Embracing Robotics and Intelligent Machine Systems for Smart Agricultural Applications

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High tech to feed the world! This slogan was launched some 10 years ago in The Netherlands to direct research on high tech for agricultural production. It responded to an urgent concern about the needs of a growing world population for food, feed, fibers, and basic chemical components. By the way, make no mistake, agriculture does not only provide food! Anyway, the slogan represented the vibrant optimism about the potential of technology in support of this quest. And for good reasons! Advances in robotics and artificial intelligence (AI) in the recent past allowed us to go beyond far-fetched visions and speculations and put these technologies to the test on the fields, in the greenhouses, in the orchards, and in livestock barns. Definitely, this trend is not limited to The Netherlands. When monitoring academic and professional literature, the rapidly growing number of publications in the past 10 years addressing robotics and AI in the agricultural context is clear proof of a worldwide trend.

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Robotics and AI have been topics of research in the agricultural domain for some 40 to 50 years now, and one might wonder why these technologies have not been widely adopted in practice. Fair enough. A good deal of technology is available and used in agricultural practice today. But upon closer inspection, this technology usually supports or replaces the farmer and coworkers on the less demanding tasks—demanding in the sense of sensing, cognition, decision making, and fast and effective eye–hand coordination when monitoring and manipulating the crop, fruits, and flowers. The use of these technologies commonly correlates with a quite well-structured environment where the location, shape, size, and color of objects to be manipulated are quite clearly defined. Seeding, planting, broad-acre application of fertilizers, and crop protection chemicals are examples of that existing category of technologies. And for sure, you will find robotic manipulators in various less demanding applications for good reasons.

More challenging conditions are encountered in, for instance, safely driving a tractor while monitoring the performance of the implement, harvesting fruits, pruning fruit trees, and monitoring plants and cattle for water status, diseases, or stress. No two plants are the same, and no two cows are the same. There is a lot of variation within crops and among crops. Occlusion is a common issue in many more challenging farming tasks. Then, parts of plants and animals are partially visible. And don't forget weather conditions. Lighting, especially, still poses a serious challenge for many automated systems. But to be more specific, a bit of home gardening will have shown you that harvesting fruits and flowers is a demanding task. Yet, in a split second, professional harvesters assess the location and ripeness of fruit and, seemingly without hesitation, detach the ripe ones and leave the others for a second harvest. Despite many years of research in robotics and AI, such farm operations are still the realm where humans excel. Well, you might argue in return that the milking robot has been widely adopted and disproves this argument. In a way, it does; in a way, it does not. Have a closer look. In the box where cows are automatically milked, cows have a fixed position and orientation. Technology makes sure that cows cannot move much during milking. Second, the herd population is commonly adapted to the machine by selecting cows for a uniform udder shape and size as well as a regular location of the teats. Still, without debate, this is the most profound example of robotic and AI technology in agriculture, and we can learn a lot from its development not only in terms of technology but also in terms of, for instance, advancing technology through the various stages of technology readiness and also in terms of societal and economic aspects of technology adoption, training, education of farmers,

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and remote maintenance, to name a few aspects.

High tech to feed the world! The agricultural playing field has dramatically changed in past decades. Providing the world population with sufficient food, feed, fibers, and chemical components is definitely still a key aspect. Yet, doing this in a sustainable way has become an even more pressing issue. Climate change; a rapidly growing scarcity of resources, such as quality water, fossil fuels, and nutrients like phosphate; and the significant impact of using plant protection chemicals on the living environment call for solutions, also technical ones, that will help humanity move forward toward a more sustainable future.

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This special issue on embracing robotics and intelligent machine systems for smart agricultural applications shows what has been said above in various ways. The nice collection of articles is representative of the trend in the agricultural engineering sciences, a trend aiming at mobilizing, investigating, and proofing robotics and AI in the agricultural context. The collection of articles also represents the wide range of applications or capabilities needed in agricultural automation. There is work addressing the assessment of new plant breeds, called *phenotyping*, a key issue at the very beginning of the agrifood chain. Other works address the monitoring of plants in terms of diseases, plant stress, and water needs—important yet challenging tasks farmers tend to do while walking through their crops. Similar issues are relevant in livestock production, where farmers need technology to support them in monitoring individual cows in a herd. One article in the collection investigates pruning fruit trees, a labor-demanding task that needs considerable expertise. Also, this special issue contains a systems study on the use of robotics and automation for closed crop production systems. On a different note, you will encounter different aspects of robotics and AI in these articles. Camera vision is still a dominant technology in robotics. But in agriculture, other sensing modalities, like detecting plants' volatile emissions and measuring stem water potential (SWP), offer opportunities as well. And for sure, when it comes to mobility, wheeled mobile platforms and unmanned aerial vehicles are commonly used technologies. As for the AI part, and in line with current trends, most of the articles contain significant emphasis on deep learning and machine learning algorithms.

We start with the contribution of You et al. [A1] on semiautonomous precision pruning of upright fruiting offshoot orchard systems. Dormant pruning is an important orchard activity for maintaining tree health and producing high-quality fruit. Due to decreasing worker availability, pruning is a prime candidate for robotics. However, pruning also represents a uniquely difficult problem, requiring robust systems for perception, pruning point determination, and manipulation that must operate under variable lighting conditions in complex highly unstructured environments. In this article, the authors describe a system for pruning modern planar orchard architectures and its validation in field trials.

Monitoring plants and animals' features is central to farm management but also extremely important during plant breeding. Although addressing different aspects of farming, technically, these concepts are closely related.

Esser et al. [A2] present a field robot for high-throughput and high-resolution 3D plant phenotyping. The robotic platform carries multiple laser and camera sensors for in-field plant scanning. 3D reconstruction yields a digital twin of the plants from which phenotypic traits like leaf area, leaf angle, and plant height can be estimated. The system is validated on sugar beets, soybeans, and maize.

Vijh et al. [A3] address an important problem in the category of plant disease detection, specifically, the detection of slime mold. They present the Upgraded Slime Mold Algorithm (USMA)–Bag of Features. The performance of the USMA is compared against state-of-the-art algorithms on 2017 IEEE Congress on Evolutionary Computation benchmark functions and applied to a classification dataset for disease identification in sustainable agriculture.

Geckeler et al. [A4] present their work on robotic volatile sampling for early detection of plant stress. Plants in stress emit volatiles that can be used as a proxy for stress detection; in a way, they start to smell. Detecting these volatiles can serve as an early warning system. The authors present a plant volatile sampler that can be deployed and collected with an uncrewed aerial vehicle. They assess the effect of the sampling flow rate, horizontal distance to the volatile source, and overhead downwash on collected volatiles, along with the deployment accuracy and retrieval successes with manual flight. The volatile sampling is validated in outdoor tests.

Focusing on orchard applications, Dechemi et al. [A5] present their work on robotic assessment of a crop's need for watering. SWP is a plant physiological metric frequently used by agronomists and growers to optimize crop irrigation schedules. Measuring SWP is time-consuming and suffers from sparse sampling and human variability. The authors present the core building blocks of a robotic system for automating this monitoring task.

Switching from plants to animals, we have the contribution of Guo et al. [A6] addressing vision-based cow tracking and feeding monitoring for autonomous livestock farming. Animal tracking and feeding monitoring are of great significance for automatic individual cow welfare measurement and are an important prerequisite for autonomous

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in presentations, or in communications with media outlets.

Technologies are indeed outpacing our discursive norms and public policies, and they can be deployed to consequential ends by businesses and states. Moreover, the incentive in media and industry will generally be to amplify sensationalist claims and to dampen important nuances. For all of these reasons, engineers must think and communicate with care and precision about the capabilities and limitations of their systems. The presenters at ARSO 2023 impressively exhibited that care on a wide range of topics. But when matters get especially sticky, consider reaching out to a philosopher. We're trained to help.

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livestock farming systems. Deformable body posture, irregular movement, and the complex farming environment render individual animal tracking in a herd challenging. The authors improved a face-based cow tracking system using You Only Look Once v5 with coordinate attention. A vision transformer was embedded in the reidentification network DeepSORT to enhance feature matching and tracking accuracy. The system was tested on a dataset with multiple cows collected on a commercial farm.

Finally, the article of Car et al. [A7] proposes a fully autonomous robotic indoor farming system. The system, called SpECULARIA, consists of multiple mobile robots and plants grown in moving containers. The work cell is structured such that the system can plan and execute procedures to control every plant's growth and hygiene from seed to harvest. The study benchmarks the proposed setup against a classical mobile manipulation approach to demonstrate its feasibility.

We would like to thank the editor-in-chief of *IEEE Robotics and Automation Magazine*, Yi Guo; the associate editors; and the many anonymous reviewers for their support while creating this special issue. We hope the special issue will motivate researchers and practitioners to develop robotics and AI technologies for agriculture. There are plenty of opportunities, but there are still quite some technical and nontechnical challenges to create a proof of concept and bring it to a marketable and accepted product. Any additional pair of hands is most welcome during this endeavor. You are all most welcome to join this field!

APPENDIX: RELATED ARTICLES

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