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Advances in agri-food robotics

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Advances in the use of robotics in livestock production

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1 Introduction and main drivers for livestock robotics

The use of robotics in livestock production dates back to the 1980s. One of the first robots to be developed was for shearing sheep (Trevelyan, 1989; Trevelyan, 1987). More recent developments in robotics have been made in aquaculture (Antonucci and Costa, 2020; Wu et al., 2022; Yue and Shen, 2022). This chapter presents recent advances in the development and use of robotic solutions in various livestock farming systems, focusing on dairy, pig and poultry production. These three livestock sectors have different characteristics in terms of the general design of the farming and housing systems used. Moreover, there can be significant diversity within each sector, which has both pros and cons when it comes to the use of robotics. These aspects will be discussed in this chapter in terms of their relationship with robotic applications.

This chapter is inspired by two quotes related to the field of robotics: *'Robots create value by performing physical tasks that people cannot, should not, or will not do'* and *'A robot is a programmable machine capable of carrying out a physical task or a complex series of actions automatically'* (Zillner et al., 2020). Given the level of drudgery involved in agricultural tasks, it is easy to see the potential applications of robotics. However, these practical definitions leave room for scientific and practical disputes over what falls under the umbrella of

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robotics. When it comes to livestock farming, for example, robotics may fall within the field of precision livestock farming (PLF), although recent practical developments in the PLF area lack robotic-based innovations (Banhazi et al., 2022). Given that robotics and PLF are based on sensor data and require a pre-defined 'world' to operate in, Section 2 will attempt to connect robotics to the concept of PLF.

It is our belief that livestock farming systems can be strengthened by integrating robotics into PLF and that robotic-based PLF solutions should be adopted and discussed in a broader context. In this discussion, awareness should be on the main driving factors for innovation. To be able to innovate with cutting-edge technology is essential.

Based on experience, and looking at previous significant innovations, Lokhorst (2018) identified developments in labor, technology, society, market, legislation and science as the key drivers for innovation in the livestock sector. Reduction in labor is directly connected to cost savings. Reduction in labor does not mean that humans will work less, but that efficiency is improved so they can produce more in the available time. This makes living and working more fun and efficient. In this respect, developments in technology can have a significant impact. Developments in information and computer technologies (ICTs) are predicted regularly by Gartner (www.gartner.com) and are used by many organizations for strategic investments. Conolly (2022) indicates that developments in ICT have the capacity to change the agricultural sector. Drones, robots, sensors, 3D printing, the internet of things (IoT), artificial intelligence (AI), virtual reality (VR), augmented reality (AR) and Blockchain will find their way into the smart farming domain. Professionals in the livestock sector must be aware of these emerging technologies and judge them on their usability for these innovations to be successful in the sector.

Wider discussions around outdoor cow grazing, or the size of mega-farms and the use of robotics, to name just two, can also drive innovation. Food producers are continuously developing new products for their customers. Markets are heavily influenced by food trends and transparency in the food chain has become an extremely important societal issue. Legislation can limit undesirable production volumes and emissions of greenhouse gases. In itself, this drives innovation, as people find smarter ways to work within the limits of the legislation. Understanding the science behind how and why processes and behaviors in the food production chain work can also lead to innovation. In conclusion, there are many aspects that stimulate innovation in smart farming.

An awareness of what is happening in society, the market, science and legislation assists in the development of robotics solutions (technological) to make living and working (labor) on livestock farming systems more effective and efficient. The main challenges we face are:

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- a lack of sufficient and qualified labor due to farmer ageing, waning interest from younger workers and restrictions on migrant workers;
- scale of economics due to the level of investment needed for environment, welfare, health, biodiversity and quality of products, which has led to fewer farms with a higher number of animals; and
- adoption of green deals and farm-to-fork strategies with more emphasis on climate, circular and biodiversity in the complexity and variety of livestock farming systems.

A recent EU report ('European Robotics in agri-food Production: Opportunities and Challenges', Sander et al., 2021) identified a 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'. Its mission is 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'. In this chapter, we will look at several specific challenges in the livestock sector that can be addressed using robotic technology.

2 The role of robotics in precision livestock farming

The concept of PLF is being developed in parallel with that of precision agriculture (PA). PLF aims to '*manage livestock farming by continuous real-time monitoring of health, welfare, production, reproduction and environmental impact*' (Berckmans, 2008, 2017). The International Society for Precision Agriculture (ISPA) defines PA as '*Precision Agriculture is a management strategy that gathers, processes and analyses temporal, spatial and individual data and combines it with other information to support management decisions according to estimated* variability *for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production'*.

This definition was formulated and agreed via an open and thorough process and also covers PLF.

In *Introduction to Smart Dairy Farming*, Lokhorst (2018) highlights the main dilemmas and issues involved in the application of precision farming to dairy production. To deal with the inter- and intra-variability of dairy farms, management tools need to be adaptive in order to support daily management of farmers and their advisors/service providers. Connected to the concept of *Livestock Farming With Care* (Scholten et al., 2013) and the central position of the farmer, PLF can be internalized if a farmer is willing to accept the following statement:

> As a FARMER I will guarantee that every SUBJECT OF INTEREST gets the CARE it requires at the right moment, in the right place, and to the right extent, and I am TRANSPARENT about this.

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The ‘subjects of interest’ are the most granular units in the process that can be controlled in farm situations. For dairy farming, this might be the individual cow or calf, as well as parcels of land. For pig and poultry farmers, this might be a group in a pen or barn, or in the case of breeding farms, it could be individual sows. The choice of the subject of interest depends on the farm and the farmer.

To support a farmer in their daily management, the implementation of PLF should align with the farm’s organizational structure. When organizing tasks on the farm, farmers have the following options:

- Carrying out the work independently, with the farmer and their family members and friends sharing the workload;
- Employing animal caretakers to help manage daily operations;
- Engaging the services of specific providers and experts (e.g. contractors, veterinarians, hoof trimmers, advisors and so on); and
- Automation through the use of robots.

In practice, a combination of the above will be used, depending on the farmer’s preference and ability to organize and coordinate these basic labor resources.

PLF involves continuous measurements with sensors and software applications acting as extra eyes, ears and noses, and models as extra brains to continuously interpret the context and status of the subjects of interest and translate these findings into concrete actions that can be performed by the available labor resources. This is part of a system and control approach. Digital data are key in this respect and need to be transparent.

In practice, robotics and PLF are mostly treated as separate concepts. We are of the belief that both should be integrated and can strengthen one another. Figure 1 shows how this concept might work. In the center, the circle has to come from data, through information and knowledge to data-driven actions. There should always be a process goal that creates awareness of what should be monitored or controlled. Even routine tasks have this at the start. Achieving this integration involves consideration of a number of key concepts.

2.1 Standard operating procedures

The concept of working with standard operating procedures (SOPs) is focused on instructing farm employees. A SOP describes work instructions. For the subject of interest (e.g. a particular activity), who should do what, when, where and how needs to be accurately and exactly described (Wind et al., 2017).

Working with protocols can be beneficial, making farms more competitive and safer. In the case of a sudden reduction in the labor force, tasks can be taken on more easily by someone else. SOP protocols help encourage the farmer to

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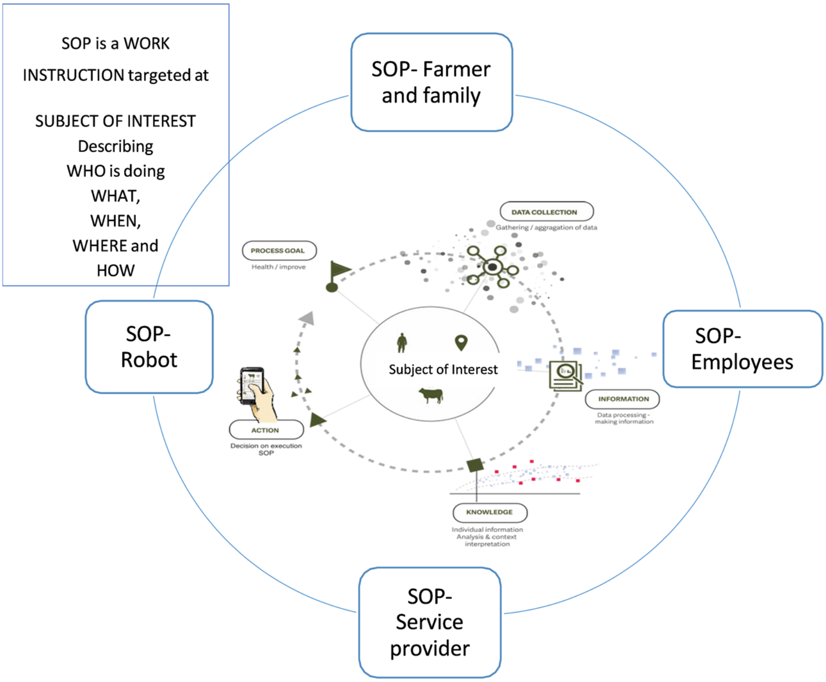

Figure 1 SOPs connecting the cycle from data to action, for different labor resources, including robots.

design farm processes in a more optimal and structural way, in accordance with their expectations and references. SOPs should not just be written instructions but also made available in electronic form. Both humans and machines can be targeted. Naturally, the instructions will differ according to the labor resource, but it is worthwhile to discover how different SOPs can be developed and contribute to greater transparency and interoperability.

While Fig. 1 demonstrates how robotics can perform different parts of the cycle of data collection to action as seen with PLF, it is clear there are core processes in the design, development and maintenance of robotic systems that are not commonly seen in the PLF framework.

Figure 2 adapts the work of Porter and Heppelman (2014) to show the increasing complexity that connects the different aspects that must be managed. With robotics, we are now at Product level 4 (Product system) and the next step will be to reach the 'system of systems' level, involving robots. To be able to reach that, the following aspects are important in the (re)design of robotic systems.

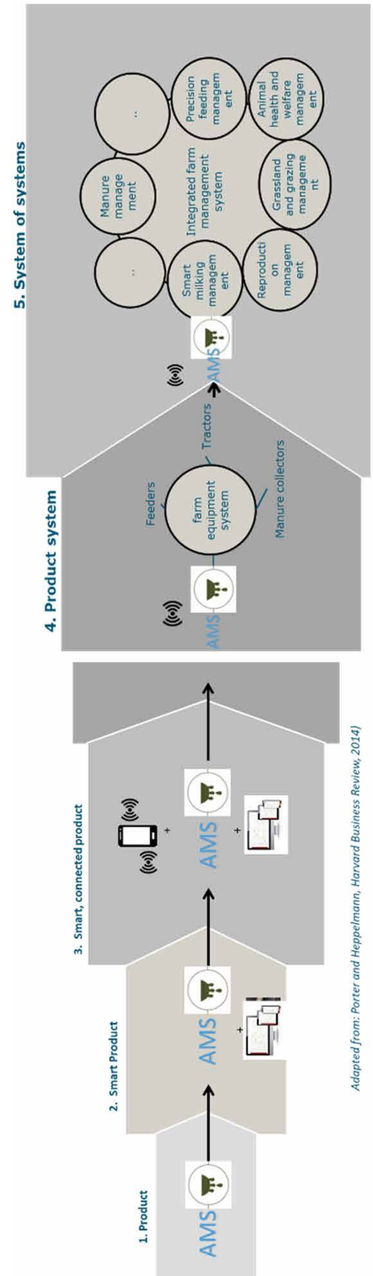

Figure 2 Redefinition of industrial boundaries. Source: Adapted from: Porter and Heppelman (2014).

2.2 Systems engineering

Systems engineering-oriented frameworks are a core component of robotic applications, and livestock robotics should be no different. The starting point is the implementation of methods such as quality functional design (QFD) to reveal the requirements of the system and provide suggestions for services. These can be further analyzed and translated into technical system requirements. *Software and Hardware Architectural Design Processes* should then be employed to ensure the robot complies with all requirements and an *Implementation Process* is needed to produce the specified system units, starting with the most essential sub-systems (e.g. milking, cleaning and monitoring). This is typically followed by an *Integration Process* in which we will integrate the sub-systems and sensing units according to the architecture. Finally, a *Validation Process* guarantees that the services provided by the robot align with what was initially specified by the prospective users. The *Demonstration Process* verifies if the robot will deliver the services in practical application.

2.3 Architecture

Robotic software applications such as robotic operating systems (ROSs) architecture, which is a cross-platform architecture that is required to build a solution on in order to run different robotic operations.

2.4 Systems integration

Achieving interoperability of systems from different original equipment manufacturer is essential to make cost-effective robotic applications. Exploiting methods and tools to implement this will enable slight changes to the specification. Core to this is the definition of standards, in which appropriate normative standards will be identified and considered within the design, implementation and evaluation phases.

2.5 System of systems

Robots can be integrated within the complete ICT system of the overall farming system, utilizing their capacity to interact with a diverse range of devices, from actuators of other control systems to tablets and smartphones. Such integration can enable smooth running of the system and contribute to continual farm process improvement.

2.6 Modeling and knowledge engineering

Information derived from a robotic system can be embellished and integrated with other available information to assist in farm model-based management decision-making. Big Data approaches employ techniques to continuously update the resolution of the models based on captured data. Data from the robotic platforms can support simulation in the decision-making loop, ranging from early warnings of outbreak of diseases to signaling the most appropriate times to carry out an operation on the farm, such as cleaning, animal removal, etc.

2.7 Quality validation, maintenance and documentation

Appropriate, statistically supported procedures are identified and applied to assure quality validation of systems performance and services, coupled with supporting maintenance procedures and documentation.

The following section provides examples of robotic developments in three different livestock sectors to show where robotics have already been successfully applied and their current focus. These developments illustrate the advances in robotic solutions in research and in the market.

3 Examples of robotic development: poultry

Poultry production is a specialized sector that produces approximately 100 million tons of meat (i.e. broiler production) every year globally. Production of broilers and eggs is a low margin business that requires large-scale production, consisting of sheds housing tens of thousands of birds. Modern poultry breeds are advanced to maximize feed conversion efficiency, with the result that chickens are one of the most efficient feed-converting animals in modern agriculture. Typically, they grow from under 50 g to as much as 2.2 kg in a 5- to 6-week cycle. They are, however, very delicate animals and can easily become stressed by their living environment. As such, accurate control of their growing environment is essential.

Poultry farmers determine what management actions to carry out based on their assessment of the living environment and chicken behavior to determine if they are healthy. Correct and timely decisions deliver improved chicken welfare, better use of feed, better health and less waste, resulting in increased income. Poultry farmers therefore depend on a mixture of intuition and experience, supplemented by automatic monitoring and control systems. A fully fledged PLF solution can offer continuous measurements, utilizing data-driven decision-making. The poultry sector has seen remarkable progression in

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the application of ICT. Use of climate and light control computers is common and there are many options on the market. Research into real-time monitoring of animals has made significant progress and various techniques are being implemented and commercialized.

Sensor systems that continuously and automatically monitor the growth and welfare of birds are now available and provide farmers with support to manage their animals remotely (even at individual animal level) (Sluis et al., 2022). Bird growth is measured by the use of automatic weighing scales and, more recently, by camera technology and sound information (Fontana et al., 2017). Welfare is more complicated and as such is not measured, but indirect parameters such as activity, animal distribution across the floor and drinking and eating behavior can be observed using commercial tools. While this type of ICT application is part of PLF, exploiting robotics to remove simple, monotonous tasks from the farmer while guaranteeing a return on investment can make a significant impact. By so doing, farmers can focus on other aspects of their business, as well as improving standards of care for their animals, leading to better productivity, health and welfare and thus an economically viable business. Through automation, the role of the stock person can change, as opposed to being reduced, as robots will allow time to be used differently. There is no doubt that robotics can be an enabler for a more productive sustainable future for poultry production.

The field of robotics is already infiltrating the poultry sector. One such example in the modern cage egg industry is the use of integrated conveyor belts to collect and transport eggs to the packing room. Conveyor belts eliminate the need to handle the eggs manually, which is especially pertinent in modern sheds with tiered cages. Egg collection via conveyor belts also reduces occupational health and safety (OH&S) risks associated with manual egg collection at height and under low levels of illumination. Other areas of application have occurred in recent years, such as the introduction of autonomous robotic vehicles that move throughout the poultry house, performing a number of tasks such as egg collection from the floor (Vroegindeweij et al., 2018) and litter management (Elijah et al., 2022). Certain key developments can have an immediate impact on the poultry industry in the following ways.

3.1 Dead bird detection

As part of daily inspection rounds, broiler farmers are required to remove dead birds from the buildings, which is not a pleasant task. Moreover, it is fraught with risk of disease control and biosecurity issues as the farmer moves between houses. The potential to automate dead-bird detection and possibly even removal from the building can be seen in the development of robotic technologies (e.g. Chickenboy ('Poultry farming: The robots are coming', 2018) currently on the market. Actual bird removal is undergoing research with many researchers proposing solutions, albeit under controlled conditions.

3.2 Litter quality monitoring

Farmers must continuously monitor litter quality in the house, as moist poultry litter is susceptible to crusting, which prevents moisture from penetrating the litter, making it slippery and uncomfortable for the birds. Poor litter quality is the primary cause of podo-dermatitis outbreaks. Moreover, nipple drinkers regularly block, and the resulting spillages cause significant deterioration in litter quality. By the time it is brought to the attention of the farmer, very often a 'dig-out' of the litter is required. Autonomous litter quality sampling is therefore a highly desirable scenario. Examples of prototypes include the Spoutnic ('Spoutnic, le robot de ponte qui limite les pertes', 2019) and the FloxLitterBox (Elijah et al., 2022).

3.3 Abnormal behavior of broiler chickens

This is an important welfare indicator, currently measured by 'gait scoring' via human observation. While new techniques such as optical flow are being studied by researchers, there is no suitable commercial system to date. The key is that the observations need to happen close to ground level, but accurate assessment of the birds is difficult without removing the birds from the building. The potential for robotics to monitor bird movement has been demonstrated by Demmers et al. (2018) at the Royal Veterinary College, who have developed a device to measure bird behavior.

4 Examples of robotic development: pig production

The application of PLF technologies in the pig sector has been the subject of research for many years. Key elements of PLF include identification of the animal via electronic identification (e-ID) or radio frequency identification (RFID) followed by automatic monitoring of parameters including growth, through the use of weighing platforms and camera technology (also known as visual image analysis – VIA), which exploits the strong correlation between the live weight and the area of pigs in plain view (Schofield et al., 1999). Another example includes a robotic system capable of placing a sensor in contact with any one of a number of pre-determined positions on the body of a loosely constrained live animal (Frost et al., 2000), the use of multiple sensors to monitor pig health and welfare (Wang et al., 2022) and the design of an intelligent monitoring system for pig health (Yanchang et al., 2021). There have also been developments in robotic solutions. Some of the technologies are highlighted next.

4.1 Bedding distribution

As with dairy production, various robotic solutions in the pig sector are utilized to provide the animals with bedding material. This is not a highly sophisticated technology and works without the need for environmental perception to control its actuation (spreading the straw). The greatest level of application of such technology exists in countries such as Denmark where the need for straw

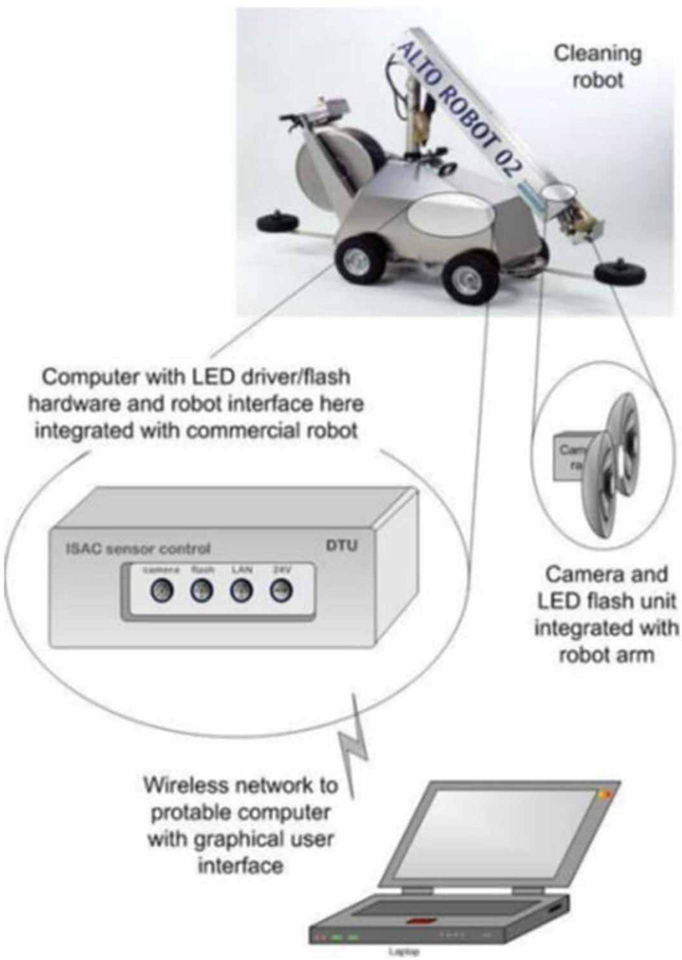

Figure 3 Overview of the novel pig building-cleaning robot by Nil Axel et al. (2005).

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(or other fibrous materials) to be available to pigs is set out by legislation. As far back as 2008, Wattagnet.com highlighted a simple robotic solution in which a straw distribution unit is transported throughout a pig house via a fixed rail system installed in the building (https://www.wattagnet.com/articles/902-robot-takes-the-strain-out-of-strawing).

4.2 Cleaning

Another area of interest is barn cleaning via a robot equipped with power washing equipment. A rationale behind using robotic applications for cleaning pig houses is the significant labor required for this repetitive, unpleasant, but highly necessary job (Lofqnvust, 2014). As with the bedding robot, these technologies function quite simply. The level of perception is limited to halting the robot when it gets close to a wall. These robots also emerged in early 2000 and are currently used in large-scale pig production sites. One of the early cleaning systems was announced in 2004 (https://www.pigprogress.net/home/simple-to-operate-but-technically-advanced/). Current building cleaning robots are not efficient in their use of water, leading to a high risk of wastage (Nielsen et al., 2012). This has been reported by some as the main reason these robots are only utilized on 60–70% of pig farms (Gjødesen, 2007).

Nils Axel et al. (2005) carried out research to improve the performance of these devices, in order to develop a 'cleanliness sensor', adding functionality to the motion controller to enable it to determine the level of cleanliness when executing its cleaning plan (Fig. 3). Further development of the water application solution has been carried out by Nielsen et al. (2012).

4.3 Precision feeding

Robotic technologies with more sophisticated functions are also undergoing research. One such application is precision feeding. Providing a diet that meets the necessary nutrient requirements without any spillage or over-consumption is one of the most important elements for economic success, especially considering that feed represents 65–75% of total production costs. Feed costs can be reduced by taking into account the variation in nutrient needs between animals, as opposed to current practice in which the nutrients supplied are based on the average of a group. Due to the variation in nutrient requirements and growth potential, not all pigs exhibit the same response to certain nutrients. The growth potential of each pig is partly determined by factors such as gender and genetics, which do not change during the fattening period but depend to a large extent on varying components such as supplied feed components, the physical and social micro-environment of each animal, their health and animal welfare.

In practice, fattening pigs are fed as a group. With advancements in technology (including electronic animal identification, weight, health status, etc.) it has become possible and affordable to feed group-housed fattening pigs individually. The idea of precision feeding for pigs is not completely new. The benefits of nutrient efficiency are mentioned in the literature (Pomar and Remus, 2019) but to date have only been demonstrated through simulation models, never in practical applications.

Relatively few applications related to the dynamic precision feeding of fattening pigs have been investigated. One of the current concepts consists of feeding meat pigs according to individual lysine requirements (Pomar and Remus, 2019). A mechanistic-empirical model for the real-time estimation of individual lysine requirements was used by Hauschild et al. (2012). After estimating the lysine requirement for maintenance, the optimal lysine concentration of the feed was determined. Pigs received feed through an individual feeding system (Automatic and Intelligent Precision Feeder) that consisted of an Archimedes transport screw mixing up to four different feeds in the desired ratio (Pomar et al., 2011). After the head of the pig appears in the feeding system, the pig is recognized and an amount of feed is delivered that meets the specific lysine requirements of the animal, determined by the mechanistic-empirical model (Hauschild et al., 2012). This method of feeding resulted in a 27% decrease in lysine intake and a 22% and 27% reduction in nitrogen and phosphorous excretion, respectively, compared to three-phase feeding.

In group housing systems for sows, the use of electronic feeders has become a standard practice. The ability to feed each individual sow to her unique needs was recognized two decades ago. Use of sorting systems also depend on the type of housing systems. In group housing systems for fattening pigs and sows, sorting systems can be used.

The research clearly demonstrates the utility of precision feeding techniques by switching from a pre-determined feed composition for an entire group of pigs to the real-time determination of individual needs to achieve a particular goal. Although weight gain and backfat thickness are important parameters in pig production, the pig farmer needs to know how much a finisher produces in net terms.

5 Examples of robotic development: dairy

In this section, we offer insight into the current state of development (and use) in professional managed dairy farms. Milking robots for cows were one of the first agricultural robots to be commercialized and appear to be most developed. Development started more than 40 years ago and a thriving professional market now exists, with robot providers including companies such as Lely, DeLaval, GEA,

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Boumatic, Fullwood and Westfalia Surge. Sharipov et al. (2021) provide a historic overview and classification. The main reason for this successful development and its impressive penetration into the market (https://www.researchdive.com/8651/milking-robots-market) is reduction of labor on dairy farms of all sizes, allowing a more flexible lifestyle for farmers (Rodenburg, 2017). Robotic milking is a very good alternative for farms up to 250 cows, but recently robotic milking has also been applied on bigger farms. As current milking robots are reliable, promote excellent cow care and allow farmers to do other farm or off-farm work, the use of robotic milkers will continue to grow on farms in the developed world. The market for robotic milking systems is expected to rise from US$1.25 billion in 2019 to US$2.94 billion by the end of 2027 (https://www.dairyglobal.net/industry-and-markets/smart-farming/robotic-milkers-where-we-are-and-where-were-going/).

5.1 Feeding

The use of robotic solutions for feeding dairy cows depends on the different feed types. Concentrate feeders have been introduced alongside milking robots, both using electronic identification of the cows. Concentrate feeders are used widely in practice. Several attempts have been made to robotize roughage feeding in the barn but robot roughage feeders such as the Mollerup feeding system (Patent # 10 660 307), which feeds individual cows, have not yet succeeded. Only in such experimental stations as the Hokofarm RIC are such methods used. Nevertheless, there have been attempts to robotize the feeding of roughage to production groups in front of the feeding gates. Trioliet and Lely are active in this market and have put various robotic products on the market. Related to this is the rapid development of feed pushers, which have the task of pushing roughage feed towards the feeding fence for the cows to easily eat. By so doing, the idea is that feed intake is stimulated. Several companies deliver such feed pushers and it can be seen as a silent success in the market. Lely introduced the fresh grass concept in 2020 and developed the Lely Exos to harvest fresh grass and bring it directly to the feed alley. This concept needs to be further developed and tested. However, cows themselves are good harvesters of fresh grass.

To support grazing, two robotic developments should be mentioned. One is the development of sorting gates between the barn and the parcels of land to prove that cows are outside in the field for a certain period of time, assuming that they graze. This has become part of certain product and marketing developments. The second tool to support grazing is the development of virtual fences or moving wired fences, the latter of which began more than 20 years ago and is still not implemented in the field (Butler et al., 2006), (nn, 2021), (Comis, 2000; Umstatter et al., 2015). Regarding feed types, we also must consider the upcoming use of feed additives, which improve the health and resilience of the cows as well as reduce emissions such as methane. Current feeding robots dispense the additives either to individuals (using the concept of concentrate feeders) or to groups. The final feeding category in which we are seeing an increase in robotics is the feeding of milk to calves. Many companies (GEA, Forster, Lely, DeLaval) and products have been developed and their use in practice is rising. However, using robotics to feed cows until they give birth to their first calf is not yet fully developed. In addition, the feeding/dispensing of water is not yet supported by robots.

5.2 Monitoring and management

The monitoring of cows has witnessed many developments in recent years. Observing cows can be highly labor-intensive, especially when the group size grows. Farms consist of multiple barns with separate compartments and require round-the-clock observation. The most effective and widely accepted measurements are those made in the milking robot/parlor, consisting of milk quantity, cell count, milk conductivity, fat percentage, protein percentage and timely detection of estrous cycles. Due to improvements in sensor quality, accuracy and longevity, as well as the capability of the IoT, the remote acquisition of activity data has become extremely successful. These technological opportunities have driven the development of a variety of new sensor and monitoring systems to observe characteristics related to cow behavior, health and welfare (Mottram, 2016; Rutten et al., 2013). The website http://www.koesensor.be/ provides an overview of available sensors in the dairy sector, such as measuring the weight and body condition of animals. This is essential at all life stages, but to date has had limited use when integrated with milking robots. Even following decades of experimentation, the use of weighing platforms has yet to reach practical mass adoption. However, most of these products and services still face challenges in the market. A lack of trust by farmers, in addition to a limited proven business model and interoperability, all hinder mass uptake. In the coming years, some of these solutions will be integrated in farming systems, especially those that focus on early disease detection and those capable of measuring and verifying that farm (and cow) level emissions and welfare are managed properly.

A relatively new field is the use of drones to observe and count cows in pasture environments (Yousefi et al., 2022) provide a useful overview of the underlying technology and data analysis.

To guide cows inside the barn, the use of selection gates is widespread. Most are integrated in the design of the milking parlor, their main functions being to separate cows that require extra care or cows that are not allowed to enter the milking robot. The development of smart feeding fences in the barn appears to have stopped. Where used, it is a mechanical solution that works well. Today's robots do not yet support catching and driving specific cows, e.g. to guide a cow to be milked or to be inseminated. Over the last decade, tools have been developed to use location information for the cows. GEA, SmartBow and NEDAP have each introduced their own location awareness systems, but uptake in the market remains low and the task is till carried out by humans.

5.3 Cleaning

Using robots to treat cows is limited to the cleaning of the udder in the milking robots and automatic brushes for grooming. The animals show a genuine appreciation of this treatment, leading to several different companies selling these products. The robots are positioned in specific locations in the barn and the cows visit them voluntarily. Other treatments, such as insemination, hoof trimming, shaving and the delivery of medication are not yet supported by robots. These treatments are rather complex and require specific skills from specialists such as veterinarians, inseminators, hoof trimmers and farmers. Robots and PLF can assist the farmer and others but cannot replace the human factor in these complex processes.

Cleaning of cows takes place when they are treated. Cleaning of the milking robot itself is integrated within the robot's own functions and cleaning of the milking parlor or the milking robot environment is mostly still done by hand. The biggest cleaning activity is carried out in the areas where the cows roam and rest. Manure-scraping belts and specific manure scraping/removing robots have been developed and are used quite a bit in practice. The main producers in the Netherlands are JOZ, GEA and Lely.

Robots for cleaning the lying beds and in confinement barns are not yet well developed or utilized. Various systems are used in practice for the distribution of fresh straw in straw beds. We do not foresee specific solutions for cleaning dairy farms themselves. In terms of cleaning the air, various new products are coming on to the dairy market that are able to 'wash' the air and remove ammonia, for example. Dairy barns are mostly open systems and air handling and washing therefore needs specific design. The Lely Sphere is one such system, but it has yet to find its position in the market.

5.4 Milk processing

Processing of milk takes place mostly at specific processing plants. The storage, transport and sampling of milk are part of a highly professional industry. In addition, there is also on-farm processing of milk. Homemade cheese, butter and yoghurt is produced by the farmer without robotic support. The introduction of the Lely Orbiter in 2020 was an innovative development that shocked the market with its ability to process, pasteurize and package the milk on the farm itself. This is a new concept and requires further development in the coming decades.

6 Challenges for research

6.1 Sectoral challenges

With over 35 years of experience, one of the authors, working at Wageningen Research, has witnessed much scientific interest in robotics, including the development of robotic milking systems and the design of innovative barn types that harnessed the potential to identify individual cows by the use of electronic identification and concrete floors. Animal scientists collaborated with agricultural engineers during this period, contributing to systemic breakthroughs. After a period in which the focus on robotics in livestock systems waned, there was a strategic shift to invest in the Wageningen Agro Food Robotics program (https://www.wur.nl/en/research-results/projects-and-programmes/agro-food-robotics.htm). The various challenges included (1) knowledge development to apply robotization to far-reaching animal monitoring (behavior and environment of individuals in groups that are kept both indoors and outdoors and interact with robots); (2) knowledge development to apply robotization in specific land-based farm systems with grassland that focus on nature inclusivity; and (3) encompassing intelligence (learning and adaptability) of robotic systems for feeding, harvesting (milking/collecting eggs), animal care, cleaning and animal routing, whereby local and remote collaboration between robot(s), humans and animals is optimally utilized.

In 2016, challenges for robotic solutions in the poultry sector were discussed with farmers in the Netherlands. The idea was that robotics could reduce the need for humans to carry out jobs such as litter maintenance, removing dead birds and determining the potential cause of death, collecting eggs outside the laying nests, carrying out health checks for blood lice, selection of non-producing birds, cleaning the barn and performing vaccinations. Considering the latest developments discussed in Section 4 on pig production, the majority of these challenges are still on the table. Reasons for this could be that the large industrial companies are focusing on climate control and egg packaging, whilst poultry farmers remain hesitant, and newcomers in the market with see a highly fragmented poultry sector with small and highly specialized sub-sectors. The number of customers for a product needs to come directly from a global market.

As outlined in Section 4 on pig production, robots in the pig sector are fairly successful in controlling the climate and feeding pigs in groups and

Table 1 Impression of 12 identified use cases and the 11 key challenges mentioned per use case

Use case theme	**Key challenges (technical, ecosystem, business, training and human capital development)**										
Innovative/ disruptively novel agri-food systems enabled by robotics	Global modeling, 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 system	Sustainable pan-European agROBOfood network	Push-to-market for agricultural robots and systems, support, education and training	Specialized robots to be used by seasonal unskilled labor	Infrastructure for practical training with access to robotics	Lifelong learning: connecting people from agri-food with people from robotics and analytics
	X		x	x		X					
Robotics, AI, and data science for breeding	X	X	x	x							
Complex handling and manipulation in primary production	X	X	x								X
Complex handling and manipulation in post-harvest		X	x	x	X						

Realizing full autonomy of already mechanized tasks			x			X	
AI and robotics for livestock farming		X	x			X	
AI and robotics for precision agriculture	X	X	x	x			
Cleaning in agri-food				X	X		
Connectivity, distributed intelligence and pervasive technology		X	x			X	
Logistics and transport	X	X	X			x	x
Ocean farming and agri-food	X		x	x		X	
Food preparation and presentation							

Source: Adapted from: Sander et al. (2021).

sows in individual feeding stations. This market is driven by large multinational companies. It is possible that the development of robotic solutions might be hindered by the current structures used in barn and pens, which make it difficult to design autonomous robots to observe pig behavior, play the role of entertainer, and maintain the environment of the pigs, keeping both the interior and exterior of the buildings in good shape. The cleanliness of the environment in which the pigs live remains an important factor and the challenge will be to develop robotic systems that replace or support this task. New farming system designs might help to stimulate these developments.

In terms of robotic developments in the dairy sector (see Section 5), it is clear that the main industrial drive comes from the companies involved in robotic milking. DeLaval is using its R&D Hamra test farm to develop and test all kinds of new innovations, and Lely, for example, is working on the vision and concept of 'fully' autonomous dairy farms, on which its product portfolio is based. Its main challenge will be to strengthen the already adopted robotic solutions and to further develop and bring to market its newly introduced concepts. An additional challenge will be to allow the different robots to collaborate with each other and with humans. It is expected that animal intrinsic treatments such as insemination, claw trimming, shaving and medical treatments will not and cannot be done by robots in the near future. For the many relative newcomers to the robotic dairy market, it will be quite challenging to develop robotic solutions that fit into the farming systems. Additional attention is required for interoperability. It is expected that most companies will focus on robotic systems for cow and barn observations. Some well-developed companies have created robots for specific tasks and niches. Examples include JOZ for manure handling, Trioliet for roughage feeding and NEDAP for finding cows. The next section looks at the challenges that need to be overcome in terms of practical uptake, as well as the further development and testing of robotic solutions in the dairy sector.

6.2 Overall challenges

It is worthwhile connecting the aforementioned sectoral challenges with those identified in the 'European Robotics in agri-food Production: Opportunities and Challenges' report (Sander et al., 2021). Table 1 gives an overview of the 12 identified use cases and which of the 11 key challenges are mentioned per use case. It can be surmised that all use cases might have a link with livestock production systems, but if we limit ourselves to robotics that support poultry, pig and dairy farmers, the following uses cases can be used to inspire future developments.

6.2.1 Artificial intelligence and robotics for livestock farming

The monitoring, feeding and care of production animals such as cows, pigs, fish and poultry are daily recurring tasks. Smart sensor systems provide the necessary additional 'eyes, noses and ears' to the workers who take care of these animals, which form groups and are housed in general on ever-growing farms. Robotic support can relieve farmers in terms of inspection, sorting and feeding, so they can concentrate their care on the animals that require their support at the right moment, the right place and with the proper care. Core functions include observing animal behavior and physiology of individuals that are part of a group; feeding and treating individuals according to their needs; and harvesting the product from the animals (such as eggs, milk and wool), as well as sorting and regrouping animals. In addition, technology providers and feed-, food-, pharma- and breed companies, as well as contractors, are involved.

6.2.2 Realizing full autonomy of already mechanized tasks

Many agricultural tasks are mechanized, but the machinery still requires operators and major decisions are carried out by human intervention, based on experience rather than on (validated) data. Supervision and monitoring tasks are not yet automated, which is a barrier to a more sustainable method of production. When sensors gather data autonomously, when data-loops are closed and enhanced with automated decision (-support) algorithms, full autonomy can begin. The farmer can override a decision at any time, injecting specific knowledge 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. This can help improve biodiversity, allow new farming methods such as intercropping/pixel farming and improve timing and 24/7 capabilities, as well as added crop value on minimal land use. The core function is the integration and demonstration of full autonomy or hybrid solutions in which robots and humans collaborate. Systems should act reliably and comply with safety standards for autonomous robots and provide convenience to the end user.

6.2.3 Cleaning in agri-food

Cleaning is a task that occurs in all stages of the agri-food production system. It is often carried out in harsh environments and at irregular times. The task requires dedication to do it properly, the key being to remove organic contamination from infrastructure and machines to prevent cross-contamination with pathogens. Examples include cleaning of animal boxes

Table 2 Identified key challenges

Targets	EU robotics requirement	Requirements related to livestock robot development
Configurability	Software and hardware reconfiguration considerations, including use of intuitive programing.	Aspects of configurability and re-configurability should be accommodated in the design brief for a robotic platform that is multifunctional and has a modular tooling selection to support farming tasks.
Adaptability	Response to changes in the operating environment, including the ability to self-learn and apply auto-configuration strategies.	Sensor and robotic platform needed to provide data on the operating environment (farm) for operational purposes, proving also the opportunity to facilitate adaptive response functions for the platform itself.
Interaction capability	Interaction with operators, other robots and other systems within a production environment.	Identification of animals with radio frequency or optical identification can be used to develop and exploit identification-assisted robotics that can be applied for 'systems of systems' interaction.
Dependability	Factoring periphery and environmental integration into the reliability and dependability requirement for mean time between failures.	Probability engineering principles and failure modes and effects analysis can feature as part of system design, with the livestock farm providing a platform for modeling robotic-agricultural environment interaction.
Capability	Kinematics and dynamics of manipulators as well as the positioning and navigation of autonomous platforms.	Livestock robotics systems should exploit developments in both radio frequency identification (RFID) and associated optical or electromagnetic sensing for positioning, navigation and mapping where needed.
Manipulation ability	Ability to handle material objects and tools in a manufacturing context. Adaptability and robustness are primary goals, along with the need for accuracy and repeatability.	Intrinsic to the design being proposed is the facility for robust and adaptable handling material objects in the form of animals/animal body parts and tools for performing farm tasks. While accuracies may not equate to levels experienced in manufacturing the same principles of measurement, measurement assurance, repeatability and reproducibility will be applied in measurements undertaken, adding to the precision base for PLF.

(*Continued*)

Table 2 (*Continued*)

Targets	**EU robotics requirement**	**Requirements related to livestock robot development**
Perception ability	Suitable choice of sensing modality, efficient signal and data analysis, as well as generating the maximum information output from the data at hand. Guaranteed safe perception is also a key requirement.	Integration of multiple sensor systems and real-time data capture, processing and communication can be seen as an integral part of the system design, with the animal-derived data sets also considered for inclusion in 'Big Data' set developments and system readiness for future 'Big Data' services and Internet-of-Things (IoT) object-connected services.
Decisional autonomy	Primary goal to increase the level of responsibility in the control processes of production systems, in which the resulting autonomy is focused on reducing energy consumption, increasing throughput and providing context-aware task control in interactions with operators.	Livestock robot systems should support self-awareness and enhance decisional functionality and contribute to the knowledge base for integrated support in farm decision-making.
Cognitive ability	Potential is for functions that contribute to a reduction in programing and configuration requirements in deployed systems.	Should be possible to enhance cognitive ability and learn the individual characteristics of animals, while also contributing to the knowledge base for integrated support in agricultural robotic systems.

Source: Adapted from: Sander et al. (2021).

in livestock systems. Stables and protected horticultural environments (e.g. greenhouses, mushroom cells and vertical farms) are cleaned upon completion of a production cycle. Lorries for livestock logistics should be cleaned following completion of delivery. Increased awareness of and demands on food safety have dramatically improved intensive hygiene over the last decade. In practice, this time-consuming task is commonly carried out manually. The chemicals are not user friendly. Another task is cleaning the products themselves. Cleaning can be carried out as a physical intervention to the product itself, such as washing table eggs. Cleaning robots should be able to navigate through constructed environments and detect organic or mineral contamination in moist environments. They should be able to apply effective strategies to remove contamination from infrastructure elements to create low-risk environments for pathogens and for cross-contamination in the production system. Sensor-based evaluation of cleaning effectiveness (detecting organic contamination) is an important part of the solution.

6.2.4 Connectivity, distributed intelligence and pervasive technology

Robotization, AI, IoT, VR, AR, Blockchain, 3D printing, sensors and drones are all disruptive technologies that have the potential to transform agriculture.

All these disruptive technologies come together under the umbrella of cooperative robotic systems with the ability to deal with the variety of small- and large-scale operations in future agricultural production systems. In agriculture, there are a variety of products and production scenarios. For a period, the trend was to increase the scale of operation and therefore the capacity of the machines used in the production process. Robotic systems emerged as an alternative to replace this large machinery. However, advances in robotization and progress in other domains such as IoT and sensors have allowed a pivotal shift from big machinery to swarms of small robots or multi-robot systems that cooperate, are more intelligent and form a pervasive part of the cyber-physical agri-food system. This could create farms in which the social and ethical structures and requirements align more harmoniously, where the economical success of the farm is increasingly correlated to the robotic and AI-driven support provided to the farmer rather than to the size of the farm, as is traditionally the case.

The first core function addressed in this use case is that robot systems should be connected so that they can be remotely contacted, known as 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. Cooperation between robots and decisions as to 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.

6.2.5 Robotics, artificial intelligence and data science for breeding

Creating and introducing new food products based on new or improved breeds of production crops, animals, insects and fish typically takes 5–10 years. The last decade's focus has been on genomics, which has resulted in sophisticated data analytics and automation of genomic laboratory procedures. The focus is now shifting toward gathering and analyzing phenotypic data.

Traditionally this is also based on manual labor, but the variety of circumstances and the phenotypic requirement for data demands advanced methodologies for data gathering and analysis. It is expected that robotics can stimulate the demand for phenotypes in view of challenges such as 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. Automated data and AI-driven decision-making and selection processes are needed to ensure diversity, traceability and transparency (e.g. no genetic modification) of phenotypic data gathering.

Table 1 demonstrates that the technical challenges are generally mentioned in the use case. For livestock robotics, it appears that the key challenge of '24/7 level 5 cooperative systems and fleet and swarm management' in which robot systems should be able to perform tasks 24/7 with a degree of autonomy similar to those currently defined for autonomous cars (SAE Level 5), will be most important, directly followed by 'Robot-to-X interaction' and 'Interactive design of trustful, safe, and ethical robotic system'. These nicely match the described challenges for the livestock sector. It is also important to take note of the ecosystem, business, training and human capital development challenges. Although not mentioned in the use cases, they are a prerequisite for further development and practical implementation of robotics in the livestock sectors.

Table 2 shows the identified key challenges. To deliver robotics that safely and effectively support the monitoring and management of livestock farming processes, research is required to advance capabilities and key technologies relevant to industrial and service robotics. As the system should be a key part of a production process in which it is operating with livestock, it needs to ensure safe, cost-effective performance, reliability and ease of use. To this end, due attention should be paid to the EU Robotics 2020 strategic research agenda and multi-annual roadmap, addressing each of the key targets in the Table 2, in the context of our target application, and the prospects for advancing key robotics technologies in the different fields. While many of the EU Robotics' key ability targets are directed at robotics in manufacturing, they may also apply within the agricultural sector, including PLF.

7 Conclusion

This chapter has demonstrated that robotics is an important topic in livestock management. Aligned with the concept of PLF, it truly offers freedom of choice to farmers. A growing awareness of what has already been achieved and what is currently being utilized demonstrates that robotics is already at the center of modern farming systems. Based on the desire for innovation, we have seen many attempts to (re)design new robotic solutions. These challenges must be met with increased vigor and accompanied by the development of forward-looking and resilient farming systems. Robotics can play a pivotal role in this field.

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