TECHNOLOGY ROADMAPS:
A CRITICAL ELEMENT TO SUCCESSFUL MEMS COMMERCIALISATION

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Industry roadmaps are critical to the successful commercialisation of technology and so it has been with micro-electro-mechanical systems (MEMS). “Technology roadmaps were originally developed by Motorola in the 70s in order to align the development of their products and their supporting technologies. Technology roadmaps are part of a methodology that guarantees the alignment of investments in technology and the new development of capabilities, so that they are able to make capital out of future market needs. It is a tool that brings important support to the innovation manager, letting them define the firm’s technological evolution in advance. The tool takes the relationship between technologies, their products and services as well as the relationship with the target markets into account. As a result, the firm’s technological status can be maintained and improved.” [1]

Roadmapping scholars see at least three generations of roadmaps. All roadmapping techniques must reflect the reality of the technology product platforms they serve. The generations are differentiated or categorised as follows:

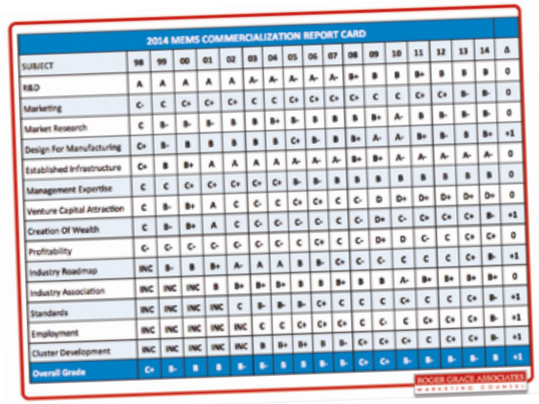
- **1st generation**, something like the Semiconductor roadmap — the technology has known critical dimensions, known manufacturing process, known packaging, known testing, known technology product that are the goals. This approach is applicable for high tech incremental technology base like semiconductor micro fabrication.
- **2nd generation roadmaps** were built for emerging technology product platform environment where this is no agreed upon universal critical dimension, no agreed upon product goals etc. One of the best examples of an Emergent Technology roadmap is the MANCEF MEMS and top -down nano roadmaps.
- **3rd generation roadmaps** are built for multi -technology based product developments, they have exceptionally different boundary conditions, rely more on trends than products and are industry specific. One of the best examples is the MANCEF Pharmaceutical landscape.

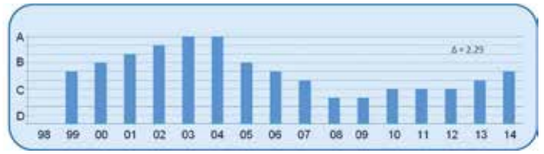
Why roadmaps?

The purpose of technology roadmapping is to bring technology into the strategic conceptualisation and operationalisation of firms, industries and regions. “Industry roadmaps are developed to help accelerate the commercialisation process and road mapping leads to standards,” said Michael Gaetan Ph.D., Project Leader of the Acoustics and Vibration Project at NIST and a long time major force in the development of standards and roadmaps for the MEMS industry including his role as the Chairman of the MEMS Technology Working Group. This group was formed under the auspices of iNemi and the International Technology Roadmap for Semiconductors (ITRS) organisations that recently have individually produced MEMS roadmaps as integral chapters to their roadmaps.

Sparked by a technological foresight work developed by the first two presidents and co-founders of the Micro and Nanotechnology Commercialization Education Foundation (MANCEF) (www.mancef.org) , who are the authors of this article, SPIE published a book [3] in which the authors established the extraordinarily long time of approximately 30 years from discovery to first commercialisation of

<< Figure 1: The 2014 MEMS Commercialization Report Card includes 14 critical success factors for the successful commercialisation of MEMS. The research study, first published in 1998, has tracked the topic of roadmaps since 1999. Courtesy: Roger Grace Associates. >>





<< Figure 2: The 2014 grade for MEMS roadmaps was B and has moved up one grade level each year in the past two years. We believe that the recent interest in the Trillion Sensors Roadmap has significantly contributed to this positive change. The standard deviation of 2.29 for the period 1999-2014 establishes it as the second highest level of all 14 Report Card topics. Courtesy: Roger Grace Associates. >>

several types of MEMS devices including pressure sensors, inertial sensors and chemical and bio sensors. As a result, MANCEF decided to generate the first ever-emergent technology roadmap [4], the MANCEF MEMS Roadmap, in an attempt to overcome this significant barrier posed by a lack of a MEMS and top-down Nanotechnology roadmap. Indeed this and its subsequent additional editions have succeeded in their purpose.

Core Steps in the Roadmap Development Process

The successful development of a technology roadmap is very much based on the level of the support from contributors, who are typically volunteers from the industry to be served. Contributors need to be expert in the chapter(s) of the roadmap to which they will support and must be willing to contribute their expertise to the roadmap process for several years through many conference calls and group meetings. The MANCEF MEMS and top-down roadmap took over four years to complete from kickoff meeting to publishing of the document and required the support of over 400 volunteers worldwide.

The six key steps in a Technology Roadmap development process are [1]:

1. **Research about the object to be analysed**
2. **Development of the Technology Roadmap**
3. **Development of the Roadmap for products**
4. **Generation of a provisional Innovation Roadmap**
5. **Technological benchmarking**
6. **Generation of the final Innovation Roadmap**

Roadmaps and the MEMS Commercialization Report Card

In the MEMS Commercialization Report Card published annually since 1998 by Roger Grace Associates, and whose results have been frequently published in Commercial Micromanufacturing [2], Roadmaps are one of the 14 topics that are addressed in the Commercialization Report Card and that has been tracked starting in 1999 (figure 1). Although roadmap grades have historically been lackluster, the past two years have seen yearly increases of one grade where the 2014 grade is now at a respectable B- (figure 2).

The following are some of the verbatims of the respondents to the recent MEMS Commercialization Report Card study specific to current roadmapping efforts:

<< Figure 3: The Trillion Sensors Roadmap efforts, now as a division of the MEMS Industry Group (MIG), will benefit for the past and future presentations at the Trillion Sensors Summits where the information in these materials will constitute the foundations of the various chapters in the Trillion Sensors Roadmap. Courtesy: J. Bryzek/Roger Grace Associates (Reference 6) >>

- Trillion Sensors showing promise and improving visibility.
- Because of the fragmented markets and products in the MEMS industry, roadmaps don't seem to be adequate. There are obvious directions like in inertial, more axes, lower power, and lower cost. But outside of main established MEMS, it is very hard to set good roadmaps since many people don't seem to know which MEMS products are going to be the big successes.
- Existing roadmaps (MANCEF, ITRS) plus developing (TSensors) are working to point the way.
- MEMS is not an industry therefore there is no industry roadmap. Sensors and display, vision, health systems, auto, and more have clear roadmaps that help guide their future.
- Still too fragmented to have a technology roadmap but T-Sensors and INEMI are making first credible efforts.
- I have not seen one that I believe in.
- This is needed and has been for a while!
- Difficult for MEMS as MEMS is a technology, not a product, and roadmaps generally require alignment to a specific application or market space. This is problematic for MEMS.

As one can see, the comments differ however the consensus of opinions is that MEMS roadmapping efforts are quite important and necessary for successful MEMS commercialisation. However, they are fraught with difficulty, delayed in their development and have fallen short of expectations. But alas — there is hope for the future. With this in mind, let's review some of the more significant past, current and future roadmapping activities that the authors believe are helping to overcome the existing barriers to the successful commercialisation of MEMS.

MANCEF Roadmaps

Several significant roadmaps have been developed specific to the MEMS industry, most notable are the ones developed by the MANCEF with this article's authors making significant contributions to the roadmapping effort. It was first published in 1990, has been updated periodically and is available for sale from MANCEF. In the halcyon days of micro systems and nanotechnologies, the international organisation of MANCEF was founded to serve the needs of the growing emergent technology based commercialisation process. Initially the organisation focused on assisting technology commercialisation based on MEMS and nanotechnologies. MANCEF was founded by many of the leading emergent technology commercialisation leaders of the day, representing both academia and the commercial sector. It initiated a series of conferences, collaborations and printed works that help to accelerate the commercialisation of these technologies. One collaboration with the aid of SEMI (Semiconductor Equipment and Materials Inc), the Engineering Foundation (EF), the US based Sandia National Laboratories, the then German national Laboratory FZK and now KIT (Karlsruhe Institute of Technology), and Netherlands University of Twente MESA (now MESA+) focuses on developing both technology roadmapping and technology foresight. This organisation took the lead in developing roadmaps and technology foresight documents to help fledgling emergent technology based product-based communities commercialise their technology product platforms faster.

To date, MANCEF has generated three major roadmapping efforts and is embarking on a fourth.

The original roadmap had 18 chapters and 450 pages. Well over 400 collaborators from six continents participated for over four years in what resulted as the first ever-emergent technology based roadmapping effort based on MEMS and top down nanotechnology. Over 800 copies were sold demonstrating its high level of industry acceptance. In in the development of the MANCEF MEMS roadmap, it was difficult to engage end-users of MEMS. However, MEMS device developers, capital equipment and materials suppliers, Silicon foundries and software design and analysis organisations provided excellent content and continue to do so.

To date, MANCEF has generated three major roadmapping efforts and is embarking on a fourth. The first, edited by Dr. Steven Walsh and Dr. Job Elders, has been credited with helping to accelerate the commercialisation efforts in MEMS or micro systems and top down nanotechnologies by at least one standard deviation. The second, edited by Dr. Steven Walsh and Mr. Robert Giasolli continue the effort on MEMS, top down nanotechnology but included a small effort on bottom up nanotechnologies discussed the commercial and technology acceleration of these industries and the transformation into at least subgroups (Dr. Al Romig et. al.) that would move toward having the basic design, universal processing and critical dimensions requires to utilise first generation roadmapping techniques and the advent and development of multiple standards relevant to many subgroups. Now others are generating industry specific roadmaps using more traditional roadmapping practice in which MANCEF members are actively contributing.

MANCEF's third foresight and roadmapping effort for emerging technologies was born of the 21st century embraces the multiple root technologies involved in their product development. Edited by Dr. Steven Walsh, Dr. Robert Tierney, Robert Giasolli and Dr. David Tolfree, it required a more industry specific focus. The activity embraced the health care industry where the lines between precautionary medicines, personalized versus doctor directed care, therapeutics, diagnostics and many others were being blurred. Once, not long ago, therapeutics were based on chemical monomer technologies, now therapeutic and diagnostic technology product paradigms are being based on multiple technologies like: tissue engineering; nanotechnologies; biology; complex chemistries; monomer chemistries; MEMS; and computational sciences. This industry is evolving, moving from predominately sick care, to a more proactive one based on health care. The expense of product development and competencies required to produce 21st century health care products has taken product development out of the hands of only large pharma and moved more to consortia of large firms, small firms, academia and federally funded research and development organisations. This necessitated the development of a third generation roadmap activity and the six-year multiple person and continent activity has just been concluded.

Challenges

The emergent technology commercialisation world community has had a major problem since technology roadmapping had been developed for products that were high tech and fast moving and which fit our needs. However, first generation roadmapping typified by the semiconductor roadmapping, had a single unit cell, single process technology, a limited number of product typologies, single critical measurement, universal testing procedure, and single packaging techniques. MEMS and top- down nano technologies as presented in the first MANCEF roadmap were typified by having no universal unit cell, no universal processing technology, few standards, no singularly applied critical dimension, no universal testing procedures, product typologies only limited by creative thought of the product developer, and a multiplicity of emergent packaging techniques. MANCEF realised this shortcoming and did develop a new roadmapping technology for emergent technologies that ended up in being recognised as exceptionally applicable by roadmapping thought generators, roadmapping operational professionals, as well as regions and firms that generated them for guidance in critical decision-making processes.

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Current/Future Activities

MANCEF, currently being inspired by societal, technological and commercial issues has initiated a Trillion Sensor Systems Roadmap effort in conjunction with the Trillion Sensors Roadmap program headed by Dr. Janusz Bryzek. Their focus is on the effective functioning of a world based on abundance that is created through the enabling nature of sensors and other technologies. These principles were set forth by Peter Diamandis and Steven Kotler in their best-selling book, "Abundance" [5]. The editors of the fourth MANCEF foresight and roadmapping efforts are Mr. Robert Haak, Mr. Robert Giasolli, Dr. Yorgos Marinakis and Dr. Steven Walsh. To date, two foresight pieces have been developed and now moving to roadmapping efforts. The concept of tens of trillions of sensors moving the globe to abundance was initiated by Dr. Janusz Bryzek [6] and emanated from many sources including the works of "Abundance". If these future -based sensors that operate mostly through the cloud and more often through edge computation are to find

wide acceptance, the basis or structure of the Internet of Things /Everything will need to change. We need to better codify the technology foresight and initiate roadmapping efforts provide service to the industry.

The European Platform of Smart System Integration (EPoSS) has generated roadmaps and Strategic Research Agendas (SRAs) for Smart Systems Integration. In the last edition of 2013, it has included MEMS in its technology chapter [7].

The most exciting news in the road mapping arena is the Trillion Sensors Roadmap effort founded and led by MEMS industry pioneer and serial entrepreneur Janusz Bryzek, Ph.D. Janusz and his team of over 100 worldwide sensor technology professional volunteers began in late 2013 to develop a roadmap that addressed the sensor technology platforms best suited to support emerging applications that are expected to achieve a "Trillion Sensors Universe". These applications are expected to serve society through several of the concepts put forth in the recent NYTimes bestseller, "Abundance", including the elimination of hunger, lack of medical care, reduction of pollution, creation of efficient energy and availability of clean water thus resulting in an enhanced quality of life for all of the Earth's inhabitants. The road mapping effort is planned to work in conjunction with the previous six Trillion Sensors Summit conferences (www.tsensorssummit.org) that have been produced internationally. Recently, the Trillion Sensors Initiative has become a division of the MEMS Industry Group (MIG).

Dr. Bryzek said: "To support the forecasted demand for 45 trillion sensors by 2034 in order to make the concept of Abundance a reality, I believe that likely 67% of this volume will be represented by new sensors. To accelerate the 30 year development cycle for the full commercialisation of sensors proposed early on by Grace and Walsh [3], we needed a way to help accelerate this process and thus create new sensor solutions that meet the performance, functionality and price requirements of their proposed applications. I believe that a Trillion Sensors Roadmapping effort is a critical item in the realisation of this effort and I am working with many of the world's leading technologists and commercialisation people to create such a roadmap." He concluded: "the results of the presentations at the previous six Trillion Sensors Summits in addition to those to be presented at the Orlando, Florida Trillion Sensors Summit in December 2015 will be reflected in 'white papers' that are planned to serve as major foundational elements in the development of the Trillion Sensors Roadmap" (figure 3).

Summary

The MEMS Technology Roadmap is considered to be a critical success factor in the successful commercialisation of MEMS. Technology Roadmaps were reported to have started in the 70's. In the early 2000's, MANCEF produced the first MEMS and top-down nanotechnology roadmap which continues to be upgraded to this day and is currently in its fourth edition. Most recently, EPoSS (2013), iNemi (2013) and ITRS (2014) have dedicated chapters of their roadmaps to address MEMS. The Trillion Sensors (TSensors) Roadmap, initiated in 2013 has gained immediate and significant attention in the industry and is in the process of quickly ramping up.

As reported in the previous MEMS Commercialization Report Cards, the MEMS Roadmap grades have been less than stellar since they first appeared in 1999; however, the recent increase in grade level from C to B- from 2012 to 2014 holds promise. Verbatims from the recent MEMS Commercialization Report Card study establish that a very high level of awareness currently exists for the Trillion Sensors Roadmap effort and widespread support and hope in the success of Janusz's and his collaborators' activities to accomplish its lofty objectives abound. With the recent involvement of the MEMS Industry Group (MIG) in the adoption the Trillion Sensors Initiative under a MIG divisional title, we believe that the organisational efforts by MIG that produced a successful MEMS and Sensors Standard [8] will be utilised to create the same successful and timely outcome for the Trillion Sensors Roadmap. Janusz and his collaborators welcome other interested parties to join in this effort. He can be contacted at info@tsensorssummit.org.

Want to Learn More?

The next Trillion Sensors Summit will take place in Orlando, Florida on 9-11 December 2015. Several of the approximately 30 presentations scheduled will address the technologies and applications, which address the expected outcomes of Abundance given above. www.tsensorssummit.org

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Dr. Steven Walsh is a Distinguished professor at UNM where also holds the Black professor of Entrepreneurship at UNM's Anderson School of Management. He also is the institute professor for entrepreneurial renewal of industry at the University of Twente. He has many business service awards including the lifetime achievement award for commercialisation of Micro and Nano technology firms from MANCEF. He has also been named as a Tech All Star from the State of New Mexico Economic Development Department and has been recognised by Albuquerque the magazine as a leader in service to the economic community. He is a serial entrepreneur that has help attract millions of dollars in venture capital to many firms.

Challenges of Commercialising

MICRO AND NANOTECHNOLOGY-BASED PRODUCTS

WORDS | **DAVID TOLFREE**, VP MANCEF & CO-CHAIR COMS 2015

Many articles have been written about the issues of manufacturing and marketing micro-nano products. They are often based on theory rather than hard experience. In reality, practice is very different from theory. Only those who have taken an idea or concept along the path to a marketable end-product know the pitfalls and barriers that have to be overcome. In more emotive language this is sometimes called the 'Valley of Death' due to the number of companies that never cross over it.

The 10 steps along this highly non-linear path are shown in figure 1. A full treatment that describes each of these steps can be found in the popular book 'Commercialising Micro-Nanotechnology Products', published by Taylor & Francis, edited by David Tolfree.

The challenges

Researchers, technologists and manufacturers are faced with many challenges when developing new products. The manufacture, production and marketing of medical devices and healthcare products sets the greatest challenge. In association with new drugs, these products have to pass rigorous assessments and clinical trials before acceptance by the regulatory authorities. Early diagnosis of disease not only saves lives but lowers the cost of health services. Mistakes, however, can produce the opposite outcome. The increasing need worldwide for these products is producing growing markets. They give the opportunity for companies to make huge profits. The medical device market alone is currently estimated to be in excess of $10 billion and for healthcare products, estimates greatly exceed $1 trillion by 2020.

Reducing the time-to-market is, more than ever before, a key element in making a product commercially competitive in the market place. This is inextricably linked to the availability of a suitable development and manufacturing infrastructure. The absence of such an infrastructure and accessible funding is often the reason why some companies have to seek manufacturing facilities outside their own countries. Large-scale production is another hurdle that needs to be considered early on if the product falls into that category. Increasingly, production can be done more economically in countries with low labour costs. Such countries, however, do not always have the skills and knowledge to meet the stringent quality control requirements essential for mass production. In countries such as India and China this situation is rapidly changing as more skilled people become available but in the long term their costs will rise.

Understanding the various steps on the path to commercialisation in the global market will be one of the main subjects at MANCEF's forthcoming international COMS2015 conference

Understanding the various steps on the path to commercialisation in the global market will be one of the main subjects at MANCEF's forthcoming international COMS2015 conference, to be hosted in Krakow, Poland between 13-16 September, hosted by the Wroclaw University of Technology. The conference was described in the June edition of CMM. These issues will be discussed by experienced entrepreneurs in sessions on 'Commercialising Micro-Nano Products' on the opening day of the conference.

In other sessions, speakers will cover technology transfer and innovation. There will be a pre-conference workshop at which mentors will be available to help and guide those who have started up a company or intend to do so. Thematic sessions will include medical diagnostics, nanotechnologies related to healthcare products, 2D and 3D printing, sensors, smart systems and the Internet of Things.

<< Figure 1 >>