Feature Article

Artificial intelligence, sensors, robots, and transportation systems drive an innovative future for poultry broiler and breeder management

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Implications

- Technological advances will ensure labor, economic, and environmental sustainability for a robust poultry broiler and breeder management system while enhancing animal welfare and production efficiencies.
- Poultry broiler production will be driven by highly adaptive artificial intelligence (AI) and data-driven systems, making it more resilient to anomalous events.
- The rapidly evolving development of advanced sensors, robotics, AI, and transportation systems will help us to address many of the challenges facing poultry broiler and breeder management.

Key words: artificial intelligence, chemical and biological sensing, on-farm slaughter and transport, poultry broiler and breeder management, robotics

Introduction

Imagine poultry farming and processing where everything is optimized by using intelligent autonomous systems with human workers remotely managing operations and only physically intervening when necessary. This vision is a potential reality for the future of poultry production where the ecosystem is fully automated and managed by constantly evolving artificial intelligence (AI). As shown in Figure 1, a paradigm shift will take place from a poultry production scheme of today to one that is highly intelligent, automated, and data-driven. That is, a scheme that is run by autonomous systems that can make decisions and act on their own based on inputs from sensors. The top of Figure 1 illustrates a future paradigm where poultry houses will be managed around the clock through a supervisory AI framework with associated sensors and robots; birds will be autonomously transported to processing plants. Rich data sets incorporating every moment in broiler and breeder production, transportation, and processing will be recorded in cloud servers, and AI will constantly process the input data and evolve over time, consistently making informed decisions. Versatile robots carry out most day-to-day tasks such as removing mortality and monitoring flock behavior to ensure the growth and welfare of the birds. In addition, virtual and augmented reality systems allow remote management and manipulation of the systems in the poultry house.

There are several challenges to address before such a vision becomes a reality. With more sophisticated mechanical devices, sensors, faster computers, and an abundance of data, it has never been more possible to revolutionize and tightly integrate every aspect of the poultry production and processing. This article casts a very novel vision of the future of poultry production, describes current limitations, and introduces some ongoing research in the context of broiler and breeder production and transportation that could signal a transformation in the future of animal protein production.

Challenges in Poultry Broiler and Breeder Management

Challenges facing broiler and breeder production today include labor shortages, disease outbreaks, food safety and quality, flock uniformity, and animal welfare. While the production is projected to increase over time, with more people moving out of rural areas (Zahniser et al., 2018), labor shortages will continue to be a primary challenge. One way to alleviate this challenge is to deploy technological solutions that can support the growing demand for poultry meat.

Disease outbreaks and food safety are issues that have significant impacts on broiler and breeder production

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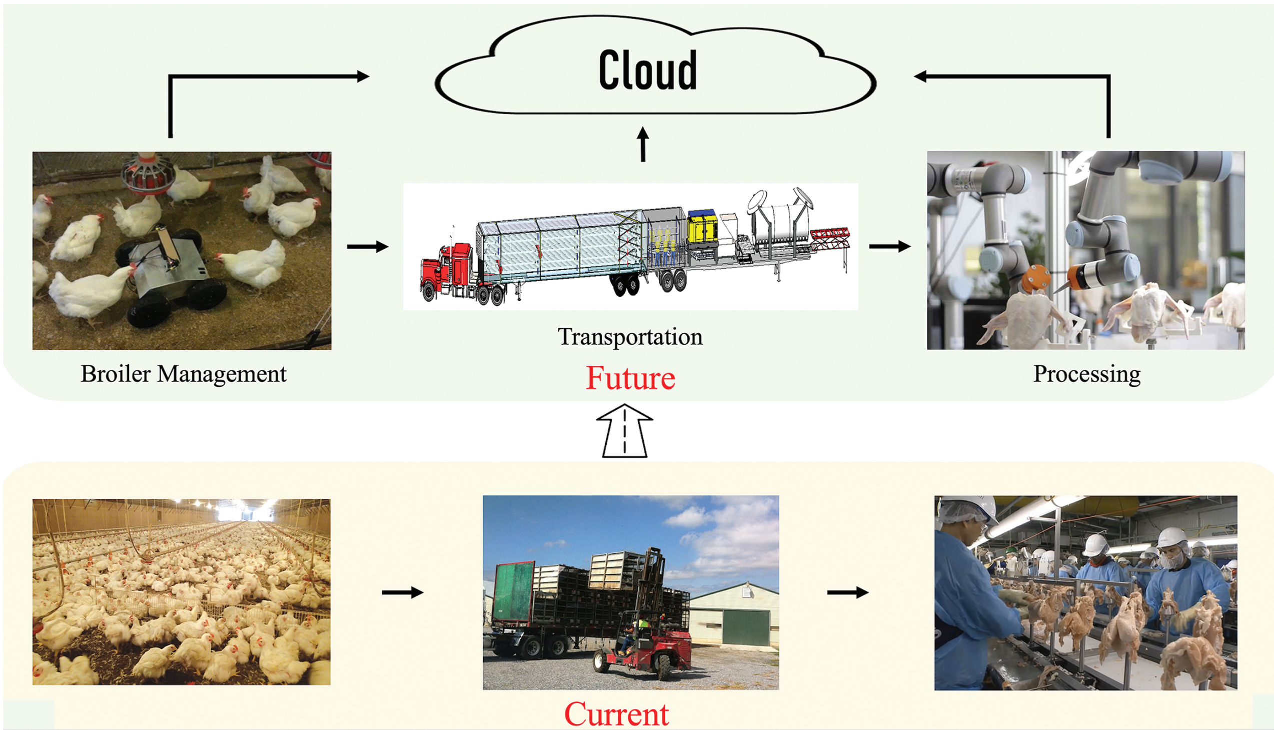

Figure 1. Current state and the future of poultry broiler management, transportation, and processing.

(Nuñez and Ross, 2019). It is estimated that the global loss since 2003 caused by high pathogenic avian influenza outbreaks could be billions of dollars (McLeod et al., 2005). Moreover, farm workers can become a disease vector by unknowingly carrying pathogens and viruses from one poultry house to another and cross-contaminating flocks. Food safety challenges are responsible for an estimated 9.4 million foodborne illnesses every year in the United States (Scallan et al., 2011). Both food safety and disease outcomes would be improved through rapid diagnostics and better predictive control.

Broiler production and processing are intricately intertwined. Processing systems as they exist today operate mostly in a fixed automation model. Equipment is adjusted based on the average weight of the incoming birds, where normal distribution is paramount. Inconsistencies in flock uniformity present challenges to this fixed automation model where the outliers in the anticipated distributions cause equipment malfunctions or result in yield loss during processing, affecting the bottom line. Tools and processes to better manage flock uniformity can directly improve processing efficiency and yield.

There are also environmental concerns related to broiler and breeder production. The litter produced in broiler and breeder houses has high nutritional value (Bora et al., 2020). However, improper management and application can lead to a range of problems including nutrient leaching (Reddy et al., 2008, Hubbard et al., 2020), soil acidification (Beausang et al., 2020), emission of harmful gases like ammonia (Joardar et al., 2020), and the spread of pathogens (Reddy et al., 2008). For instance, the Chesapeake Bay has suffered from phosphorus pollution and algae blooms over the last two decades as documented in a report released recently by the Environmental Integrity Project (Lamm et al., 2021).

Lastly, managing poultry welfare is an ever-evolving opportunity. Ammonia with levels higher than 50 ppm produced by excretion affects the bird's respiratory system's mucous membranes, a vital tool to fight off respiratory infections. Moreover, studies show that the presence of 50 and 75 ppm ammonia depressed bird weight by 6% and 9%, respectively, as compared to 0 ppm (Miles et al., 2004). The humane treatment of broilers during production and processing is also a priority. Routine pre-slaughter activities such as live catching and transport then live hang at the plant are some of the most stressful times for the bird during the production process, with known physiological and behavioral effects (Mitchell and Kettlewell, 2009; Schwartzkopf-Genswein et al., 2012; Jacobs et al., 2017; Saraiva et al., 2020). Researchers continue to better understand the natural behaviors and tendencies of birds and adapt growing environments to the birds' preferences (Ferreira et al., 2020). The ability to sense these preferences and measure behaviors in an automated and intelligent fashion will allow for better environmental controls that not only improve animal welfare but can also help with overall flock performance. Managing the distribution of feed and water can also be a welfare issue, as dominance and pecking orders can prevent some birds from obtaining full nutrition (Zuidhof et al., 2017). The following sections cast a vision for the poultry farm of the future and how it will be enabled through intelligent automation.

A Vision for the Poultry Production System of the Future

The broiler and breeder production system of the future could employ novel innovations in sensing, automated and robotic systems, data collection, and analytics, all complemented by an evolving AI framework. Manual labor could become a knowledge workforce not physically present in the poultry house but equipped with an enhanced capability to remotely manage, make decisions related to anomalous events, and take actions to resolve issues. Robots and automated devices driven by sensors and intelligent classifiers leveraging AI and machine learning could provide most of the labor-intensive tasks. Autonomous mobile robots available around the clock perform routine tasks currently done by farm labor such as picking up floor eggs in breeder houses, removing mortality, aerating bedding materials, removing litter, and spraying litter amendments, vaccines, and disinfectants. Furthermore, these robots collect localized data non-stop as they constantly roam through the houses. Drones are deployed to rapidly scout and assess the broiler and breeder houses for current and emerging issues, providing sensor data and intelligence to ground robots for fast targeted response.

Disease and food safety-related issues could be detected and addressed early through a network of smart sensors that feed data to AI classifiers enabling rapid and targeted response to undesirable pathogens. An accurate and robust biosensor could detect the presence of potential viral and bacterial pathogens in air and feces in a real-time fashion, so timely interventions can be implemented. Disease-induced symptoms are also directly detected by monitoring the behaviors of birds through AI supplied by real-time data. Based on historical data, AI predicts possible disease outbreaks before they occur. The historical data are also used to trace disease vector, mode of transmission, and other patterns, which improves the AI's early warning capabilities that could help prevent future outbreaks. When a disease outbreak or pathogen infection of birds is detected or predicted, autonomous robotic systems are deployed quickly to apply proper interventions, to remove an infected or diseased bird from the flock, or to isolate a group of birds from others in the house into a segregated space. Preliminary research has shown that autonomous ground robots can come in close physical contact with birds (Usher et al., 2015), enabling a direct measurement of disease and food safety-related pathogens on the birds themselves.

From a sustainability perspective, future poultry farms could be equipped with technologies to extract higher value materials and nutrients from traditional waste. This includes advanced adsorbing material to capture ammonia from poultry house ambient air or bioreactors to remove phosphorous species from chicken litter to be used as soil amendments (Xu et al., 2017).

Animal welfare considerations could be significantly improved by using intelligent automation systems that can capture real-time data. For instance, intelligent systems that process and classify images, videos, and audio of actual bird behaviors could drive a better understanding of environmental operational parameters such as temperature that impact welfare by associating a pattern between the birds' behaviors and the environmental condition over time. Smart infrastructure and autonomous robots equipped with chemical and biological sensors enable a collection of rich heterogeneous data which in turn can be used to 1) unveil birds' natural preferences with regard to growth conditions including lighting, air flow, and bedding materials; 2) monitor the birds' growth and health status through real-time biosensing; and 3) characterize the growing environment with respect to disease and pathogens as well as ammonia concentrations. In addition, AI may improve precision feeding systems as described in Zuidhof et al. (2017) by making a more informed decision for feed scheduling based on localized environmental, health, and behavioral data of individual birds. This could allow better control of the growth and uniformity of flocks, aiding upstream processing.

Future poultry transportation systems may eliminate the transport of live birds to minimize stressors such as physical discomfort, abnormal social settings, and other factors (American Veterinary Medical Association, 2016), which all contribute to significant stress accumulations. Activities associated with stunning and killing currently done at the processing plant could also be moved upstream to the farm. To make this possible, robots herd the birds to a stunning station and shackle the stunned birds. A transportation system delivers the shackled birds while keeping track of individual birds so that each bird's data collected during broiler and breeder management such as weights and health can be conveyed to the processing plant.

Technological Gaps Between the Current State and Envisioned Future

Recently, there has been an uptick in robot systems designed for operation in poultry houses (Ren et al., 2020). Most carry out specific or singular tasks. Examples include egg collection robots (Joffe and Usher, 2017) and disinfection robots (Feng et al., 2021). There is clearly a need for an automated robot that can execute a variety of tasks related to managing the houses. To control disease and ensure food quality and safety more efficiently, there need to be low-cost biochemical sensors to detect pathogens and viruses rapidly and accurately. Current methods of avian flu detection that use virus isolation, real-time reverse transcriptase polymerase chain reaction (RRT-PCR), and antigen capture immunoassays have serious drawbacks. Virus isolation requires 5 to 7 d for results; RRT-PCR is only available through veterinary diagnostic laboratories and requires expensive equipment; and antigen capture immunoassays, even though quicker than the other two methods, are costly and insensitive. Field-usable and rapid detection systems are needed to make timely intervention possible. In addition, vast amounts of data need to be collected to create an AI-driven model for predicting possible disease outbreaks. For localized sensing, the biochemical sensing should be tightly integrated with the robot localization for autonomous localized interventions. A way to identify individual birds is also needed to keep track of health data for each of them, and a robot would need to safely contact and interact with the birds to deploy vaccines and collect pathogen samples directly from the birds.

A real-time monitoring of the five domains of animal welfare, which includes nutrition, environment, health, behavior, and mental state (Mellor et al., 2020), is required to improve poultry welfare outcomes. Currently, all five domains are loosely monitored and evaluated manually by workers with the small sample of data they can collect due to technological limitations. Specialty environmental sensors such as ammonia sensors that are currently available on the market often face issues such as short battery life, baseline drift, selectivity problems, false alarms, and a need for frequent recalibration. Moreover, the original intent of many of these commercial sensors was for personal safety monitoring targeting the detection of low ammonia concentration, which is unsuitable for usage in poultry houses that often have high ammonia concentrations. A vast amount of data need to be collected, and AI algorithms need to be applied to autonomously recognize these behaviors in real time and assess the birds' welfare. To do this, there needs to be a quantifiable metric and a standard way of evaluating welfare. Versatile robots are also needed to quickly respond to any undesirable events, and they need to be able to stimulate certain behaviors in birds. An extensive amount of study needs to be carried out to determine how robots are perceived by chickens and what the best way is to establish a communication between the two (Hubbard et al., 2020; Savage et al., 2000). An improvement in feeding management systems through data-driven methods and providing environmental enrichment could also help reduce injurious pecking in poultry and captive birds (Dong et al., 2019).

Accomplishing the vision of fully automated and intelligent broiler and breeder management will require a supervisory AI and robotics framework capable of taking sensor data and expert knowledge inputs, processing these data, and converting them into tangible and actionable tasks to be carried out by robotic systems. Recent advancements in hardware and software including sensors, robots, 5G networks, and cloud infrastructures allow the collection of ample amounts of data from poultry houses. AI engines that make decisions based on these input data to control automated systems will continuously improve through iterative machine learning. The improved AI can equip the data-collection system with new capabilities such as predictive control and decision making. It can also inform engineers on how to improve system design so that the system can collect richer and more precise data, which in turn can be used for updating the AI itself. This iterative learning process will constantly occur over time and eventually bring the industry to the envisioned goal.

Ongoing Efforts to Close the Technological Gaps

Researchers in the Georgia Tech Research Institute's (GTRI) Intelligent Sustainable Technologies Division have been working for several decades in an effort to close the gaps described above. The following sections highlight technologies developed in robotics, computer vision, audio processing, machine learning, chemical and biological sensing, and transportation systems that could have major impacts on achieving the poultry production system of the future.

Broiler and Breeder House Robotics

Several years were spent developing and evaluating an automated ground vehicle and a drone for operation in broiler and breeder house facilities. Early efforts proved that operation of both aerial and ground-based robot systems was not detrimental to the welfare of the flocks (Usher et al., 2015). Shortly thereafter, routines enabling smart automation for a ground robot were developed and successfully demonstrated allowing it to navigate among a flock of chickens and interact directly with them through nudging, which encourages chickens to move out of the way.

Shown in Figure 2 is the ground robot platform developed at GTRI. The platform consists of a four-wheeled commercial-off-the-shelf (COTS) chassis equipped with a computer, a lidar, 2D and 3D cameras, an ultrasonic-based localization system, and a COTS robot arm with a suction cup end effector. The platform also has a suite of environmental sensors capable of recording temperature, relative humidity, ambient light levels, and several gasses such as CO_2, CO, CH_4, LPG, and NH_3.

With the high-accuracy ultrasonic-based robot localization system, custom routines were developed to allow the robot to search a space for egg picking, guaranteeing full coverage of the floor area. This is achieved by enabling the robot to remember which areas of the house it has already traversed, allowing it to explore new areas each time it iterates between fixed waypoints. In this way, the robot can search the entire house with a very limited number of pre-defined waypoints to go to, allowing for a very simple and non-technical configuration.

AI algorithms were trained to classify eggs and chickens, as shown in Figure 3, and equipment in the house allowing the robot to have awareness of its surroundings (Joffe and Usher, 2017). In addition to locating objects of interest, the localization system allows the robot to mark and store these locations in a map of the poultry house to provide to a farmer. This functionality, combined with the environmental sensing capabilities, can enable a farmer to know the locations and environmental conditions of problem areas in a house. For breeder operations, this might include the locations

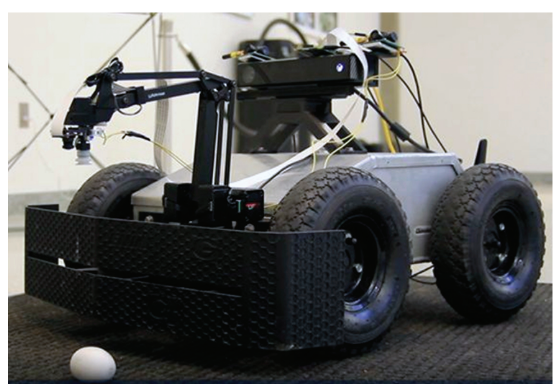

Figure 2. Ground robot research system for commercial farms.

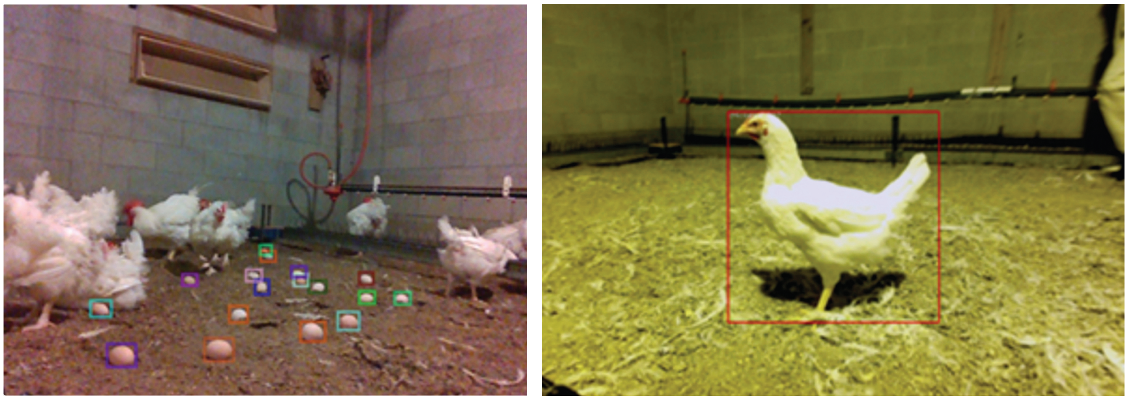

Figure 3. Sample results of AI classifier.

where floor eggs are regularly found, potentially allowing the farmer to adjust the conditions and reduce the potential of floor eggs.

The egg detection AI and 3D depth sensor allow the robot to perceive and localize eggs with respect to itself. This combined with the COTS robot arm allows for autonomous detection and removal of floor eggs in poultry breeder houses. The robot has been tested doing a variety of fully autonomous operations including navigation and egg picking for over 200 h.

Audio Sensing

Researchers have developed a system for assessing the conditions and welfare of broiler chickens through audio. Using audio signals captured in poultry houses as shown in Figure 4, researchers demonstrated the ability to detect illnesses such as laryngotracheitis, infectious bronchitis, as well as the bird's response to stress due to temperature and ammonia. This was accomplished using digital signal processing, AI, and machine learning techniques (Carroll, 2018). The result of this work has been the formation of a startup company, AudioT, which has the goal of commercializing the work to provide management tools that provide quantitative welfare measures. This would provide the farmer and broiler manager with information to manage the birds in a more holistic manner. Eventually, through repeated expert input, the supervisory AI framework could automatically deploy necessary interventions.

Figure 4. Audio system for monitoring poultry welfare.

Ammonia Sensing

GTRI researchers have developed a multi-function sensor system (Lotfi et al., 2019) with a machine learning-based robust and reproducible analysis component for continuous ammonia level monitoring as shown in Figure 5. The novel electro-thermal gas sensor is based on joule heating of an electrically conductive element and measuring the resistance change of the element which is a function of heat loss rate (Lotfi et al., 2019). When electrical power dissipation takes place in the suspended sensor heater in gas, the thermal conductivity of the gas surrounding the heater defines the rate of heat loss. Therefore, the steady state temperature of the heater is a function of the gas ambient thermo-physical properties. In order to improve the sensor's limit of detection and sensitivity, a fully differential 3-omega (Lotfi et al., 2019) has been developed to enhance the limit of detection by magnifying the resistance change of the microbridge with a minimum noise amplification. Compared to traditional chemical sensors, electro-thermal sensors have faster response times, lower power consumption, and are highly durable and low cost.

Chemical Sensing for Disease Detection

Researchers have developed a novel rapid detection biosensor to identify avian flu (Xu et al., 2007), which is inexpensive, portable, and able to detect several different avian strains simultaneously and within minutes. The sensor chip consists of two channels: a sensing channel and a reference channel. The sensing channel is coated with antibodies specific to avian flu, whereas the reference channel is coated with non-specific antibodies. The avian flu-specific antibodies are designed to capture a protein on the surface of the virus; the reference channel acts as a control designed to minimize the impact of non-specific interactions, changes in temperature, pH, and mechanical motion. The sensor then uses a process called interferometry to detect and measure the presence of viral particles.

In this process, light from a laser diode is coupled into an optical waveguide and travels under the reference and sensing channels. This creates an electromagnetic field above the waveguides, which is sensitive to the interaction between antibody and antigen. In the presence of viral particles, water molecules are displaced by the binding of antigen to the antibody-coated waveguide surface, which introduces a change in the velocity of the light passing through the waveguide. At the end of the waveguide, the light from the sensing and reference channels is combined, creating an interference pattern. A simple detector captures this pattern, and by looking at the associated phase shift, the system can determine the amount of virus present.

On-Farm Slaughter and Transport

As part of the efforts to rethink the future of poultry processing and production, researchers have been investigating poultry processing concepts that have the potential to dramatically improve broiler welfare, minimize manual poultry handling to reduce labor requirements, lower transportation costs, improve process sustainability, and implement novel technological advancements.

In the design of this new process, live transport was eliminated, thus reducing stress and significantly reducing the amount of manual handling of live broilers. For this re-envisioned process, a paradigm that moves stunning and killing tasks from the processing plant to the farm was proposed. This required the design of a mobile Farm Processing and Transport (FPaT) system consisting of two mobile units: a Processing Trailer and Transport Trailer built on standard 53-ft trailers as shown in Figure 6.

Proposed changes represent a radical departure from the current well-established process. Currently, researchers from the University of Georgia, Auburn University, USDA-ARS, and Georgia Tech are looking at the implications stemming from the

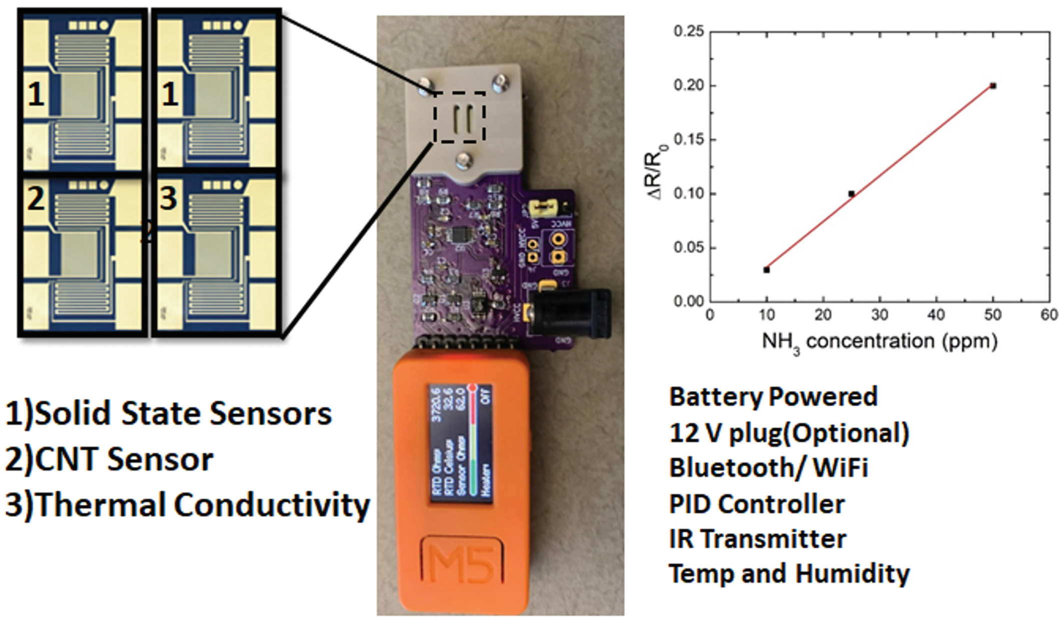

Figure 5. In-house environmental monitoring system.

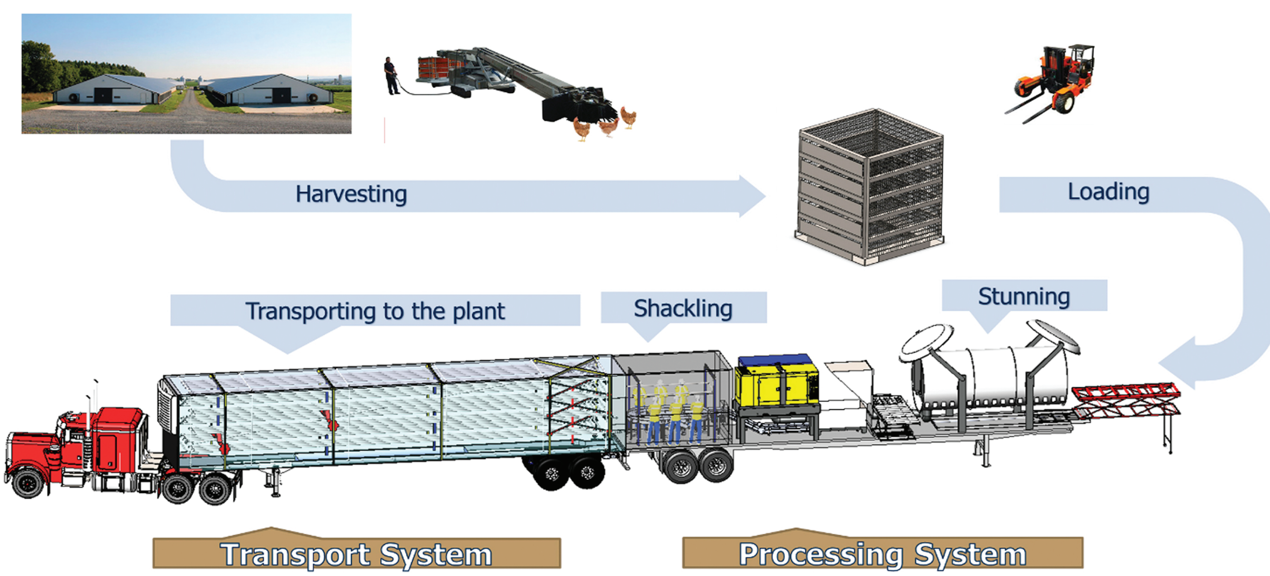

Figure 6. Farm processing and transportation system.

proposed process on meat quality and food safety. Preliminary results suggest that there are no significant differences in major food quality matrix such as physical properties and myopathy scores, visual properties, water-holding capacity, marination performance, and yield and texture properties between carcasses processed using traditional techniques and the proposed new approach. However, there is more investigation that needs to be done, and the research team is currently performing work related to FPaT processing.

In addition to improved broiler welfare and reduced manual broiler handling, there are other benefits currently under investigation associated with the FPaT system such as reduced water use due to reduced scalding requirements since the carcasses are being aged before processing, which can make the defeathering process (Mead, 2004) easier. Improved yield efficiency can be achieved by accurate accounting of the number of carcasses and weight distribution to subsequently informing a processing plant of a product that is coming ahead of time to customize carcass processing. To minimize cross-contamination between loads, the system is equipped with a washdown system that is used before carrying a different load. Furthermore, this system improves transportation safety. This is done by eliminating shifting loads since all carcasses are shackled and fixed in place, which is typical for the current poultry transport system.

Conclusion

The future of broiler and breeder production is ripe with possibilities for transformational change. Innovation will lie in highly adaptive artificial intelligence and data-driven systems together with advances in sensing, robotic, and transportation technologies. This emergence of novel research and development is poised to reshape the broiler production and processing ecosystem by solving challenges from labor shortages and disease control to food safety and flock uniformity, while ensuring environmental sustainability and enhancing animal welfare. The ultimate goal being a robust and resilient broiler and breeder management system equipped to address anomalous events, ensuring a secure protein supply.

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