GLOBAL SUSTAINABILITY THROUGH CLOSED-LOOP PRECISION ANIMAL AGRICULTURE

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The Earth is at a sociotechnical crossroads with humanity hanging in the balance – and high-tech agriculture can help bail us out. Human population growth, increasing urbanization and rising incomes are likely to drastically increase demand for animal agriculture in the coming decades. The US Department of Agriculture (USDA) predicts the need to double global food production by 2050 as the global population increases from 7.3 billion in 2015 to 9.7 billion in 2050 as shown in **Figure 1**. Much of this growth will be concentrated in the world's poorest countries where standards of living are set to rise rapidly, increasing the demand for resource-intensive meat and dairy products, which has been the historical trend. At the same time, agriculture in the 21st century faces multiple challenges: it must produce more food and fiber to feed a growing population with a smaller rural labor force, produce additional feedstocks for a potentially huge bioenergy market, contribute to overall development in the many agriculture-dependent developing countries, adopt more efficient and sustainable production methods, and adapt to climate change. Additionally, the world's arable land is already fully employed and shrinking -- the world has lost a third of its arable land due to erosion or pollution in the past 40 years. All these factors put enormous pressure on improving the production efficiency of the world's supply of food to meet the demand.

Since 1940, the number of people fed annually by a single farmer in the US has increased eight-fold. Automation and use of hybridized and genetically modified crops are widely adopted methods credited for these significant increases in agricultural production efficiency over the past seven decades. Yet, despite the rapid adoption of genetically modified (GM) crops by farmers in many countries, controversies about this technology continue, creating uncertainty and public suspicion in certain markets. In addition, introducing a new GM crop is highly expensive and time consuming, incurring a mean total cost of US $136 million per new introduction (for the period 2008–2012). The mean approval time for a GM crop in the US was 2,467 days and 1,763 days for the EU (Smart *et al.*, 2017). These regulatory issues and bias against GM crops in certain markets, coupled with increasing demand for organic foods, increase the need for automation to make up the bulk of the food production efficiency shortfall that is looming.

HUGE IMPACTS AND OPPORTUNITIES IN ANIMAL AGRICULTURE

With animal agriculture consumption poised for worldwide growth well beyond the rate of population growth, coupled with increasing concerns of environmental sustainability, food security, and the welfare of the animals we depend on, there are tremendous opportunities for technology-enabled advances in agricultural productivity for the common good. We have already seen the explosive growth of precision crop agriculture, but precision animal agriculture is fundamentally different; in animal agriculture, we care about individual animals and their psycho-physiological state changes hourly. Taken together, this necessitates the ethical development of animal agricultural productivity-enhancing practices that efficiently manage water consumption, reduce greenhouse gas (GHG) emissions, and ensure food safety while simultaneously enhancing the well-being of animals we use for food.

Environmental Footprint of Farms and Methods for Sustainability

In the US, animal agriculture accounts for 56% of the fresh water consumption with two-thirds to three-fourths of that water being used for feed stocks. Other uses for water in animal agriculture include sanitation, cooling facilities for the animals and animal products such as milk, animal waste-disposal systems, and incidental water uses.

Today's state-of-the-art animal agriculture management carefully monitors growth, consumption and production across the entire farm to drive statistical models of animal growth, nutrition and wellness. In turn, diets are actively formulated for the average member within the herds, meaning that half are overfed and the other half are underfed, so individualized feeding can have significant impact. Finally, one of the greatest concerns in animal agriculture is the relatively high levels of GHG emissions. Global estimates suggest livestock account for 11 to 18% of global GHG emissions. In the U.S. alone, GHG emissions from the entire agriculture sector are roughly evenly split between crops and animals, with each accounting for 4 to 5% of total US GHG emissions, equivalent to 344 million metric tons of carbon dioxide equivalent. Since methane is 30 times more potent as a GHG than carbon dioxide by some estimates, we project a 10% increase in metabolic methane efficiency by the year 2030 could reduce global carbon dioxide emissions by an amount equal to eliminating 12 million cars.

Opportunities to Improve Animal Health and Food Safety

Automated animal disease monitoring has potential to increase animal health and improve food safety. Most livestock animals are stoic and do not show outward signs of subclinical or clinical disease. This makes disease detection by humans difficult. Given that metabolic diseases like ketosis and acidosis are prevalent on U.S. dairies (>30% of cows) in early lactation when cows transition from low-energy diets to highly fermentable diets, many sick cows likely go undetected. Another example of a costly animal health problem that currently relies on human detection prior to treatment is mastitis. Mastitis, mammary inflammation, is most often due to bacterial infections. Mastitis lowers milk quality, can be contagious, and often results in animal culling due to chronic infections. Precision animal technologies that result in automated early mastitis detection could undoubtedly improve animal health and food safety. These examples are some of the most prevalent, but additional opportunities exist for rapid and precise intervention, such as conception, and even bullying and social behaviors. Rapid, automated detection of ailments can facilitate targeted treatment for affected animals and have positive implications for animal health and food safety.

CPS REFERENCE ARCHITECTURE FOR PRECISION ANIMAL AGRICULTURE

Our multi-university team, with support from industry, has proposed a cyber-physical system (CPS) inspired closed-loop precision animal agriculture architecture for a dairy farm exemplar based on the three components of feedback control – sensing, analysis and actuation. The sensing is done through a hierarchy of monitoring systems that include output sensors for milk yield and quality as well as animal growth, input sensors for feed and water, and process sensors including novel active in-rumen (stomach) sensors for measuring pH, temperature, and volatile fatty acid content as well as cow physical activity level. The amount of data generated on the farm is large and we are mating the sensors to a hierarchical wireless networking system that transmits this data to a cloud-based platform with big-data analytics from edge to cloud using models for health and nutrient management plus productivity. The actuation system, which implements the actions provided by the analytics, includes feed dispenser robots to manage the individual nutrient and food supplies and interfaces for human prompts for health/wellness care for the cows.

Model-Based Analytics for Health and Nutrient Management Interventions

The analysis of the data is performed on a cloud-based platform using predictive models to provide the necessary interventions. To estimate the nutrient supply and medication for each animal, closed-loop control with discrete-time Kalman filters is employed with separate models for controlling metabolic health and nutrition. Data regarding the pH and volatile fatty acids are sensed by the in-dwelling "RUMENS" robot *(Rumen Understanding through Millipede-Engineered Navigation and Sensing)* and fed back for the health management control loop. In a simplified example, low pH of a particular cow for a short duration suggests a metabolic imbalance that impacts production and quality, so the cow is earmarked for buffer feeding to ease the indigestion. Yet, if pH is low for a prolonged period, other medical interventions are necessary and are suggested to health and wellness practitioners. In fact, feeding is determined in two stages. The first stage formulates the basal ration and feeding level and the second stage suggests additives for any individualized feed supplement needs.

Network Layers Composing the Generic Precision Animal Agriculture CPS

The proposed reference architecture consists of three networking layers with appropriate analytics protocols at each layer. The variety of data mentioned above is transmitted through a network of wired and wireless nodes that implement both a "normal" path and an "urgent" path for transmission. The goal seems simple: to move data from various layers in the network from the edge to the core of a cloud-based data storage platform to enable real-time decisions regarding the productivity, quality, safety, and efficiency of the farm and its products. Yet, because of the complexity of living entities, it is not so simple and involves a novel collection of hardware layers, routing and analytics protocols, and distributed decision support across the system to support both top-down and bottom-up decisions and control.

The intelligent animal health monitoring and control system is built on a configurable three-level architecture, illustrated in **Figure 2** for the dairy farm exemplar, that is intended for farms of any size and animal type. In level 1 – the edge – each node represents a sensor, actuator, or computer with sufficient intelligence to perform the analytics necessary to carry out its dedicated functions. These nodes include the developed rumen-dwelling RUMENS robot, yield and feed sensors, and actuators. The sensor and actuator nodes are highly specialized and purpose-built, such as the dairy farm millibot "gut crawler" sensor node. These sensors and active devices intimately interact with *individual members* of the herd, so analytics at this level are not re-programmable.

By contrast, the "collar nodes" at level 2 act as consolidators of data and as mini-gateways to the higher-level analytics. The collars periodically receive measurements from in-body robotic sensors using a low-power body area network and local sensors on activity. The collar supports the protocols for basic computational and communication capabilities, which will be leveraged to perform user-defined analytics, such as simple filtering on the measurements received from the in-body sensors or activity estimation from on-collar sensors. The level 2 analytics will also be used to locally determine if information is urgent or time-critical, hence, these filtering algorithms must be downloadable by the higher control levels.

Level 3 is the network backbone for the architecture. The data gathered at multiple level 2 nodes are transmitted to level 3, which is further transmitted to the cloud through a series of repeaters and a base station. This three-level configuration integrates wireless body sensor networks (WBSNs) and mobile ad hoc networks (MANETs) to minimize power consumption without impacting opportunities for distributed analytics in a uniform architecture. The three-level network provides a high degree of configurability, rendering the proposed real-time health and behavior-monitoring architecture suitable for farms of any size, delivering true precision animal agriculture.

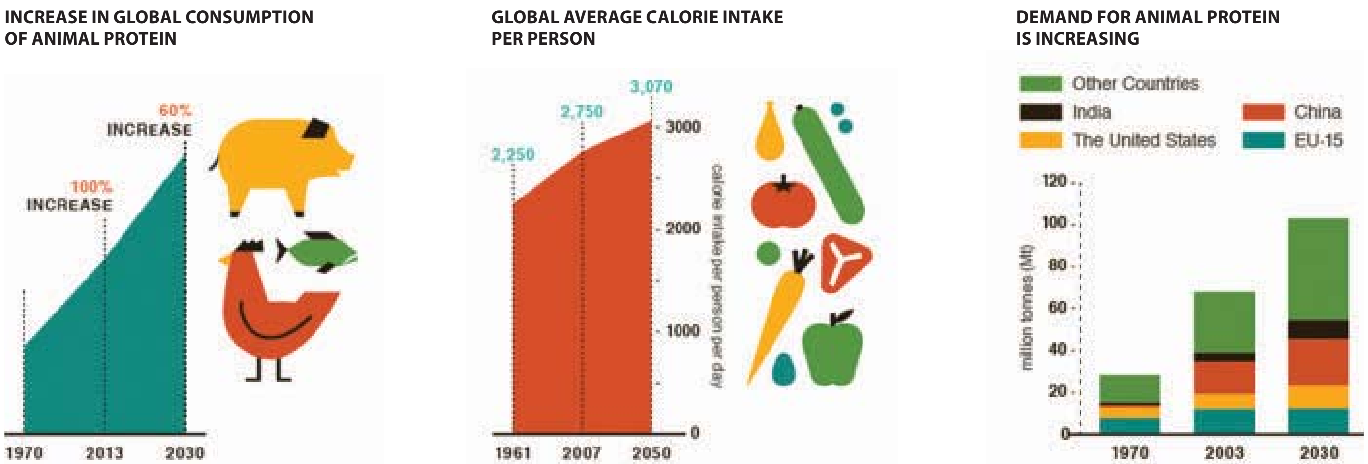


FIGURE 1 Global animal protein and food consumption estimates.

The Physical Layer of the Generic Precision Animal Agriculture CPS

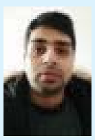
The physical layer of the developed architecture includes all the systems for generic animal and herd networking as well as the purpose-built sensors and actuators for a particular animal type. The sensor suite along with the actuated milking, feeding stations and the feed dispenser robot comprise the physical layer of the architecture. Generic elements include an enhanced animal collar/mobility sensor and field-ready wireless access points. The purpose-built elements include an in-dwelling active rumen sensor platform, automated feed delivery device, cow weight sensor, and in-line milk analysis equipment.

RUMENS Robot for Active Sensing Inside the Animal

One of the core components of the sensing suite is the novel RUMENS robot, which is an active sensing platform hosting an array of sensors such as the purpose-built polymer thin-film volatile fatty acid (VFA) sensors, pH and temperature monitors. Three primary VFAs (acetic, proprionic and butyric acid) perform the bulk of the fermentation process, yet all are formed in the rumen and are absorbed across the ruminal epithelium, from which they are carried by ruminal veins to the portal vein and hence through the liver. The proposed polymer-based VFA sensors are a high-risk/high-reward aspect of our work that we expect will enable a new type of "digestive observatory" that will produce high-density data on a greater variety of VFAs and fermentation parameters than is currently possible. Many VFAs exist in the rumen and influence fermentation, which provides greater than 70% of the ruminant's energy supply.

We are developing a pair of sensor packages for the RUMENS robot for either remote sensing or collection of physical samples, such as biopsies. The novel RUMENS robot is an in-rumen remotely operated vehicle (ROV), inspired by millipede locomotion, that is capable of navigating, sampling, and characterizing the rumen and its contents, without the complexities of legs or other appendages that could potentially harm the animal. This development will transform understanding of rumen biology and feed

ABOUT THE AUTHORS



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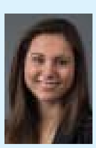

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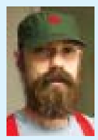

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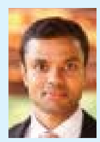

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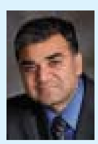

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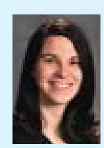
Byung-Cheol Min is an Assistant Professor in the Department of Computer and Information Technology at Purdue University and directs the SMART Lab, which performs research in multi-robot systems, robotic sensor networks, and human-robot interaction, with emphasis in field and service robotics and assistive technology and robotics. He holds a Ph.D. in Technology from Purdue University, an M.S. degree in Electronics and Radio engineering, and B.S. degree in Electronics Engineering from Kyung Hee University, Republic of Korea.



Kristy Daniels joined the department of Dairy Science at Virginia Tech in 2014 as an assistant professor. An animal systems biologist, her current research interests include elucidating mechanisms that govern rumen and mammary growth; she is especially interested in studying how nutrition affects these.

efficiency, fermentation science, and microbiology by providing a comprehensive map of the cow rumen environment in the highest resolution known to-date. This understanding of ruminant animal digestive efficiency can be scaled up to many animals and many herds.

Collar-Based Monitoring and Communication

Getting data from inside the animal to the base station is not trivial due to the fact that the rumen ROV will be submerged in a caustic, electrolytic fluid. To achieve this, we utilize wireless body sensor networks (WBSNs) to hop from ROV to a collar around the neck of the bovine. The collar uses conventional Wi-Fi to link to a base station, which is assumed to be within range. Using RF communication from the rumen will be too power-intensive so the WBSN is used because Intra Body Communication (IBC) offers low-loss coupling directly to biological tissue, which provides a low-loss, low-power path to the collar. We use capacitive coupling to the body and on to the collar as it is difficult to get sufficient electrode separation for galvanic coupling.

Feed Dispenser Robot

The new feed dispenser machine is an integral part of our sustainable dairy CPS. Upon entry into the station, a gate will close behind the cow preventing her egress for a minimum of 1 min. The cow's RFID ear tag and RFID leg tag will be read by an RFID reader. This will initiate autonomous action by the feed dispenser system. Depending on individual animal needs, as determined by the data-driven individualized models, the cow is delivered a specified quantity of feed supplements to support lactation needs or to remedy acidosis, or other conditions. The feed dispenser pan will contain load cells for automatic weighing of any feed refusals; weighbacks of uneaten feed will be weighed and discarded as the animal leaves the station. The machine is modeled after construction of automatic dairy cow feed stations (e.g., Lely Cosmix; Lely, The Netherlands). Further, to entice cows to enter the station, a grooming roller will be installed over the cow chute (e.g., Lely Luna; Lely, The Netherlands). These rollers are popular and objectively enjoyed by cows.

SUMMARY

A variety of economic, social and technological factors are converging to increase the demand for animal agriculture well above the rate of growth of human population. This presents a number of opportunities to improve the safety of the food supply and sustainability of production methods driven by the economic enabler of increased efficiency and productivity in precision animal agriculture. We believe this unique combination of social demand, economic viability and technical feasibility will allow these benefits to evolve simultaneously with the same explosive growth of the precision crop agriculture revolution.

Although we expect the growth curves to be similar, precision animal agriculture has two key differentiators from precision crop agriculture: data dependence down to the individual animal and real-time control loop closures. Consumers just don't care about an individual ear of corn or soybean plant the way they care about a cow or lamb. In addition, animal feedings may occur many times per day for thousands or tens of thousands of cycles while some plants may experience fewer than ten water and food cycles in their entire lives.

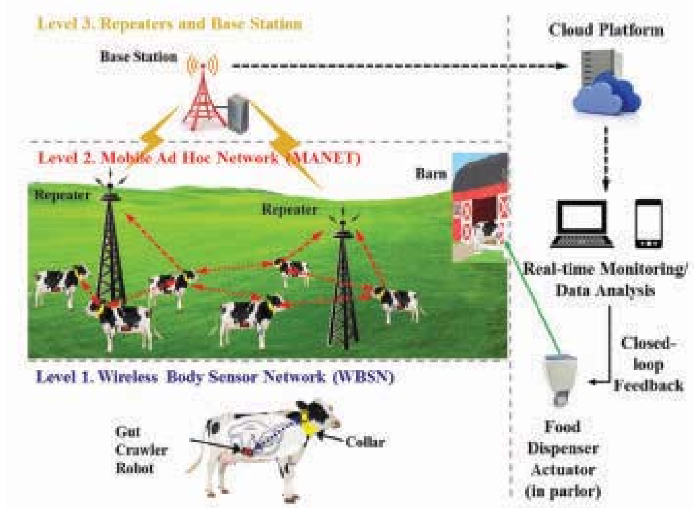


FIGURE 2 Three layer wireless sensor network architecture for precision animal agriculture.

The data-centric CPS reference architecture for precision animal agriculture that we are evolving based on the prior work of a generation of scientists and engineers holds the solution to sustainable and safe increases in productivity in a way that is scalable throughout the developed and developing world. The presented approach involves real-time monitoring and real-time analytics at three levels of granularity: the entire farm, the herd, and the individual animal. Sensing of individual characteristics is done through the developing "RUMENS" ROV, which actively and intelligently gathers animal-specific real-time data to map the animal microbiome at a level of precision never imagined before. This information is relayed through a body-sensor network to the collars around the animals' necks, where local analytics protocols add information about the aggregate local herd. A wireless sensor network of these collars and repeaters is used to transmit the data to the cloud where global analytics is performed. The processing at individual nodes (collars) is limited, but assigned a communication priority based on context (normal or urgent). The developed models for analyzing the feeding behavior, growth, sickness and metabolic activity predict the necessary feed and supplements to be provided in reaction to the sensed data and to signal quarantine. The actuation is done through a feed dispenser robot that controls the feed and supplements to support the lactation needs or to remedy illness based on the analysis. ■