European Robotics in agri-food Production

Opportunities and Challenges

eu ROBOTICS

agROBOfood

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Vision

Future agri-food production networks will be flexible, responsive and transparent, providing sufficient high-quality and healthy products and services for everyone at a reasonable cost while preserving resources, biodiversity, climate, environment, and cultural differences.

Mission

Stimulate the development and integration of innovative robotic, AI, and Data solutions that can successfully be used in flexible, responsive and transparent agri-food production networks.

Purpose

Following our vision and mission statement above, this document aims to provide:

- a contribution to the development of the Strategic Research and Innovation and Deployment Agenda (SRIDA) of the AI, Data and Robotics PPP;
- a broad and coherent view of the needs, applications, and key challenges for robotics for the agri-food production domain in combination with data and AI,
- a 360º stakeholder view addressing both technology, business, and ecosystem development,
- a basis for the vision, alignment, and development of programs, projects, groups, and consortia that aim to contribute to the development and deployment of robotics, AI, and data in the agri-food production network.

Summary

"AI, Data and Robotics for agri-food Production

Agricultural production is a key economic activity providing a growing world population with resources like food, fibers, fuels, and chemical basic components. Yet, agriculture also plays a crucial role in the depletion of resources like fresh water, fossil fuels, and nutrients (e.g., phosphate) and has a significant impact on our living environment through emissions and the use of chemicals.

Despite a growing world population, labor participation in agricultural production is declining. Technology has been instrumental in the very successful development of agriculture throughout the centuries and will play a crucial role in the European Green Deal that addresses the transition to a more sustainable agri-food production in the years that lay ahead of us. It is expected that technologies like Artificial Intelligence, Data, and Robotics will be leading in this transition. During this transition, it is critically important to support agri-food production with novel technologies. Covering the value chain from breeding, through on-farm production, post-harvest storage, logistics, packaging, and food processing, the agri-food production network is an ecosystem providing agri-food products and services. Besides food, other off-farm productions do exist including harvesting of wild food, fisheries, indoor farming, both large scale commercial, and home growing, forestry, and, last but not least, urban landscaping and maintenance where robot technologies can and will be applied as well.

The current release of this agenda mainly focuses on the food production part. Being a working document, the authors wish to express the hope that it will serve as a basis for further elaboration to encompass the whole agri-food domain in its full width and depth. With an emphasis on robotics and to a lesser extent on AI and Data, this report provides a vision and mission on what robotics should contribute and how to facilitate the transition to a more sustainable agri-food production.

Key challenges in terms of technology, ecosystem, and market are derived from 12 use-case themes within the agri-food production domain. Use-case themes represent classes of functionality that go beyond specific individual applications and application domains. Despite of aiming to identify high-level cross-domain challenges in robotics, AI, and Data agri-food and offering the opportunity to connect to other technical and application domains, this classification is not considered to be exhaustive.

Key takeaways are listed in the following table:

Robotics for agri-food Production

Use Case Themes	Key Challenges
1. Innovative/Disruptively novel agri-food systems enabled by robotics. 2. Robotics, AI, and data science for breeding. 3. Complex handling and manipulation in primary production. 4. Complex handling and manipulation in post-harvest. 5. Realizing full autonomy of already mechanized tasks. 6. AI and robotics for livestock farming. 7. AI and robotics for precision agriculture. 8. Cleaning in agri-food. 9. Connectivity, distributed intelligence, and pervasive technology. 10. Logistics and transport. 11. Ocean farming and agri-food. 12. Food preparation and presentation.	**Technology** 1. World modelling, simulation, and benchmarking. 2. Robot-to-X interaction. 3. 24/7 level 5 cooperative systems and fleet and swarm management. 4. Perception in robotics. 5. Multi-dimensional manipulation. 6. Interactive design of trustful, safe, and ethical robotic system. **Ecosystem** 7. Sustainable pan-European agROBOfood network. **Business** 8. Push-to-market for agricultural robots and systems, support, education, and training. 9. Specialized robots to be used by seasonal unskilled labor. **Training and Human Capital Development** 10. Infrastructure for practical training with access to robotics. 11. Lifelong learning: connecting people from agri-food with people from robotics and analytics.

Table 1: Use case themes and technical and non-technical challenges across use case themes

Contents

Introduction

Agricultural production is a crucial activity providing mankind with food, feed, fuel, fibers, and chemicals. The EU is a leading producer and exporter of agricultural products[1].

Yet, agriculture is facing some major challenges in the years to come. The world population is expected to grow to more than 9 billion people in 2050. Growing prosperity in developing economies is accompanied by changes in diet and increased demand for food. This trend is accompanied by a growing need for feed, fuel, fibers, and chemicals to be produced using roughly the same production area. Furthermore, consumers continue to demand safe high-quality food at a low price, putting severe pressure on the agri-food business. Food security demands a further increase of agricultural production alongside a more equal distribution as well as reduction of losses in the food chain, estimated at some 30-40% today.

But there is more. The exhaustion of fossil sources for fuels, fibers, and chemicals will put more pressure on agricultural production. Critical resources like water and nutrients like phosphate show a declining availability. Similarly, there is a strong decline in another critical resource for agricultural production, namely human labor. People move from rural areas to urban environments to provide for a stable income. Expansion of economic activities like industrial production and services stimulate that migration. Consequently, the workforce in agri-food production is rapidly aging and availability is rapidly declining. In Japan 2/3 of the Japanese farmer is over 60 and China expects that available workforce for 2042 will decline to 5% of its population. Worldwide statistics contained in the ILOSTAT Database[1] show 44% agri-food production employment in the early 90s, diving close to 24% now (2020) and will follow the Chinese projections towards 5% between 2040 and 2050. Similar trends are reported for Europe[2]. This means

that almost 80% of 2 billion people working in agri-food will move to other jobs, which means that fewer and fewer people have to provide food for a growing world population. The recent Covid-19 pandemic clearly showed how sensitive the agri-food production system is to the availability of human labour.

In addition to that, agriculture has a strong impact on the living environment through soil compaction and erosion, emissions of greenhouse gasses, and the use of crop protection chemicals and fertilizers. The use of medicines in livestock farming is related to a growing concern for infectious animal diseases. Finally, climate change dictates a rethinking of agricultural production from a much wider perspective.

All in all, these trends necessitate a more sustainable yet intensified agricultural production, providing food, fuels, fibers, and chemicals along with a healthy living environment for generations to come while assuring the livelihood of farmers who are facing the challenges of meeting these demands. This is reflected in the EU Green Deal which is an ambitious package of measures ranging from ambitiously cutting greenhouse gas emissions, to investing in cutting-edge research and innovation, to preserving Europe's natural environment. The green deal includes also the farm to fork strategy, the transformation of agricultural rural areas, and the transition to a circular economy.

Agricultural technology is considered to be as old as agriculture itself, it has played a crucial role in agricultural production over the past 10.000 years and will play a crucial role in addressing the challenges of agricultural production. Advanced technologies are essential in enabling the agri-food industry to increase production efficiency while limiting the global impact of food production on the

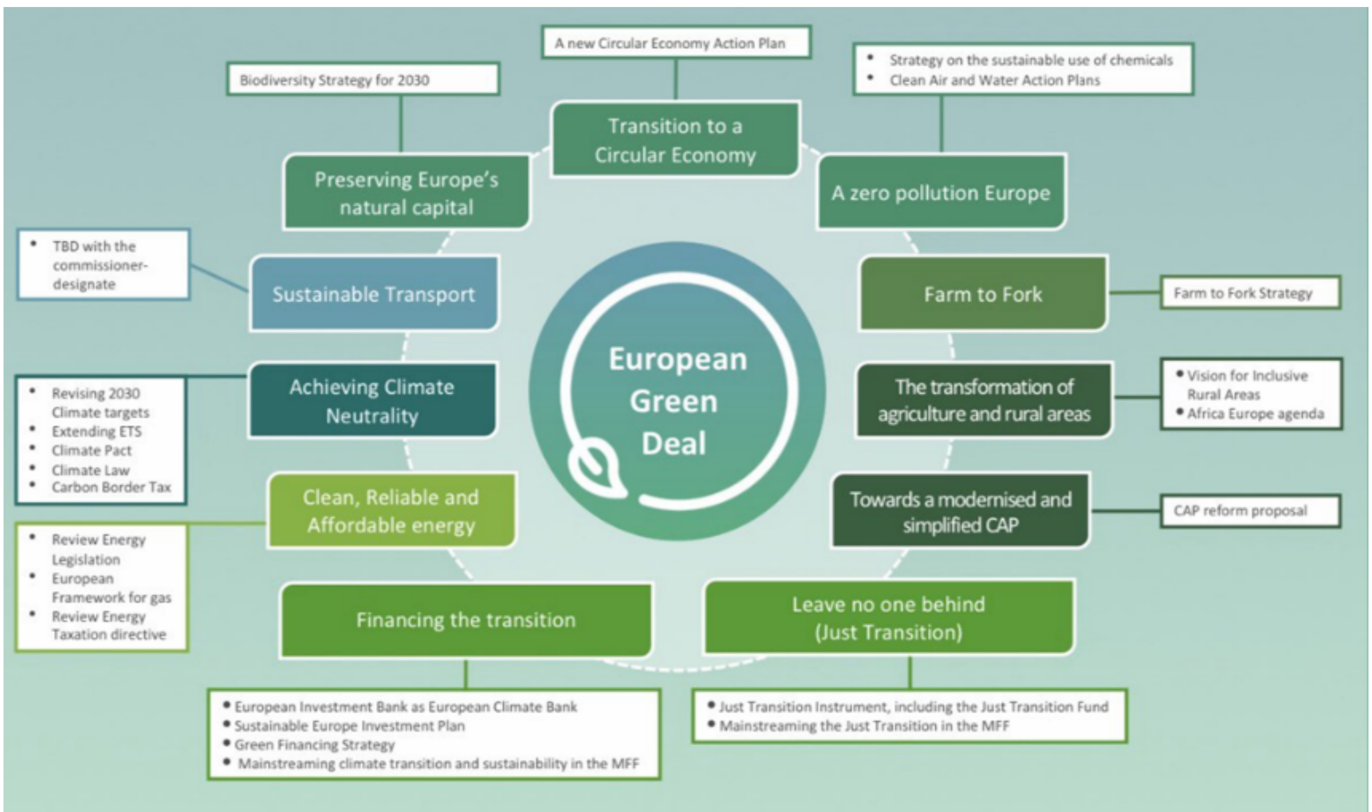


Figure 1 EU Green Deal

environment[1]. In food consumption, the main challenges will be how to feed all living beings in an affordable and acceptable manner and reduce food losses as much as possible.

Europe has the industrial leadership in Ag-Tech, being the world's largest producer of farm and food manufacturing equipment and the acknowledged global leader in innovation. The economic footprint of the industry is highly significant, being the largest agricultural input industry and representing more than 300,000 jobs (including distribution and maintenance) most of which are scarcely populated rural areas (CEMA, AgriTech 2030).

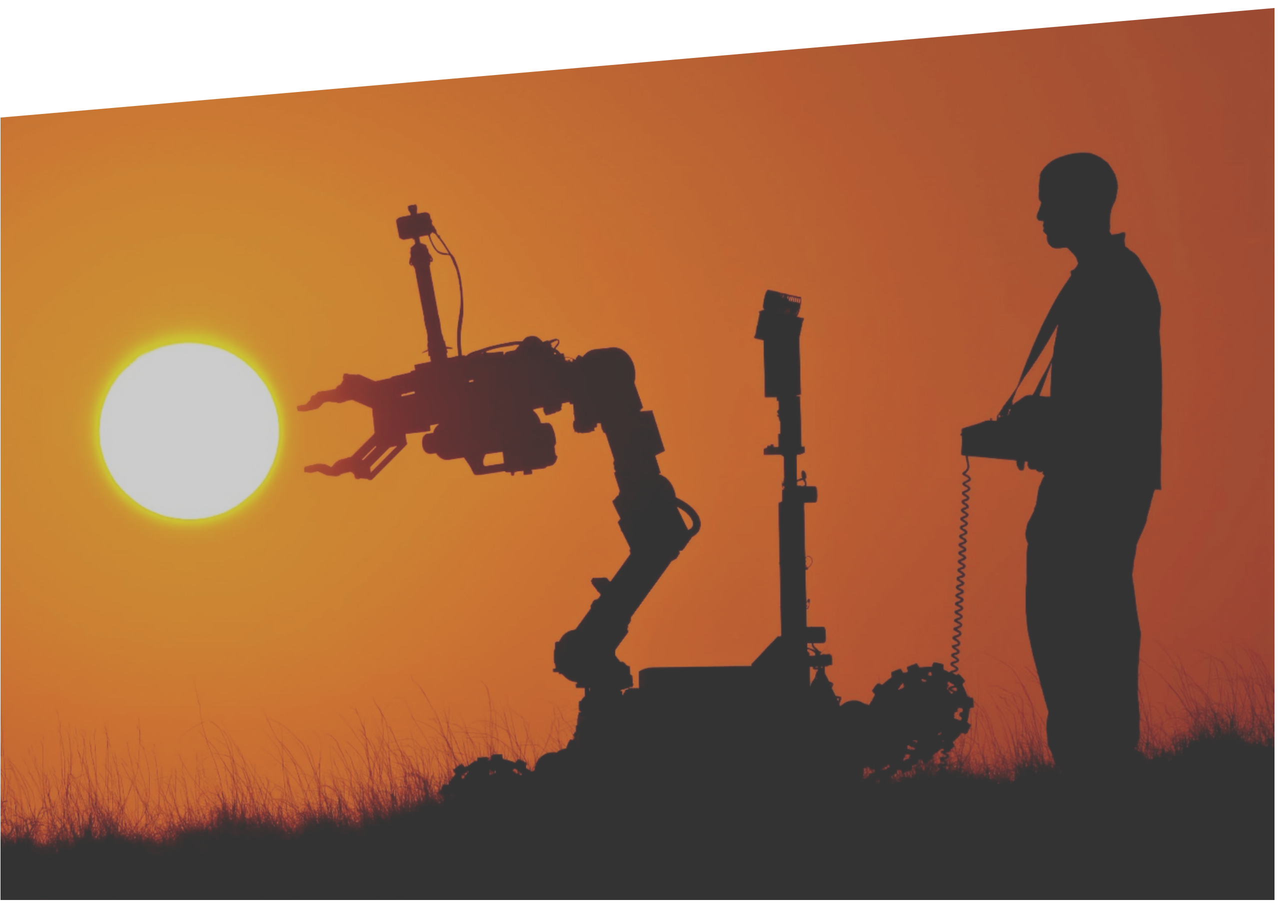
The project 'Advanced Technologies for Industry' (ATI) initiated by the EC analysed the generation and uptake of advanced technologies, related entrepreneurial activities, and skills needs in the agri-food sector[1]. The ATI report 'Advanced Technologies for Industry – Sectoral Watch states: Technological trends in the agri-food industry' defines advanced technologies as *'... future technologies that are expected to substantially alter the business and social environment and include advanced materials, advanced manufacturing, artificial intelligence (AI), augmented and virtual reality, big data, blockchain, cloud technologies, connectivity, industrial biotechnology, Internet of Things (IoT), micro and nanoelectronics, IT for mobility, nanotechnology, photonics, robotics, security*.' In conclusion, the ATI project identified Industrial Biotechnology, Robotics, Big Data, IoT (Internet of Things), and AI as the key advanced technologies for the agri-food sector for the near future. However, it also correctly identified a challenge in the fact that 'Agri-food companies do not have the inherent practice to invent technologies they are developing, but rather focus on applying and adapting technologies for their specific needs and industrial requirements.' The growing number of start-ups might change the playing field in agri-food by adopting novel breakthrough technologies and generating novel business models.

The mentioned report is a very informative state-of-the-art market and skills analysis, yet it has a high aggregation level in that it addresses Robotics, Big Data, and AI as container terms. By doing so the report does not focus on nor prioritizes underlying bottlenecks of each of these technologies for individual application domains. This strategic research agenda aims to fill that gap for the application domain of agri-food production with special emphasis on Robotics and to a lesser extent on AI and Big Data. By doing so it intends to complement the Strategic Research and Innovation and Deployment Agenda (SRIDA) of the AI, Data and Robotics PPP which is a candidate contractual PPP within the European Horizon Programme[2].

Before presenting the vision and mission underpinning this strategic research agenda, it is critical to define both the application domain as well as technologies like Robotics, AI, and Data in a bit more detail. In this research agenda, agri-food production is defined in a very broad sense. Horizon Europe Cluster 4 states that the term **agri-food** is intended to cover a wide range of food production sectors including livestock farming, fisheries, horticulture, etc, as well as produce processing, ingredient preparation, and food manufacture and assembly. If we limit ourselves to the term **agri-food production** then it refers to the delivery of products as well as associated services produced by or associated with arable farming, greenhouse production, livestock farming, orchard fruit production, full-field vegetable production, and fishing as well as fish farming. The delivery of products and services is embedded in a production or value chain, the **agri-food Production Network.** The agri-food production network is defined as an ecosystem providing agri-food products and covers the production, data gathering and distribution, and decision making of all involved stakeholders and all steps of a production/value chain.

We are aware that this ag-Tech oriented network with its focus on production should be aligned with the Food-based network with its focus on preparation and consumption of food in a variety of environments and combinations. The ATI list of 16 key technologies defines **robotics** as a technology that encompasses the design, building, implementation, and operation of robots[5]. The SRIDA complements this definition by stating 'Robots are unique because they create value by performing physical tasks that people cannot, should not, or will not do[4].' It then identifies the key challenge of robotics: 'The need to develop physically embodied systems able to interact with unknown and unstructured environments makes robotics intrinsically complex and different.' According to the SRIDA, there is a synergetic relation between AI, Robotics, and Data concerning three aspects. 'Firstly that robots are significant producers of data, secondly that they rely on data and in some cases external knowledge while operating. The third and most important aspect is that they rely on AI technologies to achieve core functions such as perception, decision making, and interaction. Robots need AI and Data to achieve their operational objectives[4].'

Building on these preliminaries it is our vision that future agri-food production networks will be flexible, responsive, and transparent, providing sufficient high-quality and healthy products and services for everyone at a reasonable cost while preserving resources, biodiversity, climate, environment, and cultural differences.



Stemming forth from this vision, we define our mission as to stimulate the development and integration of innovative robotic, AI, and Data solutions that can successfully be used in flexible, responsive, and transparent agri-food production networks.

Within Europe, we use the ecosystem approach to stimulate industry, governments as well as producers and consumers to provide the opportunity to choose for AI and robotics-based solutions. We will enable future agri-food production networks that will be based on a proper balance between labor-based, service-based, and robotic-, data-, and AI-based-solutions.

The next chapters are structured as follows:

We start by defining Use-Case themes in chapter 2. Those serve as inspiration for innovation-driven robot development in the coming decade and where identified by discussions with experts from various domains from agri-food.

Based on the Use-Case themes identified in chapter 2 and further discussions with experts from domains related to both agri-food and non-agri-food (e.g., perception, health care, ...) we identified challenges that are specially related to agri-food. The results are described in chapter 3 alongside their relation to the European Innovation Hubs and challenges in other robotic domains that are also relevant but not limited to the agri-food domain.

Use Case Themes

To identify a limited and coherent set of use-cases, their identification is based on the following guiding principles:

1) A use-case theme describes holistic processes or functions that are common to several sectors or use cases in either one application domain or for a specific class of application domains.
2) Use-case themes describe applicable functions or processes and are distributed over the agri-food chain/network, starting at plant and animal breeding as well as production and provision of resources for agricultural production, followed by on-farm agricultural and ocean production and concluded with post-harvest grading, industrial food and drink processing and packing. We do not cover yet the food preparation and presentation part of the food network.
3) Use-case themes address relevant high-level challenges in agri-food such as food security, food quality, and safety, (economic, ecologic, and social) sustainability, resource use efficiency, etc. A use-case is one example/instance of a use-case theme that inherits the general use-case theme challenges and can make those more specific or add others (e.g. use-case domain-specific)
4) Both, use-case themes and applications are relevant for the stakeholders that are involved today or will be involved soon. Stakeholders include but are not limited to: government, technology providers, and the agri-food industry.

Each Use-Case Theme consists of the following subsections:

- Description: a brief high-level description of the use case theme.
- Core Function: a holistic description of the core function
- State of the Art: "most advanced" use cases
- Key Challenges that need to be addressed including a statement of what success (overcome the challenge) will look like. Each Key Challenge is preceded by the Key Challenge Category Name (see Chapter 3), followed by a short description of the specific challenge. Since all Use-Case Themes share the challenge categories Business, Ecosystem, and Training and Human Capital Development, those are not explicitly listed in the Key Challenges Section of the Use-Case Themes.
- Success Metric: *how* can success be measured, not how success is defined
- Market Sectors: where appropriate, specific market sectors will be mentioned. A general trend here is that besides the traditional partners in the agri-food and due to the ICT developments, that stimulate the service economy, a variety of newcomers of companies and advisors will appear. This is also attractive for universities and research institutes with their roots in more technology domains who also discover agri-food as a booming market. The same agri-food market is also becoming interesting for the global players emerging from other domains (e.g., Amazon, Google, ...), telecom providers, and tech industries (e.g., Fujitsu, Mitsubishi, …). The ecosystem in the agri-food market will drastically change in the coming decade and this must be seen as a general trend that influences all Use Case Themes and Challenges.

Following these guiding principles, we identified the following use-case-themes as described on the next pages.

Innovative/Disruptively Novel Agri-Food Systems enabled by Robotics

Description

Technology is commonly used as a problem solver. Yet, robot and AI technology can also enable novel or reinvented agricultural production systems such as intercropping, vertical farming, pixel farming, algae farming, ocean farming, and others. Breaking trends of scale and an increased use of technology will require distribution and collaboration amongst robots and humans, or even swarms of robots incorporating values, perceptions, business economics, and ethics as part of new agri-food systems where robots and humans will do the needed work. This is not only valid for the agri-food production part, but also for the part of the network that focuses on the preparation and consumption of food in a variety of environments and combinations.

Core Function

We require new combinations of enabling technologies in combination with robotics, data gathering, knowledge resolving, and AI-driven decision-making to create new opportunities for markets and novel agri-food systems that can quickly advance to a pilot state.

State of the Art

- Drone-based monitoring of crops with a high variety of sensors, spectral and geometric resolution.
- Sensor-based monitoring of livestock.
- IoT-based monitoring and control of watering (for example for large agricultural fields).
- Fully organic and biological weed and pest control.
- Precision Agriculture/Precision Livestock Farming, Tracing and Tracking in chain approach are accepted.
- and logistics are highly supported by automation.

Nevertheless, new concepts appear in production, logistics, and food processing that enables production and serving of food more efficiently and diversely.

Key Challenges

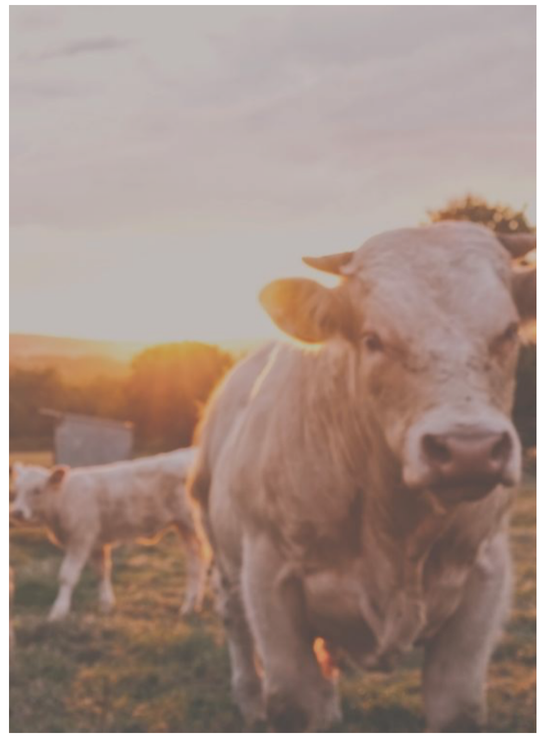
- 24/7 level 5 systems: a solution to this challenge will allow 24/7 monitoring and decision making needed to create, monitor, and improve new agri-food systems in particular where no human expertise is available.Sensor-based monitoring of livestock.
- Perception in robotics: AI-driven data analysis and decision-making. New agri-food systems will likely create new knowledge domains where human experts are rarely available. A solution to this challenge will allow human experts to learn completely new aspects of the agri-food domain and will allow an agri-food system to self-learn and optimize on its own.

Success Metric

A (re-)designed agri-food system is developed and it's shown that it can generate agri-food at reasonable costs or that it has the potential to cross market barriers. This new agri-food system is then part of one of the other use-case themes or will form a completely new one.

Market Sectors

A completely new agri-food system can be part of any of the existing market sectors or create a completely new one.



Robotics, AI and Data Science for Breeding

Description

Creating and market introduction of novel food products that are based on new or improved breeds of production crops, animals, insects, and fish typically takes 5-10 years. The last decades' focus was on genomics that resulted in sophisticated data analytics and automation of the genomic laboratory procedures. The focus is now shifting towards gathering and analyzing phenotypic data. Traditionally this is also based on manual labor, but the variety of circumstances and the phenotypic hunger for data urges for advanced methodologies for data gathering and analysis. It is expected that robotics can stimulate the demand for phenotypes in view of challenges like for example an increased resistance to environmental changes (e.g. increased temperature range based on climate change) or weeds, increased periods of low or high water availability, or an increased output or resistance to illness or pests.

Core Function

We require an automated data and AI-driven decision making and selection process to ensure diversity, traceability, and transparency (e.g. no genetic modification) of phenotypic data gathering.

State of the Art

In most cases manual labor that supports phenotypic data gathering is not sufficient to cover the needed variety and numbers of observations of individual plants/species. The use of different sensors is already started, however a dedicated platform to robotize phenotypic data gathering is still at the beginning. Also, some initial work is being done on simulation of plants/species that consider different environmental conditions or post-effects (for example the effect on the consumer (or his health) when eating the crop/meat of the species).

Key Challenges

- Robot-to-X interaction: a solution to this challenge will allow automated handling and manipulation of species (e.g. plants, animals) and environment (e.g. soil).
- 24/7 level 5 cooperative systems: a solution to this challenge will allow 24/7 monitoring and decision making for breeding without the need of human experts; intermediate solutions will provide options to the human expert (for decision making) based on multiple fused data and facts.
- Perception, simulation, and modelling of species: a solution will allow simulating the species in focus (e.g. a specific plant) such that several options (e.g. for breeding) can be ruled out before even real tests will take place.

Success Metric

The farmer/breeder chooses which parameters he/she would like to focus on (e.g. increased resistance, or higher output). An automated system collects and analyzes both, phenotypic and genotypic data, and allows the creation of the next generations of the species in significantly less time than in 2020 (which is 8-10 years for plant breeding for example).

Market Sectors

Breeding companies, laboratory technology and providers, technology providers (Data, AI), precision farming (in particular as service providers), propagation companies, phenotyping (for both plants and animals).

Complex Handling and Manipulation in Primary Production

Description

In horticulture and fruticulture, a broad range of automation and mechanization solutions are commercially available. Still, quite some operations including selective harvesting, crop maintenance operations, and various steps in customer-specific sorting and packing strongly rely on human labor. Variability in natural products in terms of shape, size, color, etc. as well as a highly unstructured working environment containing poor visibility of the target objects are still too challenging for current automation technology. In these operations, humans excel in terms of flexibility, robustness, very effective eye-hand coordination, and soft gripping. The availability of skilled human labor is declining and automation is called for long-term sustainability of these sectors. Automation also allows for improved and more constant product quality.

Core Function

Systems should be

- able to operate in complex working environments creating uncertainty about the precise location and orientation of objects to be treated,
- flexible to object variation inherent to nature, and
- safe for products and humans.

State of the Art

Automating these tasks still proves to be challenging given the current state of technology. So far, research has mainly focused on automating selective harvesting, yet the performance of prototypes still does not warrant a feasible business case.

Key Challenges

- World modeling: autonomous robots need to reason about their environment to realize tasks in complex unstructured or semi-structured environments.
- 24/7 level 5 cooperative systems: sensing systems that generalize well to task and object variation inherent in these systems (not necessarily fully autonomous).
- Robot-to-X interaction and multi-dimensional manipulation: intelligent manipulation i.e. effectively moving the end-effector technology and product, in complex environments, including effective and soft gripping.
- Training and human capital development: identify and develop human-robot co-working technology as an intermediate step towards full automation.

Success Metric

In 10 years, a number of these systems should arrive in the upper TRL levels, one or two being transformed and adopted in agricultural practice either as autonomous systems or human-robot co-working systems.

Market Sectors

Greenhouse horticulture and (open-field) fruticulture are the key market sectors. Applications include selective harvesting, crop maintenance operations like pruning, leaf removal, attaching plants to supporting structures, precision pest and disease control, etc.

Complex Handling and Manipulation in Post- Harvest

Description

When "farm" products are harvested and collected, a high number of tasks are still done manually because of their complexity, variability, and required operational flexibility. Typical tasks are sorting, picking and packing, composing, and modifying highly variable food products (seasonal, shape, vulnerability). Also, other constraints can play a significant role in the decision to robotize tasks or to leave manual labor in place. Constraints are:

Description

- The high demand for operational flexibility. Especially in the fresh food and flower chain production lines are commonly faced with a high number of changeovers during the day to other products and packages (sizes, shape, numbers/package, brands) due to an unpredictable and fast-changing retail value chain. Human workers are in many cases more flexible than the current food production lines.
- The contamination risks and the required cleaning demand is challenging and time-consuming for both complex machines and manual work spots. Food contact parts of mechanized systems need to be food-grade and chemically resistant (washable).
- A high filling-rate of low-value products in bins, crates, and containers and the composition in the final or intermediate package is required. A high filling-rate will save energy, logistics, space, time, and packaging materials. Optimal filling of heterogeneous products is a challenging task.
- The space needed by machines is often larger than the area needed for manual workforce operating next to each other. In developing solutions, the available space should be taken into account, especially when it should operate in harsh conditions where humans might fail to function (processing in the cold chain).
- Seasonal aspects require machinery available at high peaks. Lines need to scale easy and quick but should also be able to cope with variations during the seasons (due to weather conditions, pests, and diseases) and significant differences in the requirements between suppliers.
- agri-food products are in general low cost. Robots need to act with a high cycle time to become economically viable. In post-harvest processing and in the food production part some products can have a high value.
- Bacterial infected products can easily contaminate complete production lines and the track and tracing may go back to a full day production when machines are only cleaned at night. Manual workers pick direct from the bin

and can clean more often between batches. A robotic system should do the same.

Despite these challenging requirements, the demand for robotic solutions from industry is high. The availability of skilled (migrant) workers is declining rapidly, and working conditions are unfavourable and declining. More post-harvest operations are part of the cold-chain (4-7°C), due to high contamination risks. Due to mechanization and digitization, the remaining tasks are more repetitive, monotonous, 24/7, and stressful. Commonly work is paid based on human performance (datafication). The workplaces are often noisy, moistures, poorly illuminated or without daylight. The population of workers is aging and available of sufficiently skilled labour is on a decline.

Core Function

The core function is the development of a highly flexible robotic system that can pick products from a container (or bin) and checks the quality and place it in a package.

The function secures a fast changeover-time and is adaptive and able to learn new situations, products, and packages. The food contact parts in this functionality should allow for frequent cleaning, should be food-grade and be resistant to cleaning chemicals and run at a cycle-time of typically 0.5 – 2 sec. The function serves a high filling-rate of both container (to pick) and package (to pack) and production should be easily scalable by adding or removal robotic systems. Track & tracing at container and package level is secured and automated in this highly flexible robotic system.

State of the Art

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Key Challenges

- Robot-to-X interaction and multi-dimensional manipulation: pick heterogeneous natural products to form a bin with high filling rates into a packing at a high filling rate.
- Perception, 24/7 level 5 cooperative systems: enable high operational flexibility (fast change-over, automated track, and tracing, learning and adoption to new situations, seasonal or market demanding scaling).
- Perception to enable fast cleaning of food-contact parts to avoid contamination between packed food.
- Perception and multi-dimensional manipulation for product quality sensing during operation.

Success Metric

Systems run typically at a cycle-time between 0.5-2 sec. Systems can solve most of the failures by design and run multiple batches of multiple hours. Between batches, there is no cross-contamination because systems are properly and quickly cleaned in a matter of seconds.

Market Sectors

All heterogeneous natural products are handled manually such as fish, meat, all fruits (soft, stone, citrus, hard), nuts, vegetables, flowers. Ready meals manufacturing and processing such as salads or fresh pizza. Retail boxes and deliveries (e.g., Hello fresh, Picnic).

Realizing Full Autonomy of Already Mechanized Tasks

Description

Many agricultural tasks are mechanized. But the machinery still requires operators and main decisions are made by human intervention based on experience rather than on (validated) data. The supervision and monitoring tasks are not automated yet. This is hindering a more sustainable way of production. When sensors gather data autonomously, when data-loops are closed and enhanced with automated decision (-support) algorithms, full autonomy can start. Still, the farmer can override a decision at any time, allowing to inject specific knowledge that is not visible in the data.

With autonomous systems, robots can become smaller (less soil compaction/energy use) and/or limit the use of chemicals, water, manure/nutrients, and labor costs. In the end, this can help to improve biodiversity, allow new farming methods as intercropping/pixel farming, better timings, and 24/7 capabilities as well as added crop value at minimal land-use.

Core Function

The core function is the integration and demonstration to full autonomy or hybrid solutions where robots and humans work together. Systems should act reliable and comply with safety standards for autonomous robots and provide convenience to the end-user.

State of the Art

In current practice agricultural robots still run under the supervision of farmworkers/tractor drivers. A decision is made by the farmer based on his own experience avoiding risks. Systems are not flexible to other implements, acceptable safety standards are not fully implemented and sensor systems are not always clear on what measure provides the most valuable measure. Learning between systems and progressed over multiple seasons are not developed or implemented in an automated way.

Key Challenges

- Interactive design of trustful and 24/7 level 5 cooperative systems for proven sense – think – act solutions of all common agricultural situations to avoid human interaction including interoperability with farm management systems, implements carriers and implements and convenient interfacing and remote support and control by the farmer and service providers to take care for machines that are miles away.
- Secure, safe and ethical robotics systems for agriculture including appropriate legislation.

Success Metric

- Sensor systems that can provide reliable information through smart algorithms to control actuation to a higher level at full autonomy level. Sensor systems that can also cope with unexpected events typical in agriculture.
- From supervised to unsupervised operations.

- Open interfaces between farm management systems, autonomous tractors, and smart implements that can easily be exchanged. Within farm operations as well as connectivity to stakeholders outside the farm. Connectivity to systems of systems.

- Clear demonstrated best practices on how farmers control autonomous systems. User interfacing, error handling, fast and convenient changeovers to other tasks, and robustness of systems. Remote assistance - man-machine interaction - should be set up conveniently.

Market Sectors

Highly mechanized operations such as arable farming, livestock farming, fishing, forestry, greenhouses vertical farms, aquaculture, orchards, viticulture.

AI and Robotics for Livestock Farming

Description

Animal monitoring, feeding, and care for production animals like cows, pigs, fish, and poultry is a daily recurring task. Smart sensor systems provide the extra "eyes, noses and ears" to the people that have to take care of these animals. These animals are all part of groups and housed in general on farms that become bigger. To cope with this challenge robotic support can relieve farmers in their inspection, sorting, and feeding time, so that they can concentrate their care on the animals that need their support at the right moment at the right place and with the proper care.

Core Function

- Observe animal behavior and physiology of individuals that are part of a group.
- Feed and treat individuals according to their needs.
- Harvest the product from the animals (like eggs, milk, wool) or by sorting and regrouping animals.

State of the Art

Automatic milking, using activity sensors, and dispensing concentrates in the dairy sector are seen as the top examples of individual observations and treatment and are adopted by the market. This is still limited to the milking of cows, however. First commercial robots appeared on the market for robotic feeding, animal observations in poultry and pig production systems. For cleaning of floors also some robotic solutions are on the market. All robots work individually and are focused on a single process.

Key Challenges

- Robot-to-X interaction: integrate small robots as part of (large) groups to let them do their specific job without being intruded (robot-animal-human interaction).
- Fleet management and 24/7 level 5 cooperative systems and fleet management: let them work in very harsh environments and give them enough autonomy to do their job cooperatively in such a way that different robots with different functions are also working together.
- Interactive design of trustful, secure, and ethical robotic system: design them such they will be able to work inside and outside buildings and also in the field.

Success Metric

Success can be seen e.g. if we see also robots operating in groups of pigs and goats who will not disturb the robots and when they can operate in water with large groups of fish in a 3D living environment.

Market Sectors

In a variety of farming systems for production animals like dairy, pigs, poultry, goats, and sheep as well as in commercial confined fish production systems. In addition to that, technology providers, feed-, food, pharma-, and breed companies, as well as contractors, will be involved.

AI and Robotics for Precision Agriculture

Description

Large scale monocultures, as well as uniform full field applications of water, nutrients and crop protection measures, have been the keys to the success of the current highly productive and very labor efficient arable farming systems. This, however, led to non-sustainable farming methods, and high usage of pesticides, less biodiversity, and increased resistance of pests and weed to weed/pest control. Field management by the farmer is based on a kind of 'one size fits all' approach accounting for the full field response of the soil and the crop to implemented operations. Existing farm mechanization is to a large extent dedicated to supporting this large-scale farming approach. AI and Robotics for Precision Agriculture can help, counter those negative effects. This state of affairs contrasts with historical practices in farming in which farmers took into account the local state of the soil and crop and, using their knowledge, would translate their observations into more location-specific application and operations.

Description

The precision agriculture paradigm intends to revitalize this approach and aims to apply resources and implement operations location-specific, in the right amount and at the right time. Labor efficiency demands taking the farmer (partly) out of the operational management loop such that the farmer can focus on growing sustainable agri-food rather than ensuring enough qualified labor is available on time. Also, the hardware, i.e. the mechanization should facilitate a more location and time-specific application. Then sensing, decision making, and actuation become key functions. AI and robotics will provide the soft- and hardware to automate these tasks. Operations to be addressed include precision weed control, precision application of resources like water and nutrients.

Core Function

While fulfilling these precision agriculture tasks, robotic systems should be able to deal with and be robust to natural variation between fields and within fields in terms of state and appearance of the soil and crops and uncertainty and (local) variations in weather conditions.

State of the Art

The precision agriculture paradigm has received considerable attention in research and development as well as in commercial practice in past decades. Adoption in practice has been slow. GPS-based autosteer systems have been commonly adopted. Localized applications of nutrients and crop protection measures have entered the market. Information of the state of soil and crop provided by sensors aboard satellites and drones is used as input for location-specific applications. Interpretation of the sensory data, as well as decision-making on the timing and amount of the applications, are still largely left to the farmer. Location-specific weed control systems are currently on the market. Their robustness to between-field and infield variations is still limited.

Key Challenges

- World modelling and 24/7 level 5 cooperative systems: sensing systems that provide localized information about the state of the soil and the crop and their intelligent interpretation of the sensory data and translation into suitable localized and properly timed management operations.
- Perception in robotics: suitable novel or modified existing hardware for autonomous and location-specific implementation of operations like weed control, nutrient supply, etc.
- Robot-to-X interaction: human-machine co-working on the previous stages where full automation does not yet meet performance standards.

Success Metric

In 10 years, one or two fully autonomous applications using the precision agriculture paradigm should be adopted in farming practice.

Market Sectors

This use-case theme mainly applies to arable farming but the impact is also expected in full-field vegetable, fruit, and vineyard production. Markets include machine manufacturers, service providers of satellite and drone base sensing platforms, providers of internet-based databases and decision support systems, and last but not least the farmers themselves. Also, interest can be expected from plant breeding companies.

Cleaning in Agri-Food

Description

Cleaning is a task that comes back in all stages of the agri-food production system. It is a task that is performed sometimes in harsh environments and at irregular times. This task needs the dedication to do it properly. The Key is to remove organic contamination from constructions and machines to prevent cross-contamination with pathogens. Examples include cleaning of animal boxes in livestock systems and cleaning of food processing lines in the post-harvest processing stages of the agri-food value chain.

In food production, cleaning is typically done in between batches and once a day as a full system cleansing. Stables and protected horticultural environments (greenhouses, mushroom cells, vertical farms) are cleaned upon completion of a production cycle. Lorries for livestock logistics should be cleaned after the completion of delivery.

Description

Increased awareness of and demands on food safety rapidly pushed demands for intensive hygiene over the last decade. Currently, in practice, this very time-consuming task is commonly done manually. The commonly used chemicals are not user-friendly.

Another task is cleaning the products themselves. Cleaning can be done as a physical intervention to the product itself, like washing table eggs, or as part of a sorting process like sorting soil from potatoes.

Core Function

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State of the Art

Cleaning is a typical task that is done manually, time-consuming, and nowadays the demand for cleaning increases to produce safer food, and to avoid pathogen infection of livestock, workers, and consumers. Towards better hygiene, stronger chemicals are used, the task is carried out more frequently and more water is used. Cleaning systems still barely use sensor feedback. Sensors are very well capable to sense organic matter but are not able to "check every corner" of the production component, module, line or facility, because the sensor and spray angle are either stationary or have very limited degrees of freedom to move. Current systems are unable to identify risk locations in a structured and automated way. This poses a strong incentive on the agri-food chain to improve hygiene through more effective cleaning and more hygienic production systems.

Key Challenges

- Robots should be able to carry out the task in a wide variety of environments encountered in the agri-food domain.
- Robots should clean in a sustainable way using as little water, chemicals, and other resources as possible.
- Robots should be able to sense organic contamination and clean to accepted contamination levels. For instance, cleaning should focus on the parts of a food production line posing a high risk of contamination, while keeping the environment and outside machinery and constructions dry as possible.
- Sensing strategies should be developed to "check every corner" of the production or processing system and should be able to advise on risk locations in the construction to encourage better system designs.

Success Metric

- Systems can clean much more efficient than the current state-of-the-art. Systems are capable to work in multiple domains and can adopt easily in different setups.

Market Sectors

Application domains of cleaning technology include livestock, meat and food, and vegetable and flower lorries, stables, food processing lines, and agricultural machinery, protected horticultural constructions, greenhouses (inside & outside), vertical farms, mushroom cells, agri-food storage facilities. Also, in production processing, ingredient preparation and food manufacture and assembly cleaning is an important topic. Markets include manufacturers of machines and production systems (farms building, greenhouses, food storage) and their customers, including farmers, logistic companies, and the food-processing industry. Also, food safety boards might have an interest in such sensing and cleaning technologies.

Connectivity, Distributed Intelligence and Pervasive Technology

Description

Robotization, AI, IoT, VR, AR, Blockchain, 3D printing, sensors, and drones, are the disruptive technologies having the potential to transform Agriculture. Interestingly, all these disruptive technologies come together in the paradigm of cooperative robotic systems having the ability to deal with the variety and both, small and big scale operation in future agricultural production systems. In agriculture, we have to deal with a variety of products and production circumstances. For a long time, the trend was to increase the scale of operation and therefore increase the capacity of the machines used in the production process. And for a long time, robotic systems were developed to replace these big machines. However, robotization and progress in other domains like IoT and sensors allow a shift from big machinery to swarms of small robots or multi-robot systems that cooperate, will be more intelligent, and will be a pervasive part of the cyber-physical agri-food system.

Description

This could allow establishing farms where the social and ethical structures and requirements have a better fit since the economics of the farm is then more correlated to the robotic and AI-driven support for the framer rather than mostly to the size of the farm as it is now.

Core Function

- The first core function addressed in this use case is that robot systems should be connected so that they remotely can be contacted. Localization, i.e. knowing when and where the robot system is deeply integrated into this functionality.
- The second function in this use case is fleet management. The cooperation between robots and the decisions where to embed intelligence should become a basic functionality.
- The third functionality is that the robot systems become much smaller in such a way that they can be integrated into an environment without disrupting the process they support.

State of the Art

Most robots used in practice are stand-alone and sometimes even fixed to a position so that humans are shielded. Robots are constructed in such a way that can operate independently from the internet connection. If they are connected, then it is for remote support and/or data extraction. A first step is made by integrating cooperative behavior. It consists of cooperation between robots with the same functionality and sometimes the cooperation between robots who have different functionality. These developments are in an early stage for market implementation. On the size and pervasiveness of the robots, the state of the art is that it is very domain-specific. In outdoor farming systems, the urgency of having smaller robots is present to reduce soil compaction. In livestock, the robots are not truly cooperative yet and in horticulture, robots are now entering the area where the plants grow.

Key Challenges

- Interactive design of trustful, secure, and ethical robotic systems: the challenge is to design robotic systems that are so small or natural that they seem to be an integral part of the production system and do not influence the production system in which they operate.

- 24/7 level 5 cooperative systems: in particular for fleet management, the challenge is the design of decision rules and optimization strategies to manage the fleet of robots. This requires finding a balance between performance, energy availability, data transfer, and system architecture. Part of this fleet management challenge is the ‘visualization’ for an operator.
- Robot-to-X interaction: Visualisation towards involved human operators but also to other robot systems. AR and VR might support dealing with priority in rules and handling in critical situations.

Success Metric

In 10 years, there will be a generic location awareness system that connects robot systems to the Internet. There will be a couple of good practical examples where cooperation between robots and humans is using the fleet management concept. On pervasiveness, progress has been made, but robots will not have the level of embeddedness in the processes yet.

Market Sectors

This uses case is generic and sector independent and potentially serves all agri-food networks.


Logistics and Transport

Description

Logistics and transport of voluminous and diverse agri-food products occur at several places, all with specific challenges. It is coming back in all stages of the production network and pops up within 'secured' environments like a field, stable or processing plant, or between different organizations/production facilities/locations that are connected by the public transport infrastructure. Transport and logistics impose a time constraint to schedule production processes and to prevent loss of products and/or quality of the products.

Core Function

- The first core function is to load, transport, and unload a physical product (solid, wet, gas, ...) from location A to location B within a specific timeframe and in a given cost regime.
- The second core function is to preserve the product from not being harmed and also keep the quality or integrity of the product.
- The third core function is to be transparent by providing adequate information on the transport and the conditions.

State of the Art

Transport within processing plants is already highly automated. Robots have found their way in palletizing and conveyor techniques. New robot systems will be needed to make the production lines more flexible. Transport in the open field, livestock, and horticultural production systems is mainly tractor, truck, forklift, and conveyor-belt driven. Since these are used in both, public infrastructure and farmyards where people walk and work, robotization is very limited. Robots play an important role in the loading part where the products are packed in transport units, like palletizing table eggs, or filling crates for potatoes or flowers. State of the art for harmless transport is that there are specific transport lines for fresh and cool products. All parts of the chain are dedicated to keeping the product cool or even frozen. In livestock, specific attention is paid to creating an animal-friendly environment within the transport chain. Robots do not play a role in this yet. Recently due to the COVID-19 crisis, there are developments in warehousing, food processing, and food delivery using robots.

Key Challenges

- Interactive design of trustful, secure, and ethical robotic systems: the key challenge is to design flexible transport modalities that can easily be transported and handled by robots. Standardization of these modalities is key. Also, the climatization of the environment of these modalities is a key challenge. Finally, integrating any data, AI, and knowledge into robot systems of the next generation of quality-based tracing and tracking systems requires transparency and independent observers.
- Ecosystem: for the robotic challenges of transport in the open road (train, ship) infrastructure we have to rely on other domains like public transport and logistics of goods.

- 24/7 level 5 cooperative systems: a key challenge is to design new models and tools to support cooperative behavior between robots. In transport timing is crucial, transport modalities should be somewhere at the right moment and at the right time. This is part of fleet management and new supporting tools and models are needed.
- World modelling, simulation, and benchmarking: the third key challenge is to improve the knowledge that describes the relationship between product quality and perceived treatment and the environment it is confronted with.
- Robot-to-X interaction: any knowledge gained in previous iterations should be integrated into the robot systems so that they can respond to it more naturally and intelligently. Interactive design of trustful, secure, and ethical robotic systems: the challenge is to design robotic systems that are so small or natural that they seem to be an integral part of the production system and do not influence the production system in which they operate.

Success Metric

The first success can be measured in the number of applications where cooperative behavior is shown, flexible transport modules are handled by robots and robots become independent observers to guarantee transparency during transport and logistics.

Market Sectors

- Fresh Food factories: (example: integration of robots to connect production lines and work together with humans).
- Agri-food production systems: (example: loading and unloading supported by robots). This uses case is generic and sector independent and potentially serves all agri-food networks.

Ocean Farming

Description

The way how we collect food from the ocean is changing. Nowadays the ocean is seen as a valuable source for producing food. Next to fishing boats, fish and seaweed farms are rising and windmill parks go hand in hand with shellfish banks and seaweed production. And the biodiversity of coral reefs and the sea-bottom is explored to find food. On the offshore, farming and hunting robots can play a major role.

Robots can monitor fish and secure biodiversity. They can harvest seaweed and monitor fish farms underwater and the growth of shellfish banks. Robots can also serve as a taxi or logistic carrier to bring fresh fish and workers to the shore and increase the uptime of energy-consuming fishing boats. Robots can also introduce new ways of fishing without damaging the ocean biodiversity on the sea bottom and harvest seaweed.

Core Function

Use of UUVs (ROVs, AUVs) underwater or USVs/ASVs on the water to monitor biodiversity, (shell-) fish, and seaweed farms. If possible, support with the harvest and crop maintenance of seaweed and feeding and catch/hunt of ocean livestock.

State of the Art

This is a completely new field in robotics for 'commercial' ocean farming. Drones for underwater are so far used for inspection and wildlife research and are remotely controlled. Robots are not yet used to monitor shellfish banks, fish farms, or seaweed farms. Harvest of seaweed is done manually.

USVs are tested for logistic purposes but not to assist fishing boats to improve the catch. Robotic technologies are investigated to improve trawl fishing to preserve ocean biodiversity, reduce energy consumption by pulling the nets and reduce harm to wildlife that will not be consumed.

Key Challenges

- Perception in robotics, world modelling, simulation, and benchmarking: visibility is different and 3D navigation is different underwater with UUVs (ROVs/AUVs) and USVs/ASVs on water. They have to cope with poor communication infrastructure, saltwater, poor visibility, underwater flows, and other animals.
- 24/7 level 5 systems: Underwater robots are remote controlled and it is a challenge to navigate on their own solely based on their sensory input. Above water, boats are tested in logistics but not for ocean fishing and farming operation in the ocean. No ships are leaving unsupervised. It is a challenge to develop unsupervised systems for ocean fishing and farming.
- Interactive Design of Trustful, Secure, and Ethical robotic system.

Success Metric

First viable applications in the ocean in practice are available.

Market Sectors

Replacing functions of (shell) fishing boats such as finding fish, logistics of workers, and fish from the shore to the fishing boats and offshore farming areas. Assist with the ocean farms such as shellfish farms, fish farms, and sea-weed farms as well as in biodiversity scouting.

Food Preparation and Presentation

Not considered in this document is the part of the network where agri-food products and robots are used to prepare food and meals and how to present it to humans to consume these foods. The authors have limited knowledge on these parts, but they can be added in the future.

Key Challenges for Robotics in agri-food

Introduction

In the Use Case themes dedicated challenges are mentioned that need to be addressed in the coming decade. agri-food is one of the many domains where robotics is expected to be disruptive. The complexity and variety of agri-food production systems are challenging and can serve also as a unique field lab for generic robotic challenges and related AI and Data challenges. The 2020 Strategic Research, Innovation and Deployment Agenda for the AI, Data and Robotics Partnership stresses three primary areas of synergy between Robotics with AI and Data. Firstly, that robots are significant producers of data, secondly that they rely on data and in some cases external knowledge while operating. The third and most important aspect is that Robotics rely more and more on AI technologies to achieve core functions such as perception, decision making, and interaction. Robots need AI and Data to achieve their operational objectives. Furthermore, specific learning paradigms can be studied, understood, and applied in simulated and real robotics environments. These paradigms have to do with learning variable compliance interaction tasks that humans do effortlessly every day.

To show and classify that challenges not only deal with technological challenges we will use the concept of Digital Innovation Hubs and Competence Centres that is promoted in several European projects and activities already.

Digital Innovation Hubs are **one-stop-shops** that help companies become more competitive with regard to their business/production processes, products, or services using digital technologies, by providing access to technical expertise and experimentation, so that companies can "test before invest". They also provide innovation services, such as financing advice, training, and skills development that are needed for a successful digital transformation. As proximity is considered crucial, they act as a first regional point of contact, a doorway, and strengthen the innovation ecosystem. A DIH is a regional multi-partner cooperation (including organizations such as research and technology organizations [RTOs], universities, industry associations, chambers of commerce, incubators/accelerators, regional development agencies, and vocational training institutes (Figure 3.1) and can also share strong connections with service providers outside of their region supporting companies with access to their services. Not considered in this document is the part of the network where agri-food products and robots are used to prepare food and meals and how to present it to humans to consume these foods. The authors have limited knowledge on these parts, but they can be added in the future.

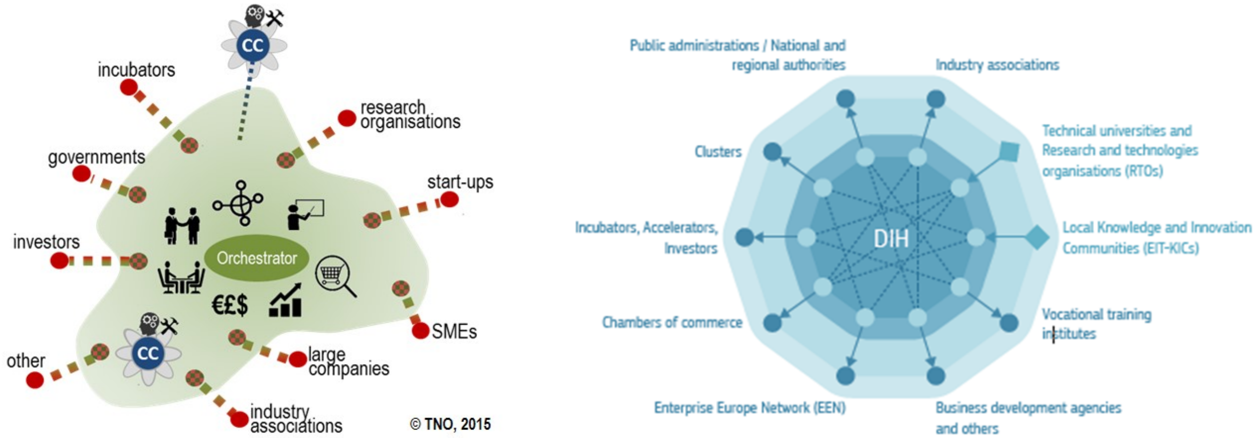


Figure 2 DIH ecosystem structure (Source: TNO)

The idea is that each DIH acts as the epicenter of a local/regional or even national **digital innovation ecosystem** able to provide access to services, facilities, and expertise of a wide range of partners (Figure 2). The aim is to ensure that the individual customers (SMEs) or the public sector get the services they need; that the target regional market segments get access to innovative, scalable solutions, and that DIHs cooperate at regional, national, and/or European level.

Figure 3 DIHs services and network collaborations (Source: DG CNECT)

Some indicative examples of services offered to SMEs by DIHs are mentioned below:

- Test before invest: Experimentation with new digital technologies – software and hardware – to understand new opportunities and return on investments, also including demonstration facilities and piloting.
- Skills and training to make the most of digital innovations: “train-the-trainer” programs, boot-camps, traineeships, exchange of curricula and training material.
- Support to find investments: access to financial institutions and investors, to get access to follow up finance to bring the results of testing and experimentation to the next phase, access to incubation & acceleration programs.
- Innovation ecosystem and networking opportunities through marketplaces and brokerage activities. The current Innovation Action that is dedicated to the concept of DIHs for Robotics in agri-food uses the following main categories for services that can be used to stimulate Industry (especially SME’s) and Digital Innovation Hubs.

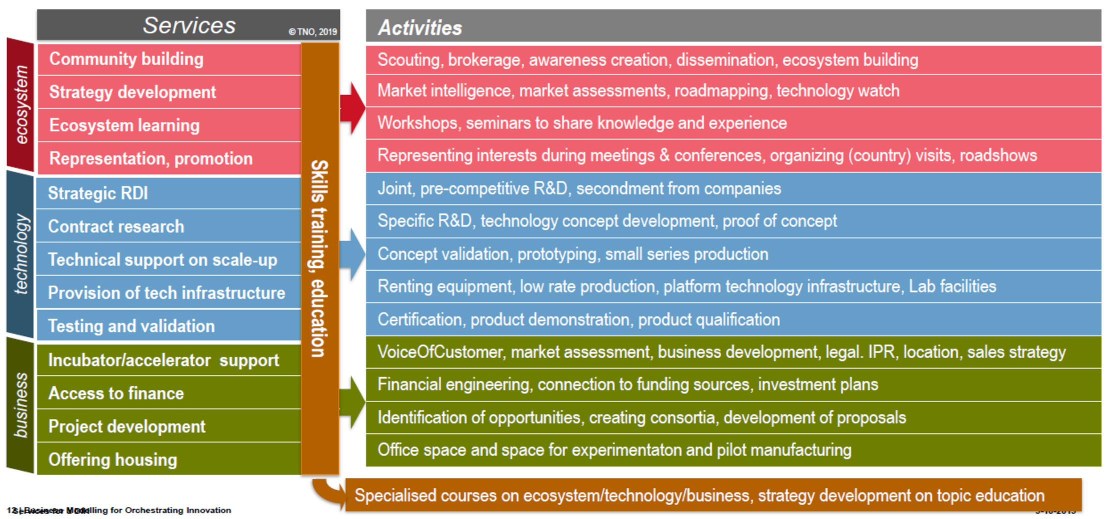


Figure 5 Services from DIH to SME

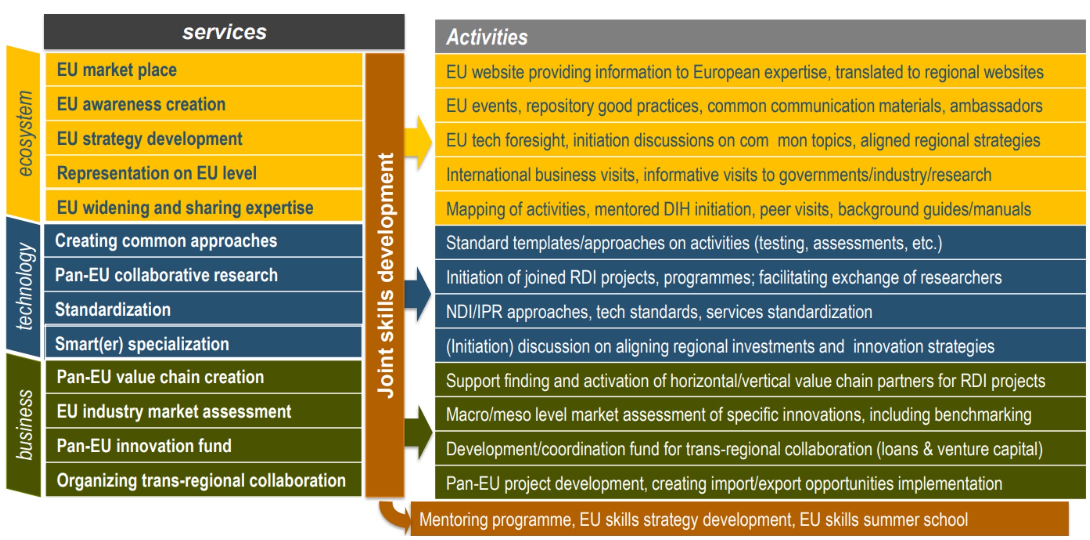


Figure 4 Services from DIH to DIH 1

Based on the assumption that DIHs will play an important role in the coming decade and that they will also influence the work on challenges we categorize the challenges for robotics in agri-food according to the following categories:

- **Technology**
  - World Modelling, Simulation, and Benchmarking.
  - Robot-to-X Interaction.
  - 24/7 Level 5 Cooperative Systems and Fleet and Swarm Management.
  - Perception in Robotics.
  - Multi-Dimensional Manipulation.
  - Interactive Design of Trustful, Safe, and Ethical robotic systems.
- **Ecosystem**
- **Business**
- **Training and Human Capital Development**

Insights for each of the categories and existing sub-categories are presented on the next pages.

Tech Challenge: World Modelling, Simulation and Benchmarking

Successful accomplishing tasks in complex, dynamic, and unstructured environments can be stimulated by having the availability of an accurate description and prediction of the environment the robot is operating in. Such a description is referred to as a world model. A world model contains positions and orientations of uniquely labeled entities in space and time and may contain semantic information referring to the particular characteristics of the individual objects, such as construction elements, plant species, or ripeness of fruit. World models are built using prior information, like CAD drawings or maps, as well as using sensor information during the actual operation of the robot, like LIDAR. World models can be used to reason about the working environment of the robot during its operation to generate for instance (active) perception strategies or plans for the motion of (parts of) the robot through the complex environment. Dynamic interactions between robot and environment, like contact forces between gripper and fruit or the impact of mobile machines and soil, can also be included. World models memorize and digitalize the environment and can be adapted during operation. The world models can also be used for simulation purposes in design processes. Then the robot can be implemented in silico. Alternatively, the model can be used to do hardware in the loop simulations.

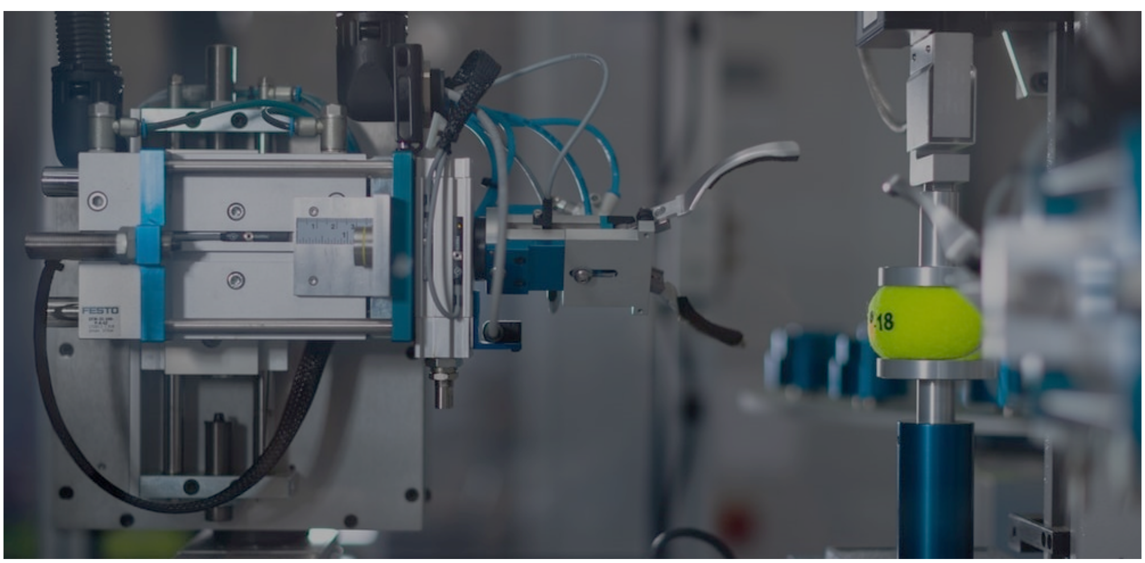
There is a strong relation between world models and Digital Twins. A digital twin is a digital replica of a living or non-living physical entity. Digital twin refers to a digital replica of potential and actual physical assets (physical twin), processes, people, places, systems, and devices that can be used for various purposes. World models also facilitate benchmarking algorithms for robot perception and action, and it is increasingly important to autonomous robotics. To go out of the laboratories and become real products, robots need benchmarks: standardized, objective ways to characterize, measure, and compare their performance in a modular and composable way. Benchmarking can be done off-line on datasets, on standardized models of real environments, or in standardized real environmental scenes.

Domain-specific challenges for robotics	Generic robotic challenges relevant for the domain
3(6,N)D modeling and simulation of species and agri-food objects	Data anchoring, i.e. creating a meaningful link between sensor data of the environment and semantically labeled objects in the world model
Modeling and simulation of soil	Data association, i.e. updating the object attributes based on measurements
Open source of agri-food basic world models to be used as 'golden standards' in benchmarking	Model-based object tracking to estimate attributes and to predict attributes of an object
	Real-time execution
	Improving predictive accuracy and speed

Tech Challenge: Robot-to-X interaction

Robotic solutions are part of a bigger system that involves robotic hardware, data gathering, AI-based reasoning, and both Human actors (that can be considered mostly as cooperative) as well as non-human actors (animals, plants, soil, that can be considered mostly as non-cooperative). Both, human actors as well as non-human actors are agents that can be a direct part of the process (for example a supervisor, a co-worker, the product) or an indirect part (for example an obstacle). The interactions between robots and those agents as wells as the sole interaction between multiple robots themselves define a challenge since this includes topological, time-based, geometric, physical, and semantic understanding, planning, scheduling, and reasoning. Closing both, the data and reasoning loop in case of sensory and modeling uncertainty in dynamic environments define a state space where current approaches will fail to provide an adequate (and safe) solution.

Domain-specific challenges for robotics	Generic robotic challenges relevant for the domain
Automated handling and manipulation of species (e.g. plants, animals) and environment (e.g. soil).	Human-robot interaction
Identify and develop human-robot co-working technology and develop fully autonomous systems with cooperative robots	Intention detection of human operators (and other humans)
Proven sense – think – act solutions of all common agricultural situations to avoid human interaction	Intuitive human-robot interaction
Human-machine co-working on the previous stages where full automation does not yet meet performance standards	System development



Tech Challenge: 24/7 Level 5 Cooperative Systems and Fleet and Swarm Management

Robot systems should be able to perform tasks 24/7 with an autonomy degree similar to those currently defined for autonomous cars (SAE Level 5). They can act fully autonomously in all conditions, even in the presence of errors or damaged sensory inputs. The tasks of such 24/7 robotic systems include for example monitoring, decision making, and action execution. Today, assistant functions/systems are available in many areas of life and agri-food. When 24/7 availability is required, also consistent knowledge of the domain is needed to reduce downtime, to schedule for (self)-maintenance, or to ensure no extra downtime for maintenance is needed at all. This also includes the coordination of diverse robotics systems, whether cooperative or non-cooperative ones. Special attention is needed for fleet management as robots become smaller, increased in numbers, and will become part of the production system. Improved decision-making processes are needed to manage such fleets of autonomous robots, ensuring both a decentralized decision-making process as well as a managed one (e.g. when a human operator needs to take over, etc). Decision-making for all steps must consider ethics, morality, and fairness to ensure an improved agri-food domain is empowered by AI-technologies at minimal risks and negative impact on labor. It is expected that hybrid systems will be developed in which humans and robots divide the work or cooperate on specific tasks. Exoskeletons are an example of very direct cooperation between a robot and a human.

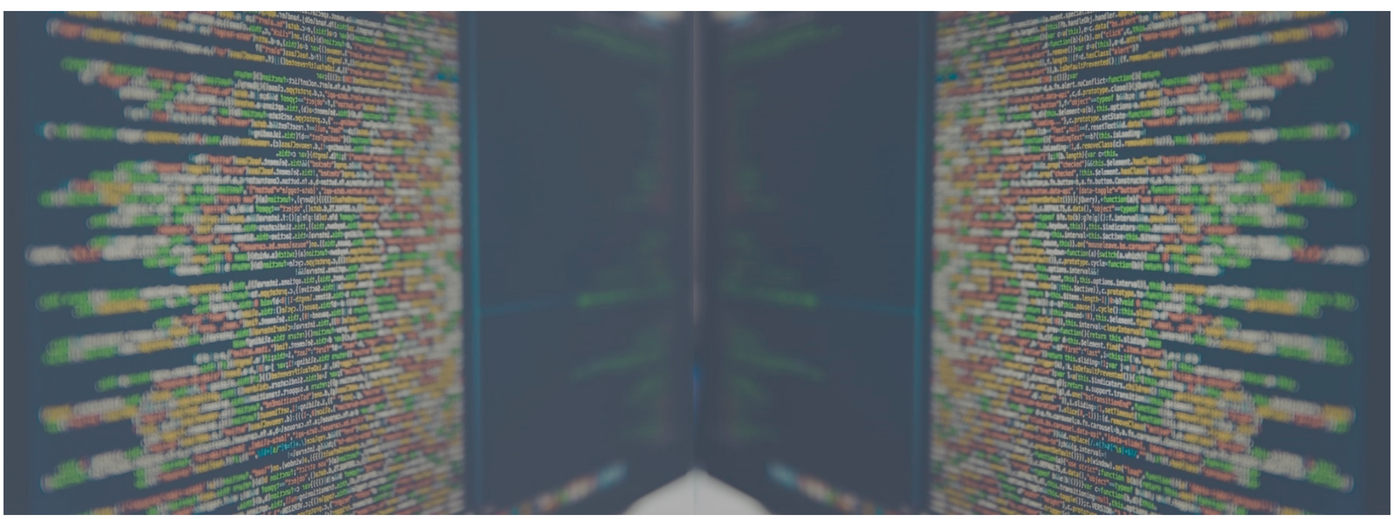
Domain-specific challenges for robotics	**Generic robotic challenges relevant for the domain**
24/7 level 5 systems for breeding allowing 24/7 monitoring and decision making without the need of human experts	Increase robot density (deployment, communication, maintenance)
Monitor and decision process to create/ monitor and optimize agri-food systems	Working in uncertain environments Risk-aware operations
Enable high-operational flexibility (fast change-over, automated track, and tracing, learning to a new situation)	Self-deployment (hands-off, “level 5 performance”, from “unboxing”: including mapping, navigation, understanding, and reporting
Heterogenous groups of robots will automatically decide what to do when by whom	Interoperability Reliable, safe, and secure communication
24/7 work in harsh environments	Design new models and tools to support cooperative behavior

Self-autonomy (no central fleet management)	Small natural robots need special (sustainable) material choice, micro (bio)sensors, 3D printing, and development of chip technology with embedded functionality
Different environmental conditions (rain, (under-)water, soil, sun, heat, cold, ...)	Multi-model sensor data integration
AI-driven data analysis and decision-making	Robust autonomy
Morality and ethical values in cooperative behavior	Automatic data analysis

Tech Challenge: Perception in Robotics

The ability to perceive the environment is key to maximize the usability of robotic systems and data-driven reasoning. To this end, iterations on three dimensions are needed, namely: the correct (physical) modeling of the environment and the assumptions taken, the sensor development and its acquisition of (raw) data, and the algorithms that will convert the sensory input (or multiple of those) into interpretable data. Only by constantly improving each category we can create (new) sensors that will allow measuring, what we need to perceive.

Domain-specific challenges for robotics	Generic robotic challenges relevant for the domain
Sensor systems robust to variation in task execution and environmental conditions as well as to object variation	New sensors / sensor system, especially mobile, lightweight (for 24/7 purposes)
Sensing of product quality while performing other tasks in parallel	Safe sensor systems (for autonomous operations)
Sensor systems able to provide localized information about the state of soil/crop/animal + AI-driven interpretation of that data	Sensor fusion and AI: needing less computation time and power -> mobile solution
Sensors able to detect organic matter for cleaning and decontamination purposes	
Sensory systems and algorithm to ensure no blind spots are left (in particular for cleaning of agri-food or machinery)	



Tech Challenge: Multi- Dimensional Manipulation

Most agri-food robots have to manipulate and/or move target objects in poorly structured environments. In agri-food systems commonly these target objects are vulnerable and difficult to reach. Effectively operating in an N-D environment is still a challenge for robots and this needs further development of knowledge and technology in various aspects, including the rapid acquisition of good representations of the N-D environment, effective translation of such information into a controlled smooth response, i.e. motion in 3D/6D workspace, without detrimental effects on target objects and environment and accounting for challenging requirements on reaction times and precision. Since operations are consecutively done on different target objects in the same environment, think of harvesting of different fruits in a crop, novel planning algorithms should account for these consecutive actions.

In the challenge multi-dimensional manipulation, the following domain-specific challenges as well as generic robotic challenges that are relevant for this domain are identified:

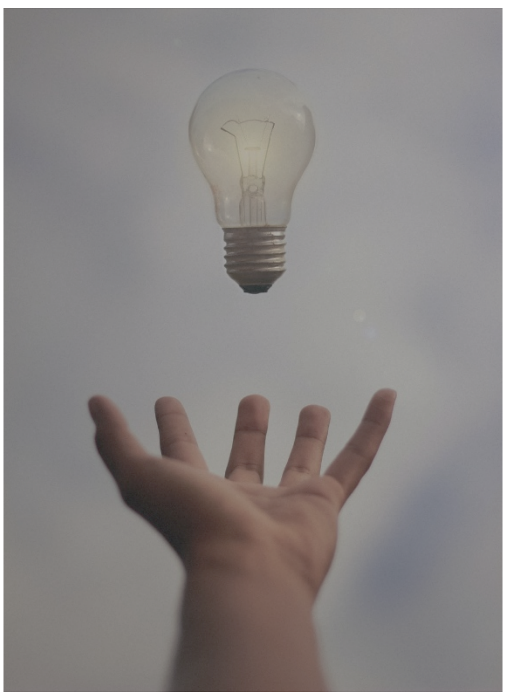
Domain-specific challenges for robotics	Generic robotic challenges relevant for the domain
Intelligent manipulation i.e. effectively moving the end-effector technology and product, in complex environments	Complex Object handling
Effective and soft gripping	Manipulation
Pick heterogeneous natural products to form a bin with high filling rates into a packing at a high filling rate	
Fast cleaning of food-contact parts to avoid cross-contamination of food	
Suitable novel or modified existing hardware for autonomous and location-specific implementation of operations like weed control, nutrient supply, etc	
Equip robots with tools to clean an environment in a sustainable way using as little water and chemicals as possible	

Tech Challenge: Interactive Design of Trustful, Safe and Ethical Robotic Systems

To increase trust in robot systems being a reliable and secure ‘partner’ in agri-food systems more attention should be paid to the design process of robot systems. The development of robot systems is not limited to technological issues. Multi-stakeholder and multi-functional perspectives, socially responsible design methods, and agile developing methods need to be aligned and further developed to be of use in (re)design of robotics systems that fit in agri-food production systems. In the design process, several aspects have to be taken into account. Trustfulness has to deal with the aspect that the users can rely on the robots, that they show predictable behavior, and that they function throughout an acceptable lifetime. In designing also this lifelong functioning and maintenance should be taken care of. Security and Safety of robots from the perspective of robots not harming their environment and from the perspective that robots cannot be intruded when connected to the digital environment. Once connected to the digital world a variety of risks occur for the robot themselves, but also for the production process they operate in. The challenge is to have a proper insight into these risks and into trustful measures to reduce these risks. When designing robotic systems also ethical issues should be taken care of. What are the consequences e.g. for jobs and remaining labor, how to deal with the welfare of the humans and animals in the environment, who is responsible for the robot, its owner, or might robots even exist independent of human owners in the future? New insights into ethical, safety, and trust issues need to be developed in a varying world of agri-food. Structured interactive design methods can benefit from developments in visualization and simulation to study the desired robot-environment system and their interactions. Humans rely very strongly on visual information. Therefore, a key challenge is to develop new visualization methods for robot systems. Can digital twins support the design and the use of robotic systems? A key question is also how and where to visualize the robotic performance. Visualization stimulated trust-building, gives insight in improving robot systems, can help to train people, and contributes to the transparency of the production network.

Domain-specific challenges for robotics	**Generic robotic challenges relevant for the domain**
Design and standardize flexible transport modalities that can easily be transported and handled by robots. Also, the climatization of these modalities is a key challenge	Operations management. World modelling The fusion of machine learning and model-based approaches
Part of this fleet management challenge is the ‘visualization’ in the decision room. Visualization forwards involved human operators but also other robot systems. How to deal with priority in rules and handling in critical situations. AR and VR might support this	Decision-support systems, decision-making Robust logistics and integration Mathematical simulator systems Simulation of Species

Get insight into specific agri-food design needs for trust, safety, acceptability, and ethics	Standards for verification, and validation Standards and certifications Robustness and reliability Mobile energy Low-energy requirements Intrinsic safety Privacy, ethics, the responsibility of robots. Improvement of social responsive design methods and integration of multi-actor processes, visualization and simulation tools Co-design and interactive design involving end-users and other stakeholders Ethical issues and questions The welfare of humans and animals



Ecosystem Challenge

The EU supports building and maintaining a network of Digital Innovation Hubs for Robotics. This pan-European network consists of local networks that function as one-stop-shops and these local networks work also cross borders to bring the robotic knowledge and contacts where needed. The challenge is to professionalize this agri-food robotic network, to make it sustainable, and to connect it to other robotic, AI, and data networks in and outside the agri-food domain.

- **Exporting / Importing excellence**: Based on complementary competence and infrastructure, DIHs could export their specialization to SMEs to the other Member States, in the form of opening up their facilities and knowledge to clients outside of their region. Vice versa, if a DIH misses certain expertise or facilities to support its regional clients they can ask the support of other DIHs who would have this expertise, and that way import expertise offered by other DIHs. This could be done on an individual basis, starting from the needs of individual customers, but also in a more proactive way where several hubs together combine their knowledge and facilities to develop common services for their stakeholders.

- **Connecting ecosystems**: Just like DIHs at the local level build ecosystems by bringing into contact actors along the value chain to develop innovations, at a European level several hubs can connect different ecosystems by identifying innovation opportunities for users and suppliers coming from different regions. This will help SMEs expand and tap into other markets, develop EU value chains, create new business opportunities for companies or help commercialize earlier innovation experiments or pilots. Also, other types of common interest projects (e.g. open platforms, standards, standardized services, shared infrastructure, etc.) in collaboration with companies and stakeholders from the different regions can connect ecosystems and will help avoid unnecessary duplication of investment or give access to infrastructure at a lower cost.The ability to perceive the environment is key to maximize the usability of robotic systems and data-driven reasoning. To this end, iterations on three dimensions are needed, namely: the correct (physical) modeling of the environment and the assumptions taken, the sensor development and its acquisition of (raw) data, and the algorithms that will convert the sensory input (or multiple of those) into interpretable data. Only by constantly improving each category we can create (new) sensors that will allow measuring, what we need to perceive.

Domain-specific challenges for robotics	Generic robotic challenges relevant for the domain
There is a need for market intelligence and insight into market developments. Explore the role of pre-competitive market information on Robotics in agri-food Make the agROBOfood network sustainable Develop co-creation tools to work remotely on robotic developments	For the robotic challenges of transport in the open road (train, ship) infrastructure we have to rely on other domains

Business and Economics Challenge

The business in the agricultural robotics market differs significantly from the industrial robotics market. This holds for structure, maturity, and thus for market size. Since agricultural robots are not established yet, most enterprises are on their way to open up or approach this small market. Various strategies can be seen. (1) Large technology providers, already established in other industries identified agriculture as an attractive (technological, financial) domain. Already existing technology (i.e. navigation, control systems, sensors) is adapted to agricultural processes. (2) Technology-oriented start-ups enter the market with often small, specialized robots or innovative technologies to be applied in the agricultural domain. (3) Manufacturers of agricultural machines with a long tradition of mechanical engineering and thus sometimes appear reluctant, if it comes to robotic systems. Here two different approaches can be seen: (3a) Seamless evolution from highly automated machines towards autonomous systems. (3b) Development of new systems, preferably small platforms, from scratch by using knowledge from traditional machines. They behave like start-ups embedded in larger businesses.

Robotic business in the agricultural domain is in general much more challenging than in the industrial domain. Reasons for that are not new at all and could also be seen in the wave of precision farming technologies, where robotics only is the next step. The environment is highly dynamic; thus only advanced robotic solutions create added value. Furthermore, agricultural investments are planned with long pay-off periods and hence, it must be shown that robotic solutions indeed provide a cost-benefit.

Robots interact with an old fashion, mixed environment. Interaction between old and new systems raises new issues (control, safety). Compared with manufacturing industries, machines are often used in different contexts, i.e. tractor & implement (multipurpose). Every reconfiguration creates a new situation to be managed by a robotic system. Seasonality and family organization of the domain require farmers and contractors to be generalists. This conflicts directly with the qualification profiles required for robot implementation and operation. This may lead to new business models, where machines are operated by third parties (contractor 4.0). The ability to perceive the environment is key to maximize the usability of robotic systems and data-driven reasoning. To this end, iterations on three dimensions are needed, namely: the correct (physical) modeling of the environment and the assumptions taken, the sensor development and its acquisition of (raw) data, and the algorithms that will convert the sensory input (or multiple of those) into interpretable data. Only by constantly improving each category we can create (new) sensors that will allow measuring, what we need to perceive.

Domain-specific challenges for robotics	**Generic robotic challenges relevant for the domain**
Environment for robotic applications is challenging	Robots need to be multipurpose but are usually specialized
Low division of labor requires generalists, robots require specialists	Autonomous and mobile systems are challenging in terms of safety
Difficulties to scale-up compared to manufacture	

Training and Human Capital Development Challenge

In the SRIDA on AI, Data and Robotics Partnership [4] it is recognized that training, education, and development of human capital is crucial also for Robotic developments. Robotics will replace physical labor in a lot of Agri-food production processes. The challenge will be to develop robotic systems that can be understood by the users. The users and developers have to be trained, especially in the context of all kinds of new and other jobs. These new jobs should also become attractive and people should be educated to work in these jobs. The biggest risk is that we cannot find people to do these new jobs in designing, fabricating, selling, and servicing robotic systems. Another challenge is how to connect the needs for life-long learning and the growth of the development in Robotics, AI, and Big Data. New training and education concepts need to be developed to connect the technological, analytical, and agri-food insights. This multidisciplinary approach needs new roles and attitudes from trainers, vocational institutes, and industry. Skills, right-skilling, training, including of teachers, adapted curricula in education and -vocational- training are vital for rolling out digitalization across Europe by creating competence, confidence, and trust, so that AI, robotics, and data can fully unleash their potential to the good in a competitive Europe.

Domain-specific challenges for robotics	**Generic robotic challenges relevant for the domain**
Attract and involve people with technological, analytical, robotic, business, legal and social backgrounds to work on agri-food topics	Enhance skill-mix for a broad range of technologies integrated within robotic systems teach awareness of robotics and the issues that physical and psychological interaction raises
Attract and involve agri-food people to become more aware of and integrate Robotics into their activities to achieve proficiency	Ensure that all stakeholders along the value chain have the understanding and skills to work with AI, Data and Robotics enabled systems, in the workplace, in the home, and online
Integrate lifelong learning in a triple helix environment and develop new didactic approaches	Promote equality and diversity within the current and future workforce to ensure diversity and balance in the educational opportunities that drive the skill pipeline
Need for an infrastructure for practical training with access to robotics and demonstration farms where end-users (farmers) can meet, exchange best practices, and are trained in digital skills	Work towards the alignment of curricula and training prograı AI, Data, and Robotics professionals with industry needs
Set up a pan-European program for adoption of robotic technologies in agri-food	Establish AI, data, and robotics skills recognition, both technical and non-technical, by certification mechanisms for courses, profes-sional, vocational training, and self-learning

Develop simulations, model-based approaches, and digital twin thinking that can be used in training	Development of complementary short-courses related to AI, data, and robotics aimed at decision-makers in industry and public administration, and those wishing to upgrade, enhance or acquire these skills Support for secondary, or earlier, education and adult learning to cover STEM skills including ethics, social, and the business aspects of AI, Data, and Robotics together with the changing nature of work Talent retention, scouting, training, exchange within the EU and between aca

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Acknowledgments

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- EU-Robotics coordinators
- EU-Robotics topic group agricultural robotics members
- agROBOfood Project Steering Group, Industrial Advisory Board, Project Officer
- EU projects RODIN, Smart Agri Hubs, ERANET ICT Agri, OPEN DEI, ATI
- Representing organizations CEMA, AEF, Animal Task Force, Manufacture, High Tech NL
- Wageningen Agro Food Robotics and Wageningen Data Competence Centre

The authors thank these organizations for their support and responses. Of course, we could not cover all topics in detail. Since the field of Robotics, AI and Data is developing quickly we see this document also as a dynamic one, with having the ability in the coming years to be adapted to new insights. Nevertheless, the authors are convinced that the content of this agenda is very challenging and they hope that it will be used to guide and/or strengthen activities that stimulate uptake of robotics in the agri-food production domain.