries and recycling experts, we proposed research in the development of an artificial intelligence (AI) model leveraging deep learning and computer vision techniques to classify various types of items comprising standard medical waste. Building upon previous work as reported in Section 2.1, we proposed a

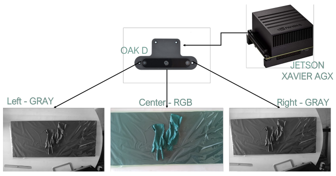

Figure 2: Acquisition system and sample images acquired in Medical Waste Treating 4.0

convolutional neural network based on the EfficientNet family. To train the network, a specialized dataset mimicking a waste collection table equipped with a stereo camera has been curated (see Figure 2). While the dataset is still expanding, initial results indicate promising performance [8]. Unlike existing studies on medical waste, the dataset is made publicly available to foster further research [9].

2.5. Smart cameras for urban mobility

In contemporary cities and urban environments, the sustainability of mobility is posing growing concerns due to several factors. These include the rise in the number of cars on the roads, budget constraints leading to a reduction in free parking spaces, and economic challenges during times of crisis, which diminish the efficiency of public transportation systems. However, the increased availability and power of computing facilities and devices offers an opportunity to address two of the most pressing issues: congestion and traffic resulting from vehicles searching for parking spaces. In our research, we have explored approaches centred around wireless smart cameras for monitoring open-air public parking areas and urban roads. More specifically, a smart camera is a vision sensor equipped with artificial vision-logic for the on-board interpretation of acquired images and video streams, along with a network interface to communicate the processing outcome. A network of smart cameras is a sensor network whose nodes consist of a set of smart cameras that cooperate for scene analysis, pervasively covering an area of interest. The primary strengths of the proposed solution lie in the autonomy and scalability of the proposed architecture. Indeed, autonomy is achieved through the intelligent capabilities of smart cameras that can deploy powerful AI methods on board, ensuring independence from external systems. Scalability is facilitated by low-cost single nodes that can be integrated into a broader sensor network without requiring expensive installation requirements. Starting with very low resource cameras leveraging classical image processing methods [10], approaches have moved to large-scale Field Operational Tests (FOT) [11], also integrating and comparing multimodal technologies [12] for parking lot monitoring; a recent survey and way forwards are discussed in [13].

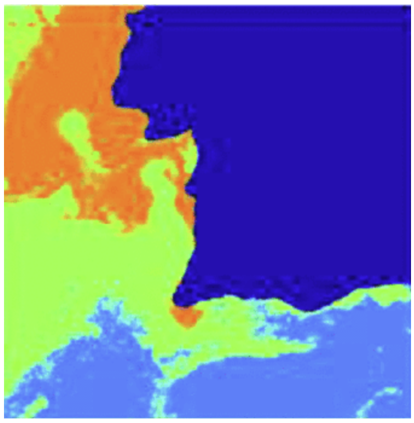

Figure 3: Sample sea surface image segmented through multi-thresholding

2.6. Topological data analysis for biodiversity

Recent advancements in remote sensing have proven to be highly effective in the realm of marine observation. This technology furnishes experts with an extensive array of data gleaned from satellite sensors, necessitating the development of automatic or semi-automatic methods for their analysis. In this context, one of the focuses of the SI Lab lies in the categorization of upwelling regimes within the Iberia/Canary Current System (ICCS), an area that remains relatively understudied within the domain of upwelling ecosystems. Of particular interest among the various underlying processes are mesoscale events such as upwellings, countercurrents, and filaments. These events play a crucial role in transporting nutrient-rich waters from deeper regions to the surface, thereby significantly influencing the biological parameters of the habitat and augmenting local biodiversity. Essentially, there exists a correlation between the biogeochemical and physical processes within a marine biological system.

Sea Surface Temperature (SST), which measures the temperature of the water at the ocean's surface, is a vital metric in this context. This temperature is assessed using satellite instruments that capture the energy emitted from the ocean surface across different wavelengths on a global scale. Subsequently, these data are corroborated with temperature readings obtained from ships and buoys. The acquisition, processing, and comprehension of sea surface data (see Figure 3) hold significant importance as they provide insights into the underlying reasons behind regional temperature variations and their repercussions on the marine ecosystem. Environmental changes can have profound effects on the lives of species inhabiting these regions, influencing factors such as food accessibility, migration patterns, and mating opportunities.

To tackle the challenging task of categorizing marine mesoscale patterns using remote sensing data, a pipeline of topological machine learning (TML) techniques has been used [14]. Such methods can be traced back to Algebraic Topology (AT), a branch of mathematics dealing with shapes. In a nutshell, AT assigns an algebraic object to a topological space. Then, it can compute several invariants and descriptors (the Euler characteristic, the Betti numbers, and the homology groups). Such invariants and descriptors are used in computational topology to compare shapes and to define distances between them. One of the most used tools from computational topology is persistent homology, which is a method for computing topological features of a space across different scales. More persistent features are detected over a wide range of spatial resolutions (have a long "lifespan") and are deemed more likely to represent important, or true features of the underlying space, rather than artefacts of sampling, or noise. Applications of persistent homology span from computer vision and shape analysis to biomedical imaging and complex network analysis. In this perspective, one of the most promising trends is the merging of persistent homology with machine and deep learning. In our work, TML is used to tackle the task of categorizing four distinct mesoscale patterns using remote sensing data—specifically patterns that can be found in SST maps from the southwestern region of the Iberian Peninsula within the ICCS. Our initial investigation attains a classification accuracy of 56% across the four labels [15]. These findings are promising, particularly given the presence of noise in the data and instances of low-quality or strong missing data (also due to weather conditions and cloudy sky).

2.7. AI for the marine environment: from citizen science to maritime traffic monitoring

The Sustainable Development Goals (SDGs) outlined by the United Nations encompass the marine and maritime domain, emphasizing the conservation and sustainable utilization of oceans, seas, and their resources. Concurrently, there is a pressing need for enhanced navigation safety, particularly in coastal regions. Presently, operational services leverage advanced technologies, including remote sensing and in situ monitoring networks, to aid navigation and environmental preservation efforts. However, the potential benefits of crowdsensing remain largely untapped. A citizen science approach to monitoring oil spills was proposed in [16] within the framework of a more comprehensive Maritime Information System (MIS), featuring proactive decision support services [17]. However, the potential of using Volunteered Geographic Information (VGI) and, more generally, crowdsensing information has not been fully exploited to address broader safety and security-related events. With this aim, in [18], we addressed this gap by introducing an app founded on a crowdsensing approach to enhance safety and awareness at sea. The app seamlessly integrates into broader systems and frameworks for environmental monitoring, aligning with our envisioned future endeavors that are currently explored in the EU Funded Nautilos project.

Additional research efforts are being spent in identifying AI methods to derive information from satellite images to observe and categorize marine traffic, possibly leading to understanding patterns as well as in identifying malicious behaviors, such as Illegal, Unreported, and Unregulated (IUU) fishing or prohibited discharges [19]. In this context, Synthetic Aperture Radar (SAR) images allow for vessel detection under most weather conditions. Image processing and computer vision methods have been used in the framework of the ESA funded OSIRIS and OSIRIS-FO projects to (i) detect the presence of vessel targets in the input imagery, (ii) estimate the vessel types based on their geometric and scatterometric features, (iii) estimate the vessel kinematics, and (iv) classify the navigation behavior of the vessel and predict its route [20]. Optical images, although they can't be acquired on cloudy days and during the night, may convey fine-grained information suitable for the analysis and classification of small vessels, potentially characterizing both industrial and small-scale fisheries, which is currently under consideration within the PNRR NBFC Project.

3. Conclusions

In this short paper, we provide an overview of the research conducted at SI Lab, focusing on themes related to sustainability. The breadth of applications showcased highlights the considerable value of AI as a tool to sensibly address the challenges of the future and facilitate ecological transition.

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