Need for a Trillion Sensors Roadmap

Sensor absorption in the mobile market (cell phones, tablets, games, cameras, etc.) exploded from 10 million units in 2007 (triggered by the emergence of the iPhone and WII gaming console) to 3.5 billion in 2012. Interestingly, none of market research organizations projected such growth in 2007.

Currently, select visionary organizations foresee the sensor demand growing from billions in 2012 to trillions within the next decade. The demand is expected to be driven by emergence of sensor based smart systems fusing the computing, communication and sensing. Such systems target supporting global evolution and solutions of global problems (hence large volumes) ranging from integration of more sensing functions into mobile devices, to elimination of hunger on earth, reduction of global warming, development of green energy and clean water, slowdown of global population growth, reduction of skyrocketing cost (and lack of) medical care, etc..

Similarly to 2007, none of the market research organizations has a trillion sensor forecast, although, as shown in Figure 1, a number of visionary organizations do.

Historically, sensor technologies have had long development cycles, about 20 years to volume production. Such long commercialization cycles result from deployed "multi-physics" and "multi-bio-chemistry" complexity, and lack of standardization (one product – one process – one ASIC - one package - one test system). Without focused commercialization efforts and availability of standardized development and manufacturing infrastructure, the development and scalability of sensors will be delayed, undoubtedly delaying Abundance.

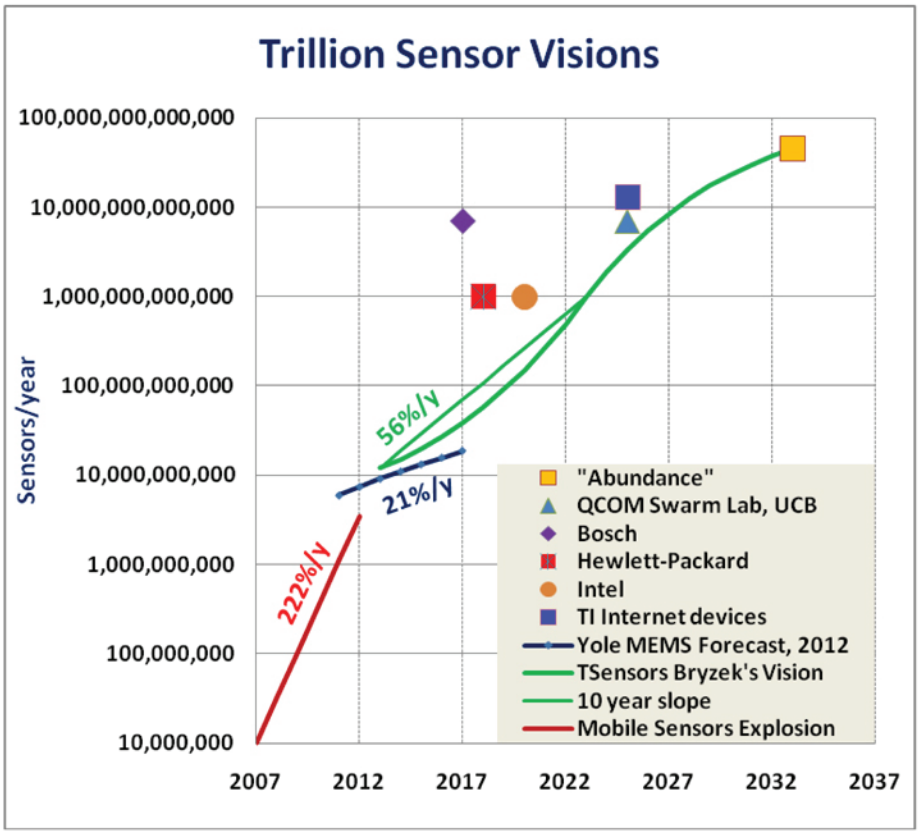

Figure 1. Mobile sensor market for volumes *not envisioned* by leading market research organizations in 2007, grew exponentially over 200%/y between 2007 and 2012.

Several organizations presented their visions for a continued growth to trillion(s). Market research companies don't yet see this growth (see Yole's forecast). So the explosion to trillion(s) is likely to be driven by applications *not yet envisioned* by leading market research organization.

As sensor development has been historically much longer than pure semiconductor technologies, TSensors Roadmap development is being launched to improve visibility of needed sensors to enable their accelerated development.

The analogy between 2007 and 2013 (lack of explosive sensor market growth visibility by market researchers) combined with a long sensor development cycles, pushed one of MEMS commercialization pioneers Dr. Janusz Bryzek (with 7 Silicon Valley MEMS startups behind), to develop an approach deemed likely to accelerate development of emerging sensors. The effort has been supported so far by volunteers and MANCEF (http://www.mancef.org/), MEPTEC (http://meptec.org/) and MEMS Journal (http://www.memsjournal.com/).

Pointers to a Potential for Trillion Sensors

In 2012 only four sensors (microphone, acceleration, gyro and compass) shipped about a billion units each. Now, multiple pointers imply a potential sensor market growth to a cumulative trillion units by 2022.

Several *global* tides are building momentum and have started to generate a large demand for sensors. Such waves include:

- Exponential Technologies outlined in Abundance[1] enable growth of supplies and services in excess of the global demand for them. In just one generation (20 years) they are expected to create abundance. Eight technologies classified as exponential include:
  - Biotechnology and bioinformatics
  - Computational systems
  - Networks and sensors
  - Artificial intelligence
  - Robotics
  - Digital manufacturing and infinite computing
  - Medicine
  - Nanomaterials and nanotechnology.

  Sensors are not only one of the eight exponential technologies, but are also embedded in other exponential technologies. Abundance[2] projects the need for 45 trillion networked sensors helping to solve global problems such as shortage of food, energy, water, healthcare and education for *all* people on earth.

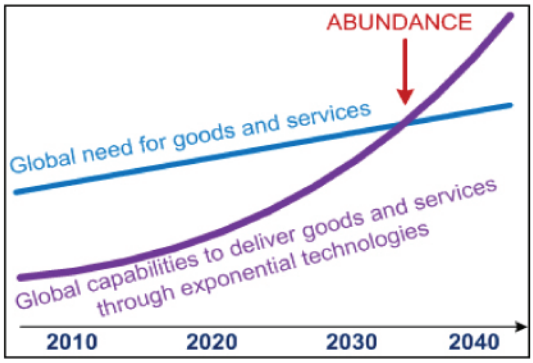

Figure 3. Exponential technologies promise growth of goods and services to match global demand for them within one generation, enabling Abundance.

- Emerging Technologies are defined by World Economic Forum[1] and Cientifica[2] as those that arise from new knowledge or the innovative application of existing knowledge, lead to the rapid development of new capabilities, are projected to have significant systemic and long-lasting economic, social and political impacts, create new opportunities for and challenges to addressing global issues and have the potential to disrupt or create entire industries. Emerging technologies are critical to long-term global prosperity. They represent the innovation that adds necessary economic and social value to materials, products and processes. And they provide potential solutions to a wide range of pressing global challenges including energy generation and storage, health care, climate change, food security and access to clean water.

  The Summit on the Global Agenda 2011 in Abu Dhabi led to the compilation of the Top 10 Emerging Technologies with the greatest potential to provide solutions to the most compelling social, economic and environmental challenges includes the following segments:
  - Informatics for adding value to information
  - Synthetic biology and metabolic engineering
  - Green Revolution 2.0 – technologies for increased food and biomass
  - Nanoscale design of materials
  - Systems biology and computational modeling/simulation of chemical and biological systems
  - Utilization of carbon dioxide as a resource
  - Wireless power
  - High energy density power systems
  - Personalized medicine, nutrition and disease prevention
  - Enhanced education technology

  While broadly diversified, many of emerging technologies represent or use smart systems, a fusion of sensors, computing and communication, thus representing another potential contributor to trillion sensors.

[1] http://reports.weforum.org/global-agenda-council-2012/councils/emerging-technologies/?doing_wp_cron=1351293779.6941258907318115234375
[2] http://www.cientifica.com/consulting/emtech-index/

- The Qualcomm Swarm Lab at UC Berkeley projects 1000 radios per person on Earth by 2025, with trillions of connected devices as the swarm around the edge of the Cloud, to link the cyber and physical/biological worlds. It is reasonable to assume that each radio may support several sensors.
- Internet of Things (IoT)[3] defined as sensors and actuators embedded in physical objects, often using Internet Protocol[4], seems to be crossing the Chasm in a path to market Tornado[5].

  Libelium[6] and Beecham Research[7] forecasts IoT deployment in the following market segments:
  - Smart Cities
  - Smart Environment
  - Smart Water
  - Smart materials
  - Energy and smart metering
  - Security, public safety and emergencies
  - Retail
  - Logistics and transportation
  - Industrial controls
  - Smart agriculture
  - Smart animal farming
  - Domotic and home/buildings automation
  - eHealth and life science
  - IT and networks
  - Industrial

  Major IoT sensor applications are expected to include:
  - Information and analysis, such as
    - Tracking behavior of persons, things and data through space and time
    - Enhanced real time situational awareness of physical environment
    - Sensor driven decision analytics through deep analysis and data visualization
  - Automation and control.

  Along the way more and more objects will get embedded sensors and gain the ability to communicate. The resulting information networks promise to create new business models, improve business processes, and reduce costs and risks[8].

  In current China's 12th 5 year plan, IoT was promoted to one of the seven Strategic Emerging Industries with 5 Billion RMB of government funding allocated during the next five years[9].

  Apple is rumored (2013) to be working on a platform for IoT[10].
- Bosch presented[11] a vision for 7 trillion sensors (sensory swarms) to serve 7 billion mobile subscribers by 2017. As a starting point, up to 18 sensors have already been embedded in mobile devices today, close to 100 in high end cars and up to 100 in high end smart homes. Bosch's vision forecasts growth to about 1000 sensors per average person by 2017, which based on the referenced examples, is not an impossible stretch over the next 5 years.
- Hewlett Packard, in multiple presentations from 2010 to 2012[12], introduced a Central Nervous System for the Earth (CeNSE). CeNSE is based on detectors and actuators, forecasted to reach trillion units by 2018. Key market segments include:
  - Climate monitoring

[3] http://www.technologyreview.com/view/509546/2013-the-year-of-the-internet-of-things/
[4] McKinsey: http://www.mckinseyquarterly.com/The_Internet_of_Things_2538.
[5] http://www.chasmgroup.com/
[6] http://www.libelium.com/top_50_iot_sensor_applications_ranking.
[7] http://beechamresearch.com/article.aspx?id=4
[8] http://www.mckinseyquarterly.com/The_Internet_of_Things_2538
[9] http://technode.com/2012/05/14/internet-of-things-not-just-a-concept-for-fund-raising/
[10] http://gigaom.com/2013/02/12/apple-patent-points-to-platform-for-wearable-sensors-internet-of-things/
[11] Muenzel H.: MEMS from Automotive to Consumer Electronics. MEMS Technology Summit, Stanford University, October 2010.
[12] Friedrich R.: CeNSE: *Awareness* through a Trillion MEMS Sensors; *the decade of* sensing *and* sense-making. MEPTEC, May 2012.

- Oil exploration and production
- Assets and supply chain tracking
- Smart highway infrastructure
- Tsunami and earthquake warning
- Smart grid and homes
- Structural health monitoring

- Intel presented[13] the emergence of sensors for Context-Aware Computing. Sensors supporting such systems are expected by Intel to absorb a trillion sensors by 2020-2022. Out of trillion sensors, 70% will be solving problems and 30% will be enhancing lifestyles. The applications will include:
  - All around me and my needs
  - Understanding situations (e.g., mood of the person you meet).
  - All around devices
  - Personal health
  - Social interactions
  - Planet context
  - Universe context

- Texas Instruments outlined in their presentation[14] the vision for growth of Internet connected devices to 13 trillions by 2025, with major markets being fixed and mobile communication, computers, industrial, medical, military and aerospace. They expect MEMS, specifically sensors, to be the enabling technology for such growth. The Intelligent Ambient, based on wireless sensor nodes, will adapt, anticipate, be transparent, dependable and autonomous.

- IBM unveiled the seventh annual" IBM 5 in 5" – a list of innovations that have the potential to change the way people work, live and interact during the next five years. These five sensor/actuator innovations include:
  - Touch: You will be able to touch through your phone
  - Sight: A pixel will be worth a thousands words
  - Hearing: Computers will hear what matters
  - Taste: Digital taste buds will help you to eat smarter
  - Smell: Computers will have a sense of smell

  The IBM 5 in 5 is based on market and societal trends as well as emerging technologies from IBM's R&D labs around the world that can make these transformations possible.

- Apple filed patent application[15] for a "personal items network" based on movement-monitoring devices. The said system would link various items such as smartphones, tablets, PCs, watch, wallet and even credit cards through sensors. The patent application details: "The invention relates to sensing systems monitoring applications in sports, shipping, training, medicine, fitness, wellness, and industrial production. The invention specifically relates to sensing and reporting events associated with movement, environmental factors such as temperature, health functions, fitness effects, and changing conditions."

  The movement monitoring devices (MMDs) can attach to virtually any item and any one. The sensors record "temperature, humidity, chemicals, heart rate, pulse, pressure, stress, weight, environmental factors, and hazardous conditions."

- Harbor Research considers Smart Systems the biggest business opportunity in the history of business[16]. They define Smart Systems as a fusion of computing, communication and sensing in the era of pervasive Internet, wherein people, devices, sensors and businesses are connected and able to interact.

- Digital Health/eHealth/mHealth based on mobile platforms (cell phones, tablets, etc.) emerges as a solution to the skyrocketing cost of medical care, aging population and lack of medical care in developing countries. The enabler will be sensors. Visible examples of the evolving market include:

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[13] Bhide S.: Emerging Usages & Apps for Sensors in 2016+, MEMS Business Forum, May 2012.
[14] Ajith Amerasekera: Ultra Low Power Electronics in the Next Decade. 2012 MIG Congress, October 2012.
[15] http://forum.eetasia.com/FORUM_POST_1000039352_1200248334_0.HTM?click_from=8800100836,9950212903,2013-02-16,EEOL,NEWSLETTER
[16] Harbor Research: The Emergence of Smart Business, 2011.

- At 2013 CES Show in Las Vegas, there were 19 Digital Health conference sessions and 350 exhibitors in Digital Health section.
- Qualcomm announced in 2012 a $10 million Tricorder X PRIZE[17], a 42-month competition to bring the sensing of 15 most common human diseases to the cell phone.
- Samsung announced a similar competition[18] with a $2.25M prize.

- Emergence of location based advertising, and forthcoming location and activity based advertising will be based on sensors in the body, on the body and out of the body. These systems need personal behavior information derived from sensors.

The new volume applications for sensors continue to be announced…

Jobs… Jobs… Jobs…

Forecasted exponential sensor market growth will result, if materialized, in massive creation of new jobs.

Let's assume an average revenue per employee in developed countries at $200,000/year for component companies and $500,000/year (equal to 2011 average for the US NASDAQ 100 companies) for smart system companies.

Let's further assume an average selling price of the sensor at $0.13 in trillion units/year volume. This would represent a $130 billion 2023 revenue level, translating to 650,000 new direct jobs.

Systems enabled by sensors (including hardware, software, data processing, data storage, etc.) will create much higher revenue. So far sensor cost in high volume mobile applications averaged about 2% of the system cost[19]. Assuming this ratio holds, systems enabled by sensors would create 50 times higher revenue, $6.5 trillion (5% of global GDP). This would create 13 million new direct jobs.

Typically, the job multiple for indirect jobs resulting from knowledge workers has been between 2 and 4 (depending on region). Assuming the midpoint of 3, this would result in three times as many indirect jobs, for a total of about 55 million new direct and indirect jobs in developed countries.

As a reference, the US created only 1.3M new jobs in the last 10 years, primarily in Government and medical sectors.

As sensor based systems require a high-tech work force, the majority of created jobs will likely be for knowledge workers. An example of a sensor based system could be Apple's iPhone 4s, which had the following breakdown of 2011 selling price[20]:

- 3% ($14) assembly (China)
- 32% ($178) components (global)
- 66% ($368) Apple's share (US)
- 100% ($560) selling price

If the iPhone model holds for emerging sensor based systems, most of generated jobs would be for knowledge workers located in the developed nations. TSensors implementations thus have a potential to overshadow most other job creating approaches considered by Governments. It may also force Governments of different countries to compete for these jobs…

[17] http://www.qualcommtricorderxprize.org/
[18] http://www.nokiasensingxchallenge.org/
[19] Galvin G.: On the Road to $1T. COMS2012, June 2012.
[20] Fortune Magazine 2011

Ultra High Volume Challenges

One of the enabling factors for the continued explosive growth of sensors to trillions will be the selling price.

Global GDP will likely be around $130 trillion in 2013 (Figure 2). Trillion sensors can't represent more than perhaps 0.1% of GDP, implying the unit selling price under $0.13. This price will need to include sensing element (or sensor arrays) with computational resources, communication, packaging and often powering capability.

Such price level will create challenges for all involved technologies, from sensor fabrication to signal processing and communication. Forexample, assuming a chip scale packaging, such smart sensing system-on-chip would have to be on the order of 1 mm^2, representing more than an order of magnitude footprint reduction from current state-of-art. At this die size, wafer requirement would be a challenging 100s millions of 8" MEMS/IC wafers.

Alternative manufacturing processes may be required to support required combination of volume and cost. One of such approaches may be a 3D roll-to-roll printing of sensors, electronics and packaging (subset of digital manufacturing, one of the exponential technologies).

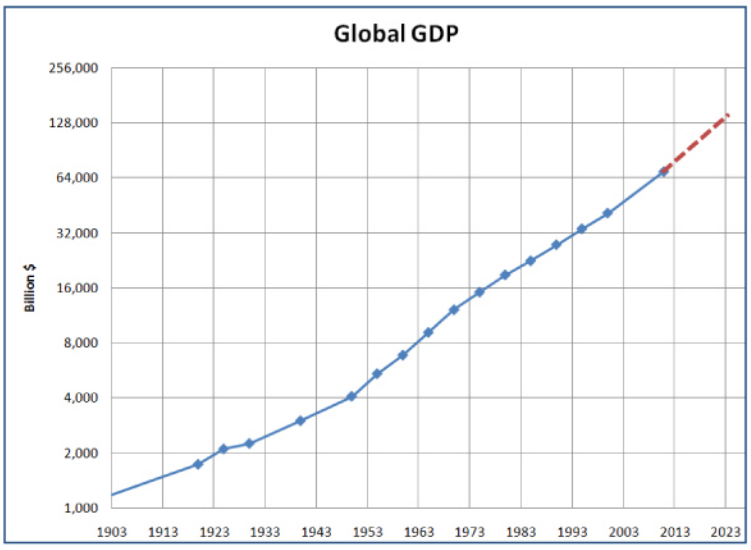

Figure 2. Global GDP is likely to reach $130 trillion by 2023. This forces smart sensor prices to a challenging $0.10 level.
(Historical Data (blue) from Wikipedia. Extrapolation (red) by J. Bryzek.)

Growth to trillions presents also significant scalability challenges to communication and data storage. For example, Hewlett-Packard was forecasting need for a 1000x growth of Internet needed by 2018 just to handle sensor data traffic[12].