Future of RFID-Nano Technology

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Abstract— True nanoRFID/Computers (nanoscale radio frequency identification devices, or "NRs") will represent a major change in the way many things are done. This technology will truly enable fulfillment of the promise of the Internet of Things (IoT). This paper presents the recent developments of producing a true nano RFID which will lead to a nano distributive meshed computer system. These devices can be styled "Intelligent Surfaces" (IS). These nano RFID/computers can prove to be a truly disruptive technology.

Keywords—nanoscale, Internet of Things, Internet of Everything, RFID, nano-computers, IoT, NR, Intelligent Surfaces, IS

I. Introduction

True nanoRFID/Computers (NRs) are microscopic communications devices that could have a transformative impact on the world enabling the vision of an "Internet of Things" or "Internet of Everything" and Intelligent Surfaces (IS). NRs do this by providing a scalable wireless communications platform that can be embedded within objects, including paint, packaging, fabric, small parts, complex machinery, and even living organisms. From the authenticity of a critical document to the integrity of high value commodities within a refrigerated warehouse, up to communications within entire buildings and beyond, NRs can provide a unique way to sense and interact with the environment in real-time with microscale precision applied to macroscale industry problems.

This technology will provide far richer information from, awareness of and control over the world where they are deployed – a "higher resolution", multi-dimensional, point of view. The result is anticipated to be huge gains in automation efficiency with industrial applications in agriculture, logistics, healthcare, merchandising, manufacturing, transportation, as well as resource management with enhanced prosperity and environmental sustainability. NRs can play an important role in safety and security, tagging with unobtrusive precision key places, objects, and personnel.

NRs are microscopic (and sub-microscopic) electronic devices that use patterns of electromagnetic waves to wirelessly communicate data through sophisticated nanoantennae. Even though NRs may be the size of human cells (or potentially smaller), they can communicate with the macro-scale world through specific patterns called "spectra". These spectral patterns, encoded like fingerprints, are sculpted into the nanostructured materials of the NRs, using the methods of high-volume semiconductor manufacture.Preliminary work in our laboratory has resulted in microscopictags that can be uniquely identified with a palm-held scanner, suitable for authenticating security seals, packaging, and documents, applicable by a variety of methods, including spraying, stamp, and embossing. These are early forms of the devices being developed.

These nano-scale devices can do much more than tracking. They can in principle be embedded in nearly any material, to serve as a platform to both acquire data from the material and to send information or instructions to the material. Beyond two-way data transmission, NRs become more than mere tracking devices but complete data acquisition, storage,retrieval, and computing systems as their macro-scale counterparts have done. Through the application of advanced materials, nano-electronics and distributive computing, the acquisition, processing, and communication of a wide range of data can become massively parallel.

This technology will change many things currently done with larger systems making them more efficient and less costly. It also will make possible things today that only appear in science fiction, such as the manipulation of blood cells, monitoring and making decisions on failure of operational items, allowing food, water, and air to send messages on their quality, a global information system available from day-to-day items like walls, clothing, and nearly any surface. NRs could provide tracking and monitoring of nearly everything that is made or modified.

NRs are invisible to the naked eye. Only tens of microns to hundreds of nano meters on a side, they can be produced by the billions using high volume nanofabrication and be embedded by the thousands in any given object (acrylic paint and plastic are early target materials). This innate redundancy enhances both their collective capability and the robustness andreliability of the resulting system. They can be manufactured by the billions using current computer chip factories, or "fabs",with great economies of scale. Such devices will have significant cost savings over existing sensors and embedded computing systems.

NRs could have mobile applications. Consider clothing, embedded with such devices. Add the potential for networking capability and it may be possible that future smart phones no longer need to be encased but rather would be distributed in clothing. A simple voice-actuated system with an ear device could be used to access the device. The video portion of the now "nano" smart phone could be provided by an optical system like Google Glass. Similar strategies can be envisioned in vehicles, or within other mobile and portable devices (wallet, keys, personal protective equipment, portable generator, binoculars, sporting equipment, highway barriers, etc.)

In the biomedical area, applications in diagnostics, drug delivery, neural interface, microsurgery, and metabolic monitoring will open a new era in providing personalized, effective, and lower-cost medicine. The key technology is the wireless link to the micro and nano scale, enabled by nanoantenna arrays to collectively communicate efficiently.

Surfaces like walls, wings, and carpets could become segments of larger interactive systems. Billions of NRs (with sensors and decision algorithms) applied across large areas enable the area to become a system, measuring, reporting, and enabling complex response.

Surfaces can then be interconnected and linked to external networks of systems and extend capabilities ("the cloud"). The possibilities of NR applications are endless. The devices would become a new "platform" like the Internet or smartphone apps.

II. RFID Technology

A. History

The original RFID was conceived in July 1969, patented in May 1970, and issued January 1973 by Dr. Mario Cardullo (US 3713148 A). Since then, hundreds of billions of RFIDs have been produced and used for tracking, inventory, and other related purposes. The impact of RFIDs has been multifaceted since inception in 1969, with applications in transportation, logistics, medicine, agriculture, retail, manufacturing, military, architecture, finance, real estate, and security (to list a few general areas). [1], [2]

One overarching trend in the development and proliferation of RFIDs is scaling and miniaturization, while also increasing their capabilities. [3], [4] Both classes of RFIDs, those using only incoming radiation (passive RFIDs) and RFIDS with discrete power systems (active RFIDs) have becomes smaller and more capable correlating to Moore's Law. Now we are at a point in technological development when it is possible to build far-smaller RFIDs incorporating a nano-computer (microprocessor) as small as tens of square microns and imperceptible to the human eye. This would allow placing a communication and computer systems even within blood cells, or engine parts, fuel, food, everyday items. Only the imagination would be the limitation on what NRs could do.

III. Basics of nano RFID/Computers

A. Communication Ability

Antenna size effectively dominates the size of an RFID device. To make microscopic RFID that might be seamlessly and unobtrusively integrated into materials and coatings, the RFID antenna needs to be microscopic, e.g., smaller than the width of a hair (<0.1 millimeters). This in turn is limited by the size of the EM itself. For example, the EM that is used for Wi-Fi at 5 GHz has a size (wavelength) of 60 millimeters. Antennas become less efficient as they are made smaller than half of the EM wavelength size to which they are tuned. Below about 1/40 of the wavelength, antenna efficiency becomes negligible. [2]

To realize functional prototypes, we optimized for wavelength and technology. To do so, we began development of Near Infrared (NIR) nano RFID/computer systems. At a 1-micron wavelength, a NIR antenna can be the size of a big virus, and much smaller than a cell. In fact, this size regime enables entire NIR antenna arrays to be built at invisible scale. This technology is sometimes called an "opticalnanoantenna". The reader for our prototypes, was a state-of- the-art, palm sized spectrometer. This powerful, flexible tool enables development in the lab and field testing as well for it iscompletely portable, stand-alone system.

These prototypes were leading to our first product. This was a microscopic transponder designed to invisibly provide multimodal authentication (MMA) for objects to which it is applied. An extension of this technology was one which integrates sensor functionality into the platform. Characterization of chemical hazards, biometrics, or physical properties such as temperature, acceleration and pH are envisioned.

The next stage would have been an integrate memory and logic into the RFID for data logging and more advanced applications. Finally, a product which can function as a node in a network for coordinated, distributed functionality: sensing, communications, computation, and control.

B. Size

With these well-known advantages for ultra-miniaturization of electronics, it may be surprising that the smallest RFID systems being marketed today are relatively large, with many marketed devices being multi-millimeter in scale and elite devices topping out at 50 microns in their smallest dimension. PharmaSeq was awarded SBIR funding to create a series of devices starting at 250 microns and decreasing in subsequent generations to be implantable within cells. [7] However, PharmaSeq will be faced with the problem of a suitable antenna system.

The most significant impediment to progress in shrinking the size of NRs is antenna scaling. For 2.4 GHz communications systems, currently one of the standard antenna designs is relatively large, with compact designs down to a few millimeters in the literature. [8] – [13] The "antenna problem" represents an impediment, which must be solved for ultra-miniaturization to progress. As the size of the device decreases the amount of radiated energy the device receives also decreases, thus making communication with the device more difficult and unreliable – and requiring the communicating device to be closer and closer to the material in which the NR resides.

The antenna problem has several potential directions for resolution. Surface plasmon resonance technology has enabled nanoscale antennas to be created that operate from terahertz to optical frequencies. Printed metamaterial-array technology has real potential to aid scaling. [14]- [17] But a key to effective use of these approaches may well be augmentation through the integration of multiple devices as a "swarm"— a coordinated ensemble to network *in situ* to improve the communications range and or bandwidth. Ensembles of NRs may act cooperatively and collectively. [18] In this approach, the myriads of NRs would have a multiplier effect with the swarm antennae receiving energy and distributing it among all the NRs. Each device's antennae are individually nanoscale. The plurality of antennae on each device and the plurality of devices harnessed collectively in the swarm increase the receiving and transmitting "gain" of electromagnetic (RF, optical) radiation signals. This potentially would enable NRs to extend their communications range in some cases enable communication with the NRs that otherwise be impossible.

C. Manufacturing NRs

The smallest RFIDs are currently being manufactured in 90nm CMOS technology and have an area of approximately 2500 um^2. By employing the current most advanced CMOS manufacturing technology – 15nm node – these same device capabilities can be shrunk to the size of a red blood cell (~8um diameter), or, with modified layout, to submicron dimensions in width, for example.1 Fabrication using MEMS techniques and SOI technology will facilitate device release from substrate and multi-chip integration and packaging.

The principal challenge will be fabricating suitable antennae elements for devices in the micron and sub-micron scale. We envision employing techniques such as seeded nanowire growth and directed self-assembly to form and/or connect antennae and potentially ancillary modules to the NR devices. Antennas may incorporate many nodes where NR devices connect, allowing multiple devices and antennas forming synergistic arrays. While there is R&D in reducing the size of RFIDs to nano scale the major IP of the team was the introduction of self-assembled, metamaterial and "swarm" antenna solutions coupled with the introduction of a distributive nano computer system.

Roll-to-roll nanofabrication techniques are poised to reduce micro manufacturing costs even further and have been the subject of early testing at nR. Indeed, the dramatic improvements of microlithography, deposition, etch and planarization enables significant cost reductions through the application of fully depreciated nanofabrication technology, currently in the 15nm node for flash memory (the 10nm node is about to be marketed for high end logic). [6]

D. Programming NRs

The NRs would need to be programmed for specific functions. This could be achieved either by designing the materials and circuitry of the nano devices to function in a specific manner (hardwired design of both passive and active NRs, including reconfigurable semiconductors like EPROMs) or digitally programmed with software (primarily active NRs in the near future due to power requirements). In its simplest form, the analog response of a passive nano-RFID isprogrammed by its unique structure. These devices can provide identification tagging, authentication, and remote sensing functions, with sensing including from temperature, magnetic fields, and humidity, to chemosensors for electrolytes, pH, toxins, and other chemicals. Somewhat more complex, active nano-RFID devices would be digitally programmed in manufacture with read-only memory. Even more complex systems would be re-programmable and would run autonomous and networked algorithms. Power, size, and bandwidth constraints may be offset with collective behavior atthe expense of latency.

E. Inserting NRs

To obtain detailed information from various components of a complex system, the NR devices may be deployed in avariety of ways, depending upon the type of information and the kind of system. Nevertheless, while medical applications differ from industrial uses in terms of specifics, the strategies for deployment are similar, emphasizing unobtrusive integration of information handling nodes close to the source ofthe desired information.

Medical applications would require forms suitable for topical application (static or trans-dermal patches, powder, lotion etc.), inhalation (aerosol), ingestion or injection of NRs devices into a living host. Appropriate formulation analogous to a pharmaceutical, including testing for safety, would be requisite. Truly sub-micron scale devices would be inserted within cells or even organelles using methods analogous to gene transfection technology (Biolistic, electroporation, etc.).

Industrial and consumer applications allow strategies including incorporation into the materials of construction— for example, stress sensors in high-load concrete, vibration sensors in critical aerospace joints, wear monitors in bushings and seals. Other strategies may comprise incorporation into tape, decals, patches, and adhesive materials, paint, and specialty coatings. Any region that can tolerate a blood cell-sized inclusion at ambient temperature is a candidate location for a NR.

F. Operating NRs

The NRs would be interrogated and operated by the means of a transceiver device. In this instance, the transceiver would send out a signal of a specific frequency or set of frequencies, which would serve to power the system and send and receive data. The most effective frequencies would vary among applications and systems. Near infra-red (NIR) and IR wavelengths will be useful in medical, industrial and consumer applications for relatively close to the surface applications. Millimeter wave and terahertz frequencies have significantly better penetrating ability. It is important to recognize that the size regime of the device is smaller than even millimeter waves, which makes antenna design at these wavelengths morelimited. While terahertz NR devices may be envisioned,

[1] Note regarding size that the red blood cell layout just provides an example for a feasible device size that could navigate within the human body. Using the same area to accommodate the circuitry, but employing a width approaching micron scale, would be achieved in a filament several hundred microns long. This layout may even allow antenna fabrication, or at least a significant portion of the antenna fabrication during the CMOS flow.

current performance limitations in the technological infrastructure are expected to delay NR applications here.

Dermal and transdermal medical applications may be able to use IR and near-IR light, while deeper insertion of devices into living systems will necessitate use of longer wave lengths, which have deeper penetration capability. Similarly, for industrial and consumer applications, near-IR and IR would be potentially useful for surface treatments, while longer wavelengths would be necessary for buried or obscured locations. Antenna design and fabrication is therefore intimately related to the specific requirements of the application. Advanced systems of NR devices may rely on relaying information from device to device as a mesh network (like cell phones talking one to another to another to create a communications system that is not dependent on cell towers) to partially address these concerns. This "swarm" approach should be scalable and tunable to meet the different demands and conditions of various uses of NRs

Once the NR is energized by the external signal, operations are straightforward. Low input power can extract a fingerprint spectrum from a passive device and can interrogate a limited number of onboard sensors. Encoded in the transmission of power to the device or as a secondary channel, digital instructions would be received and decoded by the NR and sent to an onboard microcontroller, which then would orchestrate the functions of memory, sensing and communications. One key feature of this approach is that advanced systems form networks allowing multiple devices to share information and compute in a distributive and resources. In an extension of this approach, specific NRs in the same "swarm" of NRs will have different functionality and logic—for example, dedicated relay devices might aggregate, and retransmit information harvested from local sensor devices.

G. *Cost of NRs ecosystem*

In considering the application of NRs, it is important that a total ecosystem cost be developed. The cost analysis for this major new technology ecosystem will vary from application to application. In simple applications, such as inventory tracking within a supermarket, the cost of NRs may be much lower than existing systems. In this case, the labels of the various products would have embedded the NRs for both inventory control and check out. Such a system would also reduce the cost of restocking as dates for products are accessed at check out. Moreover, consumers can be charged without the need ofclerks. At home, the NRs would enable consumers to monitor what they have within their residences. There are many other possible applications using simple NRs, many of which cannot be foreseen now, just at the ideas and functions behind the more than 1.5 million apps for the iPhone were not imagined by its inventors when the device debuted in 2007.

For the microscopic, red blood cell-sized NRs manufactured on 300mm wafers, the number of potential die (units) would be on the order of 1 billion. With the cost of a 300mm wafer manufactured in a 14nm flow (est.$10K); the unit RFID cost would be on the order of $0.00001 ($10K/109).Post processing for attaching antennae, separation fromsubstrate, "packaging" and testing, etc., would increase the cost by perhaps a factor of 3. Even with substantially costlier post-fab processing steps, the NRs unit cost would be very attractive. Implementation of roll-to-roll Flex manufacture stand to reduce manufacturing costs for commodity NRs as much as 5 to 10x over high end wafer-fabricated NRs.

In more complicated applications, such as auto monitoring and biomedical, the cost would be higher. However, now is not possible to determine the cost of this or for that matter any NRs ecosystems.

IV. VALUE

The multi-mode authentication (MMA) market is currently $5-10B with an estimated growth rate of 15-18% per year to 2022. The RFID market is currently $10-12B with an estimated growth rate of 10-12% per year. [3], [4] These estimatesare for existing markets, nR's technology will likely open many new markets that don't currently exist for existing RFIDs since of size limitations. We estimate the cost of nano RFIDs to be on the order of $0.00001 per unit, based on standard VLSI nano-electronic manufacture.

We believe that a significant fraction of the growth in both markets is addressable with nano RFID and that potential products represents a point of entry that is a solid tactical and strategic opportunity. These products combine simplified process integration, extendibility with the low cost of ownership of NIR technology. Compared to millimeter-wave and terahertz technology, NIR is lower risk, lower cost, and leads to physically smaller devices sooner.

A United States utility patent was issued to Cardullo, "Nano RFID Method and Device", Patent #9,639,797 (issued May 2, 2017. This patent describes the various ways to accomplish these objectives.

V. POSSIBLE APPLICATIONS

Successful ultra-miniaturization of RFID technology has the near certain potential to expanding many current applications and open entirely new application that rely on compact packages (i.e., aerospace, security, biomedical), and/or low cost (retail, agriculture, logistics). New applicationsinclude swarm-based remote sensing, process control, biological mapping, therapeutics and diagnostics, authentication, ecological monitoring, soil and water analysis, air quality reporting, inventory control, materials QA, andmany others.

A. *Biomedical*

In a biomedical application, it is possible for NRs to collect data on certain vital functions if those devices also contain specific sensory capabilities. At the same time, NRs are possibly the only way to collect this data, as the sensors must be nano-sized to collect data on these vital functions. These sensors then use the communication functions of the NRs to transmit that data to the interrogator. Moreover, the NRs can also be used to deliver specific medications to a designated area within an individual, such as to a cancer cell. Since the device can receive signals, its location can be tracked by the reflected data. Early passive devices would provide unique identification and authenticity, leading to basic chemosensing. Advanced active devices will integrate event counting, data- logging and time stamping functions, enabled through couplingto external power.

Biomedical applications include the potential for extracellular as well as intracellular implants for diagnostics and therapeutics. Neuronal implants could yield very precise manipulation of signal processing (i.e., seizures, input-output errors, tinnitus). It may be possible for NRs to enter the brain via the circulatory system, and then locate adjacent to key synapses to deliver information and or pharmaceuticals. Man-machine interface may be facilitated in this way, enabling information to be encoded directly (direct-write) into the optic and auditory nerves from external sources (potentially direct-write of information into the areas of memory and processing). Wirelessly read implanted arrays of microscopic sensors would facilitate detailed extraction of complex representations of information being processed within the brain without distorting the delicate living connections therein.

Entire organs may be monitored in 3 dimensions with suitable miniaturized NR devices introduced intravenously or implanted within the organ. The applications of NRs to vials, petri dishes, microwell plates, cell culture media, and other consumables allows precise tracking. The tracking of medicine can ensure correct doses are administered at correct times with logging of salient data (identity, approval, storage location, inventory, authenticity, ownership, etc.). An audacious proposal is incorporation of nanopore technology that could enable proteomics and other "omics" data to be acquired locally and compared across organs and entire individuals to map gene expression. Incorporation of antibodies into NRs would enable the self-directed tagging of specific cell types and tissues of every organ. Once tagged, the NRs could assay through onboard sensing and then render treatment at thatlocation for example, a magnetically susceptible tag could be inductively heated to destroy a small volume of tissue with precision. Extensive studies and testing of the long-term effects of insertion of NRs into the human body would be required before these devices could be approved for use in humans.

B. Commercial

In a commercial application of NRs, the potential uses are numerous. These devices can be embedded in the surface of any item. This can provide a means of tracking of those items such as batch number, date of expiration, cost, location, and have the ability for this or similar data to be updated.

Therefore, inventory control could become a much simpler task. NRs can be embedded in such things as paint so that it is possible to determine when a room was painted what was the original colors, etc. These devices could also be embedded in many items to determine if they are counterfeit or original. Most of the above identification/authentication functions may be achieved in suitably developed passive devices

A possible application of NRs is in the automobile industry. The devices could be implanted in each component of the vehicle. Coupling these devices with sensors it may be possible for real-time feedback from any of the vehicle's components. This could include such things as stress levels, failures, need for repair, or other data, which possibly can then beretransmitted to both the owner of the vehicle or the manufacturer. If the NRs were injected into the fuel, they could potentially provide feedback to the vehicle's control system to adjust the efficiency of the engine's consumption of fuel. The application of these devices would also assist in finding stolen vehicles and external tracking of the vehicles.

Another commercial application of NRs is in the airline industry. Counterfeit parts for commercial airlines are a problem posing especially great safety hazards. Coating of airline parts by a manufacturer in such a way that the coding could not easily be removed, could ensure that the part was genuine. NRs also could be integrated into parts subjected to vibrational stress to identify wear as well as to track the parts from cradle to grave, especially those with critical replacement schedules. On engineering test stands, these invisible devices could provide strain gauge, thermal and vibrational measurements with high spatial resolution. Propellant, coolant and environmental systems might include chemical sensing functionality to identify leaks and provide control data.

Security applications for NRs include invisible and difficult-to-remove tracking devices, including providing biometric data on individuals. Specific locations may be unobtrusively marked allowing precise relocation at later time, with the remote extraction of data. The potential of creating very large arrays of nano-devices may enable significant range, allowing advanced systems to provide real time networking and location information. High signal strength, high-resolution interrogation of very large sets of these arrays might be accomplished from mobile platforms to provide detailed information from specific areas of interest.

NRs systems internal encryption and the system's complexity provides unique challenges to would be forgers and counterfeiters- the application of many types of unique identification is "Multimodal Authentication" MMA. The nano-architecture and materials science of NR design allow for intricate MMA attributes to be encoded with virtually no impact on overall NR size. Ownership may also be authenticated through biometric data. Identifying signatures on NRs may include unique characteristics such as field dependence or multiplex band response. Munitions and arms, documents, containers, currency, vehicles, personnel, materials, infrastructure, territory may be tracked and interrogated for data provided by onboard sensing. Highlysensitive systems (CBN systems) may be authenticated. [2] Interlocks may be designed with integrated NR to assure safe

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[2] This application is analogous to MEMS systems developed at Sandia National Labs in the early 2000s but would be considerably more efficient both in application and cost.

operations—an additional feature here is that the historical state of the system (when interlock has been activated and for how long) may easily be tracked, potential capturing biometricdata.

NRs directly enable the Internet of Things (IoT) for retail purposes. Packaging can track expiration, storage, and quality of contents. A classic example is a refrigerator that monitors its own contents, where each item inside can report to the refrigerator its individual history. This extends to all consumable materials inventories—cold storage warehouses, transportation, displays, production lines. Wearables may coordinate invisible networks of NRs collecting user data. Compatibility of tools, cartridges, and modules within the systems they are associated with can be assured. In this way, substandard counterfeit parts can be eliminated from critical spares.

NRs could be employed for a home inventory system. Product packages with embedded RFID contain information such as use date, buy date, and contents. An external interrogator, such as a refrigerator, pantry, or handheld device, could quickly assess what buying decisions may be necessary to keep a family or community provisioned.

C. Agriculture

Agricultural applications include on-site soil science (moisture, fertilizer, temperature, minerals), monitoring of plant growth and ripening (ethylene sensing), and tracking of agricultural products for quality. To monitor quality, dilution with substandard material could be ascertained by monitoring the concentration of NRs within a freight car of grain, corn syrup, protein concentrate, meat, etc. Similarly, the application of pesticides and fertilizer could be precisely tracked if NRs were incorporated into these materials at constant levels and then assessed as deposited or after. Early passive NRs for basic tagging/identification would lead to more complex humidity, temperature, and chemo- sensing, ultimately including micronutrients, biomarkers for maturation, rot, fungi, and pest. As noted above, the history of storage conditions could be ascertained to ensure safety and food security through reduced spoilage and contamination. Water quality could be determined and monitored through incorporation of NR-sensors in water storage and delivery systems, for example monitoring arsenic, turbidity, chlorination, etc.

D. Military

The military applications of NRs could change warfare, as we know it. The obvious uses of these devices for tracking of materials, personnel, and operations can greatly improve the logistic of the military. Many of the commercial uses discussed above are also applicable for military uses. However, consider the application of NRs for “friend or foe” identification. While larger RFIDs can possibly be compromised, those embedded in clothing, individuals’ skin or for that under the skin of personnel, may be difficult to counterfeit or detect. This would also accommodate more easily identifying personnel who otherwise due to injury resulting in death could not be easily identified. Basic authentication/identification functions achieved with earliest, passive designs. The NRs could acquire data on the chemical environment of the device as a remote sensor, and the NRs could contain medical data that could be accessed immediately to administer to a wounded, injured or sick person.

The weaponization of NRs may be possible. One example of an NR weapon is like the medical device to specifically deliver a substance, action or energy to the surface or from within the target. The weaponized NR may debilitate or kill combatants without revealing the presence of the NRs. However, the international laws may prohibit certain applications of weaponized devices – and in fact, the NR community could lead the way in proposing international bans on such weapons under the Biological Weapons Convention (BWC) and the Chemical Weapons Convention (CWC). Weaponized (and surveillance) NRs indeed have potential to generate unique ethical concerns regarding design, application and proliferation.

E. Environmental

Environmental monitoring could be an application. Air and water transport could be monitored downstream from and upstream release. NRs could be used directly, or mounted on aerodynamic assist systems (dandelion seed, insect, MEMS). As discussed above, array enhanced signals could allow for significant standoff in the case of monitoring or assessing hazardous environments. One environmental aspect is the fate and degradation of NRs. It has been clear that engineered durability is important in nano cosmetics (polyurethane microbeads have been replaced, for example due to bioaccumulation). Environmental fate is an additional consideration with functional as well as ethical considerations.

F. Other

Many of the applications above are process control applications. Industrial processes may be monitored in detail by use of NRs. Circulating coolant can report temperature at key locations, potentially mapping turbulent systems. Conditions within bioreactors might be mapped in 3-D (pH, lactate, Ca++, etc.). Fluid flow, loading, temperature, vibrationare ubiquitous data in chemical engineering that may be captured with high resolution. Reporter-NRs might be incorporated in drug intermediates in process and be used to track reaction rates, process time for the batch, etc.

VI. Disrutive Technology

Successful ultra-miniaturization of RFID technology has the near certain potential to expanding many current applications and open entirely new applications that rely on compact packaging (i.e., aerospace, security, biomedical), and/or low cost (retail, agriculture, logistics). New applications include swarm-based remote sensing, process control, biological mapping, therapeutics and diagnostics, authenticity verification, ecological monitoring, soil and water analysis, air quality reporting, inventory control, materials QA, and many others.

However, this may be a very disruptive technology to existing systems. Creating meshed RFID/computer systems which have very low cost will have considerable consequences to the device industry. Consider that an intelligent surface which is powered by harnessing ambient energy present within the environment of the system. Envisioned wearable computer system consisting of a meshed nano devices interacting with intelligent surfaces and costing orders of magnitude less than current systems.

The nano RFID/computers can open the way for many services which are either difficult or costly to currently implement.

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