TRANSFORMATIONAL FOOD MANUFACTURING WORKSHOP

8 – 9 MAY 2019
NORTHWESTERN UNIVERSITY
EVANSTON, IL

EXECUTIVE SUMMARY

Overview: A consortium of industry and university partners have engaged in a series of workshops under the banner *Transformational Food Manufacturing*. From the perspective of food as an advanced manufacturing industry, the overarching goal of these workshops is to lay the groundwork for a national public-private partnership that will revolutionize food processing and manufacturing in the US. This will enhance food safety and security worldwide, increase American manufacturing competitiveness (not just in food, but in the supporting industries comprising the entire supply chain) and in so doing, grow the US manufacturing workforce into the 22nd century.

Progress-to-date / Workshop objectives: Over the past four years, a group from industry, government, non-profits and academia convened to articulate and begin exploring the technology barriers facing the food and beverage industry. Broad technology gap areas include: automation and control, advanced materials, sensors, data and analytics, workforce, regulation, public policy and education. While important insights were gained from these discussions, there is a level of actionable detail that is still missing. As such, more focused dialogue, with support from NIST, has begun to more significantly advance the understanding of the problem and what needs to be done to advance this critically important manufacturing sector. This phase of the conversation is built around three workshops, of which this was the first. Specific objectives for these workshops are:

i) broadening the existing consortium to better represent major segments of the food manufacturing supply chain,
ii) identifying industry-wide technology gaps and
iii) building the framework of a roadmap to address those gaps.

Workshop structure: This workshop was structured around two sets of presentations, one set on the morning each day. The purpose of these presentations was to provide the participants with high level overviews of state-of-the-art research that, while not directly in the milieu of food science and technology, has significant potential to be applied in the food space. Speakers included Jian Cao (Northwestern), SonBinh Nguyen (Northwestern), David Hu (Georgia Tech), Jiaxing Huang (Northwestern), Prahalada Rao (Nebraska), Ali Tamayol (Nebraska), Caecilia Gotama (BRDG – bridge to success) and Scott Halliday (Navajo Tech). The presentations on the morning of the first day were nominally around advanced materials related to sensing, while the presentations on the second day were loosely centered on surfaces and coatings.

Following the presentation sessions on each day, time was provided for questions and discussion with the goal of generating project ideas or concepts that could be individually or collectively carried out as part of a comprehensive, transformational food manufacturing technology development enterprise.

Outcomes: Discussions from the workshop yielded a set of eight project concepts, of which three have two sub-projects:

1. ***Replacing foil with graphene-oxide (GO) for multi-layered flexible packaging*** - Develop GO based materials with mechanical and barrier properties of aluminum at costs comparable or even lower than PET.
2. ***Graphene-oxide additive materials for enhanced PET material properties*** - Use graphene-oxide as an additive to PET to manufacture bottles that are lighter, stronger and more durable with the same (or improved) barrier properties.

3. ***Advanced nanomaterials for real-time sensing*** - Functionalized GO films to sense and report unsafe levels of key chemical markers using two related sub-categories, optical and electronic sensors.
4. ***Small Low-Cost Gas Chromatograph Sensor*** - Leverage MEMS technologies to look at creating micro-sized gas chromatographs.
5. ***Enhanced bio-inspired sensing technologies*** - Increase the effective concentration in sensor sample volumes to levels that are detectable with current sensor resolutions using bio-inspired sensing behaviors and methodologies.
6. ***Data analytics and modeling*** - Employ data analytics and artificial intelligence to incorporate these data into science/data-based models for prediction and control. This can be developed systemically, *i.e.* across the supply chain, or more locally at the process level.
7. ***Antimicrobial surfaces and coatings*** - Develop antimicrobial materials and coatings for food contact surfaces to dramatically improve food safety, reduce cost, enhance sustainability and increase productivity. Two sub-categories include producing antimicrobial surfaces using physical/mechanical or bio/chemical approaches.
8. ***Bio-inspired gripper technology for non-uniform product manipulation*** - Understanding the mechanics by which animals conduct highly delicate tasks can provide inspiration for new robotics and control technologies for food handling and processing.

Conclusion: This first workshop was highly successful in identifying specific, actionable project ideas at the intersection of advanced manufacturing and food; the next two workshops in this series are expected to expand the portfolio of project ideas. These project concepts address key technology gaps at the nexus of advanced manufacturing and the food and beverage industry. Research and development on these projects (and additional concepts to be developed in subsequent workshops) represents the foundational work to ignite the catalytic spark that not only transforms food manufacturing, but society as well; and to do it in a way that positions the U.S. food industry for increased global market share and to maintain a competitive advantage for decades to come.

Contents

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I. Introduction and Progress-to-Date

A consortium of industry and university partners have engaged in a series of workshops under the banner *Transformational Food Manufacturing* [1]. From the perspective of food as an advanced manufacturing industry, the overarching goal of these workshops is to lay the groundwork for a national public-private partnership that will revolutionize food processing and manufacturing in the US. This will enhance food safety and security worldwide, increase American manufacturing competitiveness (not just in food, but in the supporting industries comprising the entire supply chain) and in so doing, grow the US manufacturing workforce into the 22nd century.

Within this context, then, these workshops represent a structured and strategic next step in an initiative specifically focused on addressing two grand challenges of national and global importance:

- ensuring a stable and sustainable supply of affordable, safe, nutritious food not only for the US, but for the world, and
- equipping and empowering US food manufacturers and their supporting industries, to establish highly competitive manufacturing plants around the world.

Global access to high quality food is essential for long-term global security and stability. And creating the manufacturing technologies for U.S. companies to compete overseas is essential for growing the US economy and American technological competitiveness in a core manufacturing industry sector.

Perhaps the greatest impediments to solving these challenges lie in the fact that food manufacturing is a highly competitive, low margin industry that, in many ways, has not fundamentally changed since the early 20th century. The vision, then, is to transform the industry into one that systemically integrates data-rich, highly efficient processes with a well-paid, highly skilled labor force.

The pathway to transformation is to focus on pre-competitive technologies around the themes of food safety, security and waste. In the context of commerce, these issues can be directly correlated to data and standards that transcend the supply chain. And in terms of science and technology, they can be expressed in terms of sanitation and traceability. Indeed, the cost of sanitation necessary to keep our food supply safe is ~2-3% of sales; this translates to ~$10B across the industry annually and represents a window of opportunity for capitalization of the transformation once the revolution is started.

Achieving these goals requires strategies to transcend eight major technology gaps/themes:

1) using reconfigurable ***automation/control*** equipment,
2) developing ***materials/coatings*** to make food contact surfaces safe while hostile to contaminants,
3) deploying ***sensors*** for automation, sanitation, and traceability,
4) creating a ***data*** and ***analytics*** ecosystem along the entire food supply chain, *i.e.* from farm-to-fork
5) preparing a highly skilled, technologically literate food manufacturing workforce,
6) establishing manufacturing and data standards integrated with safety standards,
7) exploring long-range R&D opportunities related to new food sources and manufacturing methods,
8) building a focused public policy and education effort showing the relationship between advanced manufacturing on the one hand and food quality, safety and security on the other.

II. WORKSHOP OBJECTIVES

Over the past four years, a group of food manufacturers, food processing equipment companies, material coating companies, universities, standards organizations, manufacturing partnerships/consortia, *etc.* convened to articulate and begin exploring the above technology barriers. While important insights were gained from these discussions [1], there is a level of actionable detail that is still missing. As such, more focused dialogue, with support from NIST, has begun to more significantly advance the understanding of the problem and what needs to be done to advance this critically important manufacturing sector.

This report focuses on the first of three NIST funded workshops whose objectives are: to i) broaden the existing consortium to better represent major segments of the food manufacturing supply chain, ii) identify industry-wide technology gaps and iii) build the framework of a roadmap to address those gaps. The deliverables from this effort will be a focused set of project concepts, *i.e.* key technology gaps and strategies, that form the basis of a national initiative on advanced manufacturing related to food. This effort represents the foundational work to ignite the catalytic spark that not only transforms food manufacturing, but society as well; and to do it in a way that positions the U.S. food industry for increased global market share and to maintain a competitive advantage for decades to come.

III. KEYNOTE PRESENTATIONS

This workshop was structured around two sets of presentations, one set on the morning of each day. The purpose of these presentations was to provide the participants with high level overviews of state-of-the-art research that, while not directly in the milieu of food science and technology, has significant potential to be applied in the food space. The presentations on the morning of the first day were nominally around advanced materials related to sensing, while the presentations on the second day were loosely centered on surfaces and coatings. Synopses of the presentations are provided below.

Jian Cao – is the Cardiss Collins Professor of Mechanical Engineering, and Civil and Environmental Engineering at Northwestern's McCormick School of Engineering and the founding Director of the Northwestern Initiative for Manufacturing Science and Innovation (NIMSI). She is also an Associate Vice-President for Research where she oversees the strategic direction, new initiatives, and long-term sustainability of the University's core facilities. She also fosters collaboration between the physical sciences and engineering and the other disciplines across and beyond Northwestern.

Jian provided a welcome to the workshop participants and provided an overview of Northwestern, its students, faculty and research strengths. In addition, along with her staff, Prof. Cao helped arrange for tours of the Northwestern University Atomic and Nanoscale Characterization Experimental Center (NUANCE), Integrated Molecular Structure Education & Research Center (IMSERC), and the advanced manufacturing laboratories within the McCormick School of Engineering & Applied Science.

SonBinh Nguyen – is the McCormick Professor of Teaching Excellence and the Dow Chemical Company Research Professor of Chemistry at Northwestern University. His group is currently pursuing research in the following areas: silicon surface chemistry, polymer-inorganic nanocomposites, graphene nanocomposites, and modeling environmental interfaces. Applications include developing new technologies for disease detection and therapeutic delivery, creating and functionalizing new materials.

SonBinh gave two presentations on the morning of the first day. In his first presentation, he described the physical properties of graphene and graphene oxide (GO) and presented some of the underlying chemistry. He showed that GO could be formulated and manufactured to produce desired chemical and electrical properties. For example, making GO sheets with folded or crumpled layers can increase gas barrier properties. He also showed how the electrical properties of GO can be used for sensing and communication. His second presentation, which followed those of Profs. David Hu and Jiaxing Huang, was structured to stimulate discussion leading to transformational project ideas specifically in the areas of real-time sensing and packaging. A number of the concepts are included in §IV below.

David Hu – holds joint appointments in the Departments of Mechanical Engineering and Biology at the Georgia Institute of Technology. His research focuses on fundamental problems of hydrodynamics and elasticity that have bearing on problems in biology. He is interested in the dynamics of interfaces, specifically those associated with fluid-solid and solid-solid interactions. The techniques used in his work include theory, computation, and experiment. He is also interested in pursuing biomimetic technologies based on nature's designs.

In his presentation, David presented a number of examples from his bio-inspired work with potential relevance to the food industry. In one example, he showed on how the aerodynamics of animal sniffing can provide higher concentrations of marker chemicals to the sensors of the animals' noses. He also showed videos of an elephant picking up a potato chip with its trunk without breaking the chip. As discussed below, this catalyzed a project concept of developing robotics tools for food handling and transport. And in another example, he talked about the intestine muscle contractions of wombats actually causes them to produce cuboidal feces. While wombats are believed to use this to mark their territory, David proposed that similar control algorithms could be used for more efficient packaging.

Jiaxing Huang – is a Professor of Materials Science and Engineering at Northwestern University. He and his research group aim to create new knowledge, materials and techniques that are potentially useful. And through his teaching, he strives to develop intuition, inspire creativity and bring the best out of students.

The focus of Jiaxing's presentation was on the challenges and opportunities of functionalizing GO for practical application. A key feature of the presentation was on the process of working with industry and the media to transition the basic science of GO to a consumer market application. In particular, he highlighted his work on using the color changing properties of GO as a safe, environmentally friendly hair dye. He then showed how the same color changing properties could be used as an optical sensor for food safety. An example from his laboratory was using a thin GO film as an optical sensor to detect ammonia, one of the byproducts of decomposing fish.

Prahalada Rao – is an Assistant Professor in Mechanical & Materials Engineering at the University of Nebraska. His scholastic passion can be encapsulated in three words: manufacturing, sensing, and analytics. His research focuses on thermal modeling, in-process sensor-based monitoring, and diagnosis of additive manufacturing processes (3D printing).

Prahalad presented his work on 3-D printing. His specific areas of research focus on prediction and failure modeling of 3-D metal printers and methodologies for identifying printing errors and correcting in real time. Using a hybrid approach, he uses micro-machining (*i.e.* subtractive manufacturing) to correct localized printing errors and then reprint a correct layer (additive manufacturing) to replace the error. The relevance to food manufacturing is that 3-D printing can be used to make functionalized surfaces with micro-scale features that make the macroscale surface hydrophobic. This could, in turn, reduce or eliminate fouling and thereby mitigate the need for frequent cleaning.

Ali Tamayol – is an Assistant Professor in Mechanical & Materials Engineering at the University of Nebraska. He will be joining the faculty in the Department of Biomedical Engineering at the University of Connecticut School of Dental Medicine in the fall of 2019. His research involves design, fabrication, and characterization of microsystems and fibrous materials for emerging engineering applications such as tissue engineering, regenerative medicine, and wearable devices.

Ali provided a brought perspective on his work in biomaterials. The primary emphasis to date has been on implantable materials that replicate specific physiological function and are readily integrated with existing native tissue. Applications range from vascular grafts to drug delivery mechanisms. One area that would be particularly innovative and important to the food industry is the 3-D printing of food. Ali pointed out that one of the greatest challenges right now is incorporating texture into printed food. His work on the building of biomaterials with both prescribed biological and mechanical properties can be directly translated from the medical field to food manufacturing.

Caecilia Gotama – is the founder and Executive Director of *BRDG – bridge to connect*, a non-profit bridge program focused on supporting 3rd year under-represented engineering students through to graduation with their BS degrees. The basic idea is to provide "under-represented" students, who have missed stories and lessons from participating in a professional family's dinner time discussions, an opportunity to catch up during their college years. The ultimate goal is to generate a pool of diverse, well rounded and socially aware future leaders available for employment within technology industries. She provided an overview of BRDG which catalyzed a discussion about workforce needs for a transformed food industry. The conversation was specifically focused on the challenges and opportunities associated with building and training a highly diverse, technical workforce.

Scott Halliday – is the Director of Navajo Technical University's Center for Digital Technologies. He was recently awarded a $3.5 million grant from the National Science Foundation to establish the NTU Center for Advanced Manufacturing with an emphasis on 3D modeling and simulation, polymer and metal additive manufacturing, and advanced manufacturing post processing techniques. It will also focus on materials testing and characterization, and metrology, or the science of measurement. NTU was also awarded a $1 million grant by the U.S. Department of Commerce with matching funds of $1.5 million from the Navajo Nation to build a metrology and materials testing center within the Center for Advanced Manufacturing, which Halliday plans to make a certifiable lab to assist in student learning. Scott presented an overview of the laboratories and capabilities available to TFMI at NTU. This led to a continuation of discussion about diverse workforce focused on the Navajo Nation. It also precipitated conversation about research and collaboration opportunities with NTU.

IV. *Project Concepts*

Following the presentation sessions on each day, time was provided for questions and discussion with the goal of generating project ideas or concepts that could be individually or collectively carried out as part of a comprehensive, transformational food manufacturing technology development enterprise. As part of the discussion, there was a sorting and evaluation exercise with individual and small sub-groups of participants helping to more clearly articulate the individual ideas. This yielded a set of eight project concepts, of which three have two sub-projects. These are briefly outlined below. In each description, the first paragraph highlights the challenge and transformational nature of the concept while the following paragraph(s) points to the specific technical idea.

1. Replacing foil with graphene-oxide for multi-layered flexible packaging

Aluminum foil has long been used as a packaging material. It is strong, flexible, formable, recyclable and an excellent oxygen and moisture barrier. It is, however, unsustainable in a laminated format and can 'flex crack' during lamination or forming processes. When this happens, the barrier may be compromised with the potential for significantl reduction in shelf life. Aluminum is also more expensive than other packaging materials, *e.g.* PET. And this cost differential will be exacerbated if tariffs on global metals sales are applied.

Graphene-oxide (GO) can be up to several hundred times stronger than aluminum [2]. It has the same mechanical and barrier advantages as aluminum but can potentially be manufactured at costs comparable or even lower than PET. Because of its electrical properties, there is opportunity to integrate sensing capabilities directly into the packaging material (*see Project Concepts #3a and #3b below*). Depending on how it's manufactured, GO can be tailored for specific barrier properties [3-5]. For example, replacing foil with GO may allow the *amount* of oxygen transport across the package to be tuned for specific products.

2. Graphene-oxide additive materials for enhanced PET material properties

Polyethylene terephthalate (PET) is ubiquitous as a packaging material in the food and beverage industry. It is a strong, lightweight, formable material with excellent barrier properties. It is also low cost and recyclable. But, because of accumulated contamination and degradation, there is a finite number of times that PET can be recycled. Perhaps more importantly, PET is neither biodegradable nor compostable. And the vast majority of PET bottles are either discarded, ending up in landfills, or littered; that is, released directly into the environment. It appears unlikely that the use of PET by the food and beverage industry will cease in the foreseeable future. The challenge, therefore, is to significantly reduce the amount of PET used in bottles without reducing the strength and barrier properties.

One way to address this challenge is to use graphene-oxide as an additive to PET. This makes it possible to manufacture bottles that are lighter, stronger and more durable with the same (or improved) barrier properties. There is also potential to make the material recyclable or compostable. It is estimated that a ~40% reduction of PET resin is achievable through the use of GO additives. Based on current pricing of ~70¢ per pound of resin and an annual production of 36B bottles, this would result in an annual 400,000 *ton* reduction of PET production or ~$600M per annum.

3. Advanced nanomaterials for real-time sensing

Food safety and security is a critical problem in the US and worldwide. A 2017 USDA study [6] reports 12.3% of US households experienced low to very low food security, *i.e.* enough food for an active, healthy life. Meanwhile, recalls of meat alone almost tripled in the past ten years [7], averaging 134 recalls per year from 2015 to 2017. At an estimated $10M cost per recall, food recalls are costing the US food industry (and the consuming public) $50B annually [8]. An underlying challenge to food safety is waste; up to 40% of food, $161B, is wasted in the US [9] after harvesting. That amount never leaves the fields in developing countries. A common denominator is food loss along the supply chain, particularly during transport between processing steps; this is both a safety as well as a waste issue.

Advances in nanotechnologies are creating opportunities for low-cost, real-time sensing of food, contaminants or decomposition byproducts. Specifically, GO films can be functionalized to sense and report unsafe levels of key chemical markers. This addresses threats from traceability disconnects along the supply chain. Embedding sensors into individual packages enables monitoring at much higher resolution. It also permits traceability across disconnects in the supply chain, *i.e.* during transport, which has not heretofore been possible. Sensing of this type can be divided into two related sub-categories, optical and electronic sensors, described below.

3a. Optical sensors for food safety

Optical sensors can be developed wherein the sensing material changes color in response to the presence of certain chemical markers. Examples include ethylenes and amines released as byproducts of decomposing plants and fish, respectively. Color indicators could also be added to mark changes in temperature and time. Options for optical sensor output range from dynamic bar codes for quantitative tracking of food quality to clear visual indicators for direct consumer use, *e.g.* warning labels that are activated when concentrations of certain contaminants exceed threshold levels.

3b. Push RFID tags for traceability

While optical sensors are conceptually cheaper and easier to develop, there are limitations to the accessibility of data, *e.g.* the need for line of site. Current RFID technology is still too expensive for many food applications and has not been deployed. This has prevented the food industry from benefiting from this technology as other industries have. Electrical properties of advanced nanomaterials such as GO, however, open possibilities to develop inexpensive, commoditized Advanced Push RFID or Push Live Digital Barcode technology deployments for tracking and traceability. This will revolutionize food safety and security by providing data continuity and analytics across the entire supply chain.

4. Development of a Small Low-Cost Gas Chromatograph Sensor

One of the challenges with doing any kind of meaningful discrimination on food quality or safety is the ability to characterize, detect, and maybe even predict spoilage and food product conditions either directly or indirectly. This requires a sensing capability with the ability to characterize the chemical and or physical changes to the food or the headspace in the packaging of the food over time. The ability to do wide scale sensing in an interconnected framework would enable significant opportunities to explore large data analytic approaches and machine learning techniques for doing rapid analysis of the observed constituent materials.

One proposed solution would be to leverage MEMS technologies to look at creating micro-sized gas chromatographs. In addition to the underlying fabrication process of the sensor, the fundamental research questions would revolve around sensitivity, specificity (or tunability), reliability, calibration, and general robustness of the technology and approach. Volatile Organic Compounds (VOCs) associated with manufactured foods can be rather complex with many contributing factors and agents, making first principal based analysis approaches cumbersome and somewhat limited.

5. Enhanced bio-inspired sensing technologies

One of the greatest food safety challenges is being able to detect contaminants and pathogens at concentrations below current sensing technologies. In many sectors of the industry, current safety standards require the manufacturer to hold product for prescribed periods of time to be sure that no pathogens grow to detectable threshold levels prior to shipping. While this incurs significant cost in terms of storage, handling and refrigeration, the standards are actually 'negative' tests that simply indicate that up to the point of shipping, no problems have been detected.

In addition to increasing the electro-chemical sensitivity of the actual sensors, then, there should be a parallel effort to improve the sampling technologies to increase the signal level of the desired markers presented to the sensor. That is, for a given concentration of microbial contaminants, develop ways to increase the effective concentration in the sensor sample volume to levels that are detectable with current sensor resolutions. One approach is to use bio-inspired sensing behaviors and methodologies. This includes sniffing or 'bubble stability' to either increase the sampling rate or to increase concentration in the sampling volume [10, 11].

6. Data analytics and modeling

One of the greatest technology barriers across the food and beverage industry is the lack of continuous data streams across the supply chain. The ability to ensure food safety and security, and to monitor or predict shelf life (*i.e.* reduce waste) are all severely limited by data gaps; particularly at the interfaces between farm, ingredient preparation, processing, market and consumer. One source of these disconnects is the failure or inability to transmit of data with the ingredients/food. Another key limitation is the inability to monitor food products during transport from one location to another.

The preceding project ideas address the need for spatially and temporally resolved data. They are examples of transformative sensing technologies that will fill critical gaps across the supply chain. This project concept addresses the concomitant need to employ data analytics and artificial intelligence to incorporate these data into science/data-based models for prediction and control. This can be divided into two sub-projects; the first addresses analytics across the supply chain while the second focuses more at the process level. These are described below.

6a. Creating a data analytics platform across the supply chain

At present, there are no comprehensive analytics tools developed for the food industry supply chain incorporating detailed, time-resolved data about the state of food during transport. This is because such data, if available, are not widespread. The challenge then is to proactively develop data management and analytics methodologies in conjunction with the sensor development described above. As noted, key drivers will be tracking of ingredients and product, ensuring safety and security, and intelligently assessing and managing shelf life.

6b. Digital twin of food process modeling

At the local level, science/data-based process modeling capabilities need to be advanced to allow for rapid and accurate modeling of product performance. This is not only for efficiency and productivity; it can drive food safety and consequently consumer confidence. For instance, data can be made publicly available via an IDE (Integrated Data Exchange) and private sector data innovators can study the data and offer insights to the industry. By creating a public data exchange, new food products can be added and evaluated. There is a huge number of SKU's in the food marketplace, so many different interests will need to upload their data and private sector innovators can perform analytics and provide intelligence on the data models.

7. Antimicrobial surfaces and coatings

Stainless steel is widely used for food contact surfaces across the food and beverage industry because of its strength, corrosion and wear resistance. It does not, however, have any antimicrobial properties. As a result, the nation's food manufacturers annually expend ~$10B, or 2-3% of sales, and up to four hours daily, on sanitation. These are energy and water intensive processes using highly caustic chemicals with real and potential impact on the environment and natural resources. By developing antimicrobial materials and coatings for food contact surfaces, there is potential to dramatically improve food safety, reduce cost, enhance sustainability and increase productivity.

The challenge is to create an environment that is hostile or inhospitable to pathogens that is simultaneously food safe, long lasting and does not leach into the food product. That is, the coatings must be wear resistant, non-toxic and effectively retain their antimicrobial properties with zero or minimal maintenance. There are two approaches to producing antimicrobial surfaces, physical/mechanical and bio/chemical described below.

7a. Physical/mechanical surfaces

Advancements in nanomaterials and additive manufacturing are making it possible to create surfaces that are superhydrophobic or are hostile to microbes at the cellular level. In applying the former, the goal would be to change the food contact surface properties such that nothing, particularly microbes, would stick. An example of making a surface hostile to microbe would be to apply a properly functionalized GO coating; GO at the microscopic level can be very sharp and can be deployed to puncture or cut pathogen cells without affecting the bulk food materials.

7b. Bio/chemical surfaces

Other surface treatments employed in the medical and pharmaceutical industries should be examined as well [12, 13]. From the bio/chemical perspective, the possibility of applying drug or chemical surface coatings that attack pathogens should be explored. This could potentially be a more involved approach if wear or depletion of the active agent necessitates maintenance of the material. The point, however, is that technology transfer from other industry sectors, *i.e.* biomedical, should be explored.

8. Bio-inspired gripper technology for non-uniform product manipulation

Unlike traditional manufactured parts and systems, food ingredients and finished products are generally highly complex with variable dimensions and material properties that can change with geographic location and season. As such, the human is still the most effective handling ‘system’ available in many applications. Repetitive stress/strain injury, worker safety, food safety and security are omnipresent problems when there are high levels of human contact with food. In addition, food production currently can only scale with the number of workers available.

In his talk, David Hu showed a video of an elephant deftly picking up a Pringles potato chip with its trunk. This is particularly remarkable, he pointed out, because an elephant is extremely short sighted and cannot actually make out what it is picking up. Understanding the mechanics by which animals conduct highly delicate tasks [14, 15] can provide inspiration for new robotics and control technologies for food handling and processing.

V. CONCLUSIONS / NEXT STEPS

A workshop focused on developing specific R&D project concepts that will lead to a transformation of food manufacturing was held 8 – 9 May 2019 at Northwestern University. This was the first of three workshops designed to provide details to a technology roadmap. The workshop was highly successful in identifying a significant number of projects principally around the themes of advanced materials for packaging, sensors and antimicrobial surfaces. Additional ideas were germinated in the areas of bio-inspired robotics and sensing. Another topic which arose, but was not developed, was the idea of 3-D printing of food.

Planning for the remaining two workshops is underway. The next one will be hosted by Georgia Tech, 25-26 September 2019 broadly around the theme of automation and control. The third workshop is slated for December 2019/January 2020 to be hosted by UC-Davis around the themes of sensing and data. In addition, efforts are in progress to build the R&D partnerships to begin actively developing these projects.

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