Roadmap Advanced Instrumentation

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Cover
The cover is a customized version of the Word Art creation by Nadesh Ligthart. It illustrates an action plan of the HTSM roadmap Advanced Instrumentation. The images are advanced Instruments and market products made by Dutch companies, based on advanced scientific knowledge and co-creation:

- ASI — X-ray, electron and ion cameras for color X-rays, electron microscopy and mass spectrometry based on technology developed for high-energy physics
- Cosine — Silicon pore X-ray and particle optics developed for astronomy with applications in beam lines, material analysis and health
- 3D Metal Forming — Cockpit parts manufactured by high-energy hydroforming, also used for large vacuum systems for scientific equipment
- Optics 11 — Micrometer cantilever fiber sensor based on Dutch microtechnology and fiber optics research
- Malvern Panalytical — Medipix detector developed for high-energy physics used in X-ray diffractometers and reflectometers for almost any industry
- Single Quantum — Superconducting nanowire single photon detector originating from Dutch university research
- VDL/TNO — Support structures for the primary mirror of the ELT astronomical telescope

and products from Boessenkool Machinefabriek BV, Heinmade, Hositrad Vacuum Technology and Sumipro Submicron Lathing BV.

Contents

Scope

The roadmap Advanced Instrumentation aims to:

- Develop and innovate advanced key technologies and instrumentation to face societal challenges in the health, energy & sustainability, safety and agri-food & water sector;
- Enlarge innovation power and competitiveness of Dutch businesses by developing and applying advanced instruments to increase quality and efficiency of current and new production processes;
- Increase possibilities for Dutch companies to co-create and supply (Big) Science advanced instrumentation;
- Maintain and increase very high standards in quality and output of Dutch fundamental and applied sciences. Science and instrument development go hand-in-hand: the best science can only be achieved with the highest level of instrumentation and the most advanced scientific knowledge and skills are required to create the most innovative technologies;
- Innovate advanced key technologies for application development in the health, agri-food, robotics, big science (including space) and energy & sustainability sector.

Vision

It is our vision to form the bridge between scientific research, applied research and product development for the benefit of the Dutch innovation power.

We encourage private companies and public researchers to cooperate at an early stage of a technological development (low Technology Readiness Level (TRL)), in order to sharpen the focus of the scientific research, jointly identify R&D priorities for the Netherlands, reduce the technology risk and shorten the product development process. If the technology appears successful and gains a broader support, it can be transferred to one of the other roadmaps having an implementation and application scope in a specific industrial or societal sector.

1 Roadmap

This roadmap is written by the roadmap team consisting of representatives of companies, academia and institutes active in the area of instrumentation development and is based on a large number of contributions and input from academia, institutes and companies including many SME's.

1.1 Roadmap team

The 2020 update of the roadmap is provided by the current team:

- Marco Beijersbergen (chair, cosine/LU)
- Frenk van den Berg (Tata Steel)
- André Bos (S[&]T)
- Hans Priem (VDL ETG)
- Eugène Reuvekamp (Malvern Panalytical)
- Kees Buijsrogge (TNO)
- Paul Hieltjes (SRON)
- Daniëla Mikkers (ASTRON)
- Frank Linde (Nikhef/UvA)
- Vera Meester (NWO, secr)

Others who contributed previous versions of the roadmap are Henri Werij (TNO), Pieter Kruit (TUD), Marjolein Robijn (NWO) and Lambert Speelman (NWO).

1.2 Scope of the roadmap with respect to other HTSM roadmaps

One needs to realize that for Advanced Instrumentation multiple disciplines and state-of-the-art solutions need to be brought together in complex systems. Where isolated "Photonics" developments may have reached a TRL (Technology Readiness Level) of 4, the status of the same technology when considering integration into an advanced instrument will have a TRL < 4, requiring R&D at TRL ≤ 4. An example is microscopy and imaging topometry, which are widely used techniques in laboratories (TRL 8), however, integration of these techniques in inline production processes to ensure 100% product inspection for quality assurance, is highly innovative (TRL 2). The roadmap Advanced Instrumentation will therefore remain informed on actual developments in other enabling HTSM roadmaps and aims to combine new innovations into complex systems and instruments with new application potential.

The roadmap Advanced Instrumentation clearly relates to several other HTSM roadmaps, and other Topsectors. With its focus on enabling technology development, cooperation with other technology developments and areas of application is not trivial.

1.3 Partners

- Companies: See the list at the end of this document (with ~225 'active' companies).
- Universities: TU/e, TUD, UT, RUG, RUL, RUN, UU, MU, UvA, VU, WU, NOVA (research school for astronomy).
- Institutes: TNO, AMOLF, ASTRON, CWI, DIFFER, NCSR, Nikhef, NIOZ, SRON, NRG.

1.4 Regional knowledge clusters

To establish a local, direct, link to the roadmap for as many (small) companies as possible we approached industrial representatives such that all regions in the Netherlands are covered (regional knowledge clusters). Synergy will be sought with the agendas of the regions.

Regional knowledge clusters, representatives.

Knowledge cluster	Representative
Noord (Groningen, Friesland, Drenthe)	Mikkers (ASTRON)
Oost (Overijssel, Gelderland)	Reuvekamp (Malvern Panalytical)
Zuid/Eindhoven (Noord- en Zuid-Brabant, Zeeland)	Priem (VDL ETG)
West (Noord- en Zuid Holland, Utrecht, Flevoland)	Van den Berg (Tata Steel) Beijersbergen (cosine) Bos (S[&]T)

2 Societal and economic relevance

Advanced instruments are found throughout our society, although often behind the scenes. They allow radical new science, support research and development, secure our safety, ensure effective production and offer the basis for solutions of grand societal challenges. Advanced Instrumentation is about design and development of complex measurement and control systems using a high mix of technologies. The instruments are typically built in low volumes and are used in (big) scientific programs, R&D-centers, industrial production and in societal applications such as high-tech medical technology.

The community working on the development of advanced instruments in The Netherlands comprises of a several hundred companies, large and small. These develop and market advanced instruments, mainly for industrial purposes and some for scientific use. This innovative ecosystem with recognized track record and profitable markets employs several tens of thousands of people. Also, a dozen or two of institutes (universities, scientific institutes and GTI's) are developing advanced instruments, typically for scientific purposes with limited spin-off to industry. By increasing the interaction of these two worlds a higher level of innovative products is foreseen.

Innovation is favored at the interface where basic research meets applied sciences and high-tech industry. The history of the Netherlands is paved with examples where this type of innovation has led to major technology spin-offs. Being gifted with numerous high-tech industries and high-level universities, The Netherlands is very well positioned to incubate innovation by stimulation of high-tech eco-systems and public-private partnerships.

The roadmap Advanced Instrumentation has the ambition to promote this ecosystem by strengthening the collaboration between the companies and the institutes with the aim to increase the return-on-investments in four ways:

- Improved *economic* return-on-investment by supporting Dutch (SME) companies in the development of world-class instruments using the know-how of relevant institutes;
- Improved *scientific* return-on-investment by stimulating that Dutch (SME) companies are highly involved in science projects enabling quicker, more robust and more effective instrumentation;
- Improved *societal* return-on-investment by stimulating that the developed technology know-how is used by (Dutch) SME's and mass production firms to develop and market instruments that help solving societal issues regarding health, ageing, mobility, energy and safety, etcetera.
- Improved *human capital* return on-investment by educating and training employees and students into highly skilled professionals.

The relation between the fields and the potential benefits of improved cooperation of all parties involved is sketched in figure 1.1, nicknamed the "Advanced Instrumentation conveyer belt". This system conveys knowledge and technology rather than goods, and combines technology push from (Big) Science and market pull from the Grand Societal Challenges. The blue blocks show the direct results, the others demonstrate the economic (green), scientific (orange) and societal (red) impact. This is a continuous process rather than a roadmap, which is continuously driven by (Big) Science as well as the Grand Societal Challenges, and needs constant 'lubrication'. Strong cooperation of all parties, together with a national program for development of instruments and instrument-technology will lead to a dynamic, vivid and profitable sector.

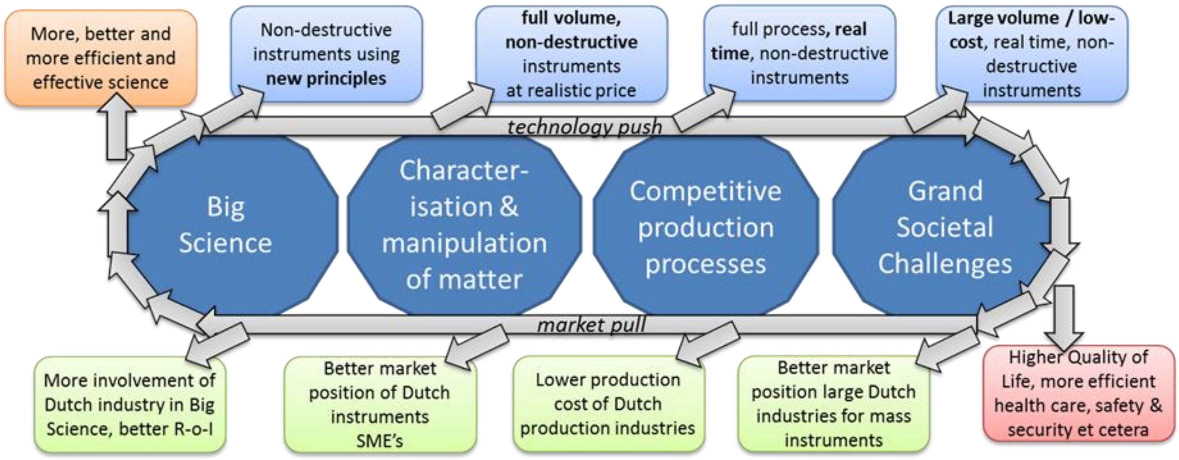

Figure 1.1 The conveyor belt of knowledge and technology in Advanced Instrumentation yields economic (green), scientific (orange) and societal (red) impact through better instruments (blue).

2.1 Societal challenges and missions addressed in this roadmap

Advanced instrumentation technology is enabling technology for many areas of science as well as applications. The roadmap develops and innovates key technologies that are crucial for the missions defined by the Dutch government in the Knowledge and Innovation Agenda's (KIA's):

1. KIA Energy and Sustainability
2. KIA Agriculture, Water and Food
3. KIA Health
4. KIA Security
5. **KIA Key Technologies**

Advanced instrumentation is a key player in the KIA Key Technologies with a primary focus on the following five Key Technology clusters:

- Photonics and Light technologies
- Engineering & Fabrication technologies
- Nano technologies
- Chemical technologies
- Digital technologies

The clusters Advanced Materials and Life Science technologies are also embedded in the roadmap.

2.2 World-wide market for this roadmap, now and in 2025

The total world-wide market for 'societal' instruments, from safety cameras to MRI-scanners is a multibillion European market. This roadmap is aimed more towards the design and development of high-tech instruments, which constitute only a small fraction thereof, but is expected to have significant impact on the total market, for instance by developing new sensing technologies, control loops and Big Data technology.

The Dutch government invests more than 100 M€/year in Big Science projects alone, which in several cases (CERN, ITER, ESRF) only lead to low effects for Dutch Industry, although in other cases (LOFAR, ESA, ESO) the economic return-on-investment is much better. In 2019 the Rathenau Institute emphasized in a report on the importance of large international research infrastructures and the return on investment, which was supported by the Dutch government in a cabinet response. Research infrastructures are a magnet for talent and knowledge-intensive companies. Because industry collaborates with science on new technologies, industry can expand or improve its existing expertise and thus introduce new technologies to existing markets or enter new markets. We aim to increase the return-on-investment considerably for all Big Science projects that the Dutch government invests in. For this, we will closely collaborate with the Dutch ILO-net, which is a collective of Dutch Industrial Liaison Officers (ILO's), who are connected to Dutch universities and research institutes and to international Big Science organizations.

The markets for R&D-instruments and for instruments used to optimize production processes are less well defined and thus less quantifiable but the large number of companies with a relation to advanced instrumentation as listed in the appendix indicates that they are substantial. This is a potential growth area for Dutch industry and will remain a point of attention on our agenda.

2.3 Competitive position of the NL ecosystem (market and know-how)

Typical for the Dutch ecosystem is that it holds an excellent international market and know-how position in niche markets and applications for low volume, high complexity and high mix systems. The development of such systems is one of the key elements of the Dutch economy, contributing significantly to the Dutch export and positive trade balance. A key success factor of the industry involved is its ability to develop very advanced systems faster and more reliable than its competitors. Continuous improvement of skills and competences and thus of competitiveness is realized by rapid transfer of knowledge between science and industry.

2.4 Relation with academic themes in National Science Agenda

There is a strong relation between this roadmap and the route *Measure and Detect* in the national science agenda (NWA). On this route the NWA *Startimpuls* program Measure and Detection of Healthy Behavior is executed. In this program innovation of advanced instruments plays a key role.

Advanced Instrumentation also foresees a direct collaboration and strategic alignment with the NWA route *Building blocks of matter and fundaments of time and space*. There is a large NWA *Startimpuls* program on gravity including gravitational waves, with for example the Einstein Telescope as one of the game changers. The roadmap can contribute to this scientific route by collaboration on instrument development.

The roadmap Advanced Instrumentation has also direct or indirect links with the following other NWA routes:

- Origins of life on Earth and in the universe
- Water as a road to innovation and sustainable growth
- Circular economy and raw material efficiency
- Sustainable production of health and safe food

- The energy transition
- Health research, prevention and treatment
- Materials
- The quantum and nano revolution
- Smart industry
- Smart liveable cities
- Value creation through responsible access and use of big data

For several of these routes, existing collaborations in research and development already exists, for others they have to be established. Examples of existing collaborations will be mentioned in the following chapter.

3 Applications

In this chapter, the four clusters of Advanced Instrumentation (*Big Science, Material characterization and manipulation, Instrumentation for competitive production processes, Societal Instrumentation)* are described. We outline the connection to the KIA Key Technology clusters and associated long-term programs (MJPs), the state of the art, future developments and questions and milestones of these clusters.

3.1 Big Science

3.1.1 Essential contribution to the KIAs, key technology clusters and MJPs

Big Science makes a direct and essential contribution to the Dutch governmental missions in the KIA *Energy and Sustainability* and the KIA *Agriculture, Water and Food* through the establishment of Earth observation infrastructure. The technology developed for Big Science also contributes to the other Dutch governmental missions in the KIA *Health* and the KIA *Security.* Applications of Big Science technologies essential for the governmental missions include imaging, radiation and detection technology, earth observation technology such as satellites, and sensors, robotics and lab-on-chip technology.

For applications in Big Science the following Key Technology clusters are essential:

- Engineering and Fabrication technologies
- Photonics and Light technologies
- Digital technologies

To invest in innovation of Big Science instrumentation MJP 84 *Dutch contribution to international Big Science Facilities* is developed in collaboration with the roadmap Advanced Instrumentation.

3.1.2 State-of-the-art

The Netherlands has a strong position in the development and realization of instruments and infrastructure/equipment for Big Science facilities like SKA, ESO, ESA, CERN, KM3NeT and the Einstein Telescope. Growth is possible in ESRF, ITER and CERN, where a position is already realized in specific subjects, but overall the involvement and return on investment of Dutch industry could be improved.

3.1.3 Future developments

The roadmap Advanced Instrumentation is ultimately aimed at a healthy return of Big Science investments to the Dutch ecosystem; academia, knowledge institutes and industry regarding the realization and exploitation of big internationally funded scientific projects. Our focus is on the following areas:

- Astronomy, both ground-based and space-borne, with as prominent examples: the Extremely Large Telescope (ELT) built by ESO; Square Kilometer Array (SKA), and the Advanced Telescope for High-Energy Astrophysics ATHENA mission by ESA.
- Particle and Astroparticle Physics, with as primary targets future CERN projects such as the High Luminosity upgrade of the LHC (HL-LHC), the Compact Linear Collider (CLIC) and the future European deep-sea research infrastructure for neutrino detection KM3NeT.
- Nuclear fusion, where the world-wide activities are focused on ITER and F4E.
- ESA to facilitate the current global move towards commercial space applications (e.g. earth observation, communication)
- The Einstein Telescope (and ET Pathfinder), currently under investigation. The strong scientific position of Dutch scientists in this proposed next-generation gravitational wave detector, possibly sited in the Belgium-Dutch-German border region, allows to take a leading role both in the scientific and industrial aspects.
- Advanced material science at European Spallation Source (ESS) and European Synchrotron Radiation Facility (ESRF). Although the DUBBLE beamline is planned to be suspended, research with these facilities may be part of international collaboration projects.

3.1.4 Challenges and Ambition

The short-term and long-term challenges and ambition of our roadmap for Big Science are depicted in figure 2.1. To reach our goals and successfully tackle the international competition, a close collaboration between academia, knowledge institutes and industry, based upon added value, and a joint market approach is crucial. Such collaboration, built upon mutual trust, should be achievable within the coming two years, where the first examples already exist (ELT). In a timeframe of 5-10 years this should lead to a situation where Dutch industry with its partners is responsible for the development and manufacturing of e.g. the support structures of the ELT M1 mirror segments, a large part of the detector modules of KM3NeT, the ATHENA X-ray optics, components of the Einstein Telescope, modules for the CLIC-accelerator of CERN, and diagnostic and handling systems for ITER. For all these instruments securing sufficient life-time is an essential issue. This requires continuation of the close collaboration with the Industrial Liaison Officers of the national academic institutes, connected via the ILOnet, and active participation in international efforts in industrial participation in big science projects (e.g. Big Science Business Forum, Holland@CERN, ESA industry space days). These activities should also lead to spin-off businesses (e.g. in the medical market) and new high-tech companies. In the long run, this should result in a situation where the international recognition of the Dutch scientific-industrial ecosystem for its innovation and highly competitive high-tech products leads to new companies, commercials products and services and scientific recognition at the same time.

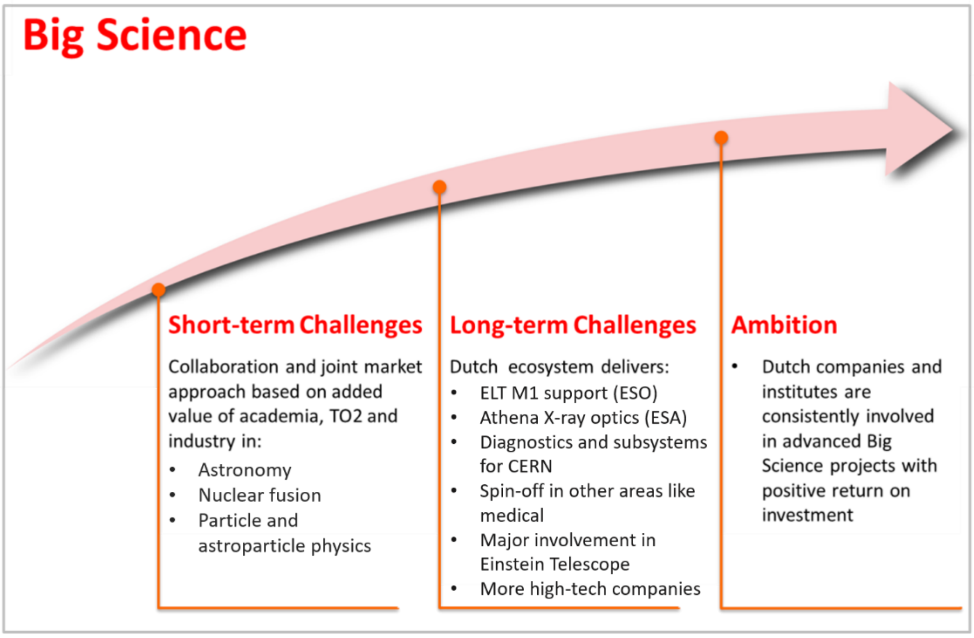

Figure 2.1. Challenges and ambition for Big Science.

3.2 Materials characterization and manipulation

3.2.1 Essential contribution to the KIAs, key technology clusters and the NWA

Instrument developments for material characterization and manipulation directly contribute to the Dutch governmental missions in the KIA *Energy and Sustainability* and KIA *Security*. Besides that, this cluster also contributes to the KIA *Agriculture, Water and Food* through smart sensors and imaging. Applications of material characterization and manipulation essential for the governmental missions include satellite remote sensing and imaging, (gas) sensors, smart materials, material analysis, detection technology, robotics and remote handling.

For applications in materials characterization and manipulation the following Key Technology clusters are essential:

- Advanced Materials
- Nano technologies
- Chemical technologies
- Engineering and Fabrication technologies

The MJPs linked to this theme are MJP 10 *Nano4Society*, MJP 18 *Flexible Electronics*, MJP 32 *Materials Innovations*, MJP 70 *Catalysis and process technology*, MJP 71 *Measurement and Detection technology (M&D)*, MJP 72 *Evidence Based Sensing*, MJP 82 *Materials – made in Holland*, MJP 88 *D-ART: D-RACE Advanced Radar Technology* and MJP 90 *Advanced research center for nanolithography*.

3.2.2 State-of-the-art

With regard to R&D-instruments for characterizing and manipulating matter, excellent positions exist in optics, electron optics, X-ray, radio and RF-instruments. Well known examples that fall under Advanced Instrumentation are:

- *Multispectral imaging instruments*, for example satellite-based, which offers unprecedented possibilities for remote sensing of polluting and greenhouse gases.
- *Instrumentation for nano-analysis and nano-material synthesis*, for the realization and characterization of structures and layers, particles and colloidal systems on nano-scale.
- *X-ray imaging, RF and TeraHertz technologies* originating for Astronomy and now developed for other applications such as non-invasive chemical analysis of luggage and parcels for security and safety purposes.
- *4D Radar surveillance systems*, to respond to the continuously changing threats to our society.

3.2.3 Future developments

Materials Characterization and Manipulation in the near future will focus on fast 2D- and ultimately 3D- characterization methods from the atom scale up to the micro and macro range, as well as nano- and micro-manipulation techniques of 2D- and 3D structures and morphologies. These methods allow to obtain fundamental knowledge on (surface and bulk) structure – property relationships on different scales, serving as input for multi-scale models that can predict properties of (artificial) materials that are built ‘bottom-up’ from atom-level onwards. Knowledge-based design and DACE (Design and Analyses of Computer Experiments) are powerful tools to re-use current knowledge, to speed up the innovation and to design on robustness by process window studies. This approach offers a broad horizon of possibilities for the design of new materials like meta-materials, added manufacturing, molecular engineering, chemical- and bio-manufacturing, expanding to the development of novel medicines and healthcare solutions. Similarly, these developments create opportunities of new products and processes in the more traditional technology areas like (petro)chemistry, metal alloys, building materials, mining, microfluidics, photonics and aerospace engineering.

Important to the mechanisms of ‘detection’ and ‘characterization’ is the ‘excitation’: often (laser) light, electromagnetic radiation or X-ray radiation is used to investigate materials. Hence it is considered important to invest in powerful and miniaturized sources for light and radiation, like the Smart*Light initiative.

3.2.4 Challenges and Ambition

The short-term and long-term challenges and ambition of our roadmap for Material Characterization and Manipulation are depicted in figure 2.2. To reach these goals, a close collaboration between academia, knowledge institutes and industry is crucial. The above mentioned examples already illustrate successful collaborations and we aim to enhance these collaborations to strengthen the international position of the Netherlands in this field. Besides focusing on existing initiatives like Smart*Light, short term challenges lie in the area of 3D material characterization with imaging and spectroscopy and on creation and design of new materials by molecular printing. On a longer term, this should result in controlled manufacturing of layered meta-materials, with application possibilities in different areas.

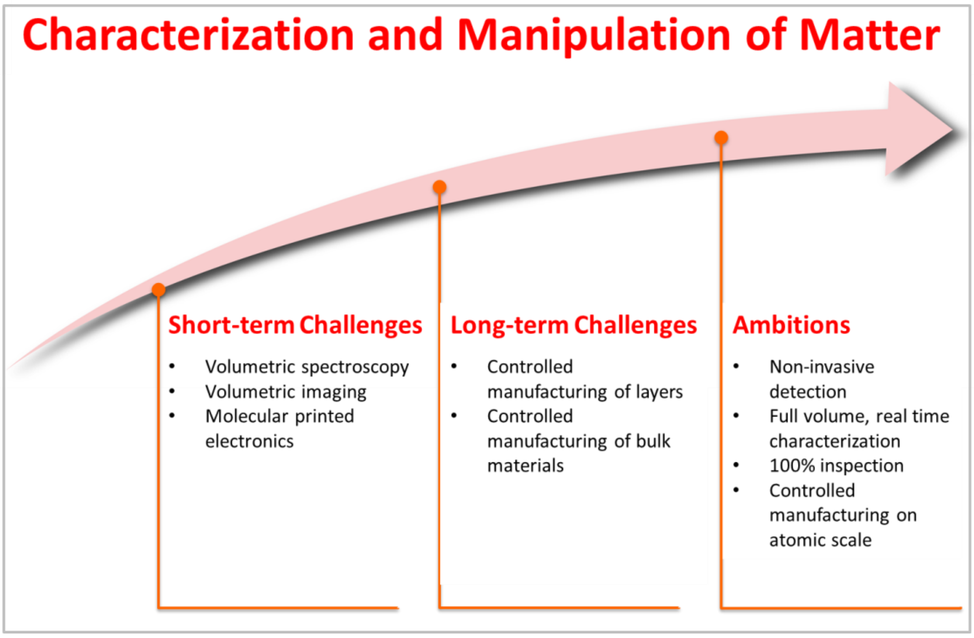

Figure 2.2. Challenges and ambition for R&D instruments, materials characterization and manipulation of matter.

3.3 Competitive production processes

3.3.1 Essential contribution to the KIAs, key technology clusters and the NWA

Instrumentation for competitive production processes directly contribute to the Dutch governmental missions in the KIA *Energy and Sustainability*, KIA *Health* and the KIA *Agriculture, Water and Food*. Applications of instruments for competitive production processes essential for the governmental missions include recycling processes for a circular economy, point of care, patient monitoring, robotic surgery, production processes for agriculture and food, robotics and light weight drones.

For applications of instruments for competitive production processes the following Key Technology clusters are essential:

- Engineering and Fabrication technologies
- Nano technologies
- Digital technologies

The MJPs linked to this theme are MJP 26 *System architecture and system integration*, MJP 34 *Smart Industry, MJP 48 AI enabled Electronic components & systems addressing societal solutions*, MJP 71 *Measurement and Detection technology* and MJP 72 *Evidence Based Sensing*.

3.3.2 State-of-the-art

Whereas historically an advanced instrument is commonly regarded as a highly performing single sensor there is an increasing demand in modern production processes that requires advances instrumentation being based on sets of sensors supporting more robustness and precision in decision making and control. This implies that future advanced instrumentation will likely be aggregated systems of (connected) sensors including layers of automated data processing. This could allow for meaningful interpretation of sensor data which can be used as critical information in production selection decisions and process control. Sensor data fusion will be boosted by advanced IoT technologies. Data science technologies, such as artificial intelligence / machine learning, are expected to contribute strongly to convert data from complex sensor systems to valuable information.

Development and implementation of instrumentation for industrial processes is driven by the need for accurately controlled, efficient manufacturing processes, which in turn is driven by the need to remain competitive in a world-wide economy and the need to be flexible to manage the current reality of volatile markets, limited natural resources, limited funding and limited availability of highly educated technical experts.

Optimal quality, early detection of failure, and cost control are the main drivers for the need for continued investments in advanced instruments. Advanced instruments ensure real time control of the full product flow, measuring quantities such as shape, size, roughness, hardness, color and composition (i.e. know-your-product). Other instruments allow flexible manufacturing by recognizing all sorts of shapes and positioning them very rapidly. This must be done non-destructively and robustly, rapidly and precisely.

3.3.3 Future developments

Currently, the Netherlands is ramping up Smart Manufacturing. The Smart Industry agenda will certainly contribute to this, aiming to advance Dutch industry to increase production with value adding solutions. Improved national and international cooperation may considerably advance the position of the Advanced Instrumentation industry that holds world-class positions in e.g. (opto) mechatronics, robotics, precision machining, vacuum and cryo technology.

3.3.4 Challenges and Ambition

The short-term and long-term challenges and ambition of our roadmap for Competitive Production processes are depicted in figure 2.3. For the roadmap Advanced Instrumentation, short term focus will be on non-contact sensor technologies, multiple sensor data fusion and real-time data processing. For the longer term, this will be extended to process control, through (a combination of) artificial intelligence, machine learning and model-based control algorithms, with the ambitions of zero-defect production, adaptable systems and autonomous production processes.

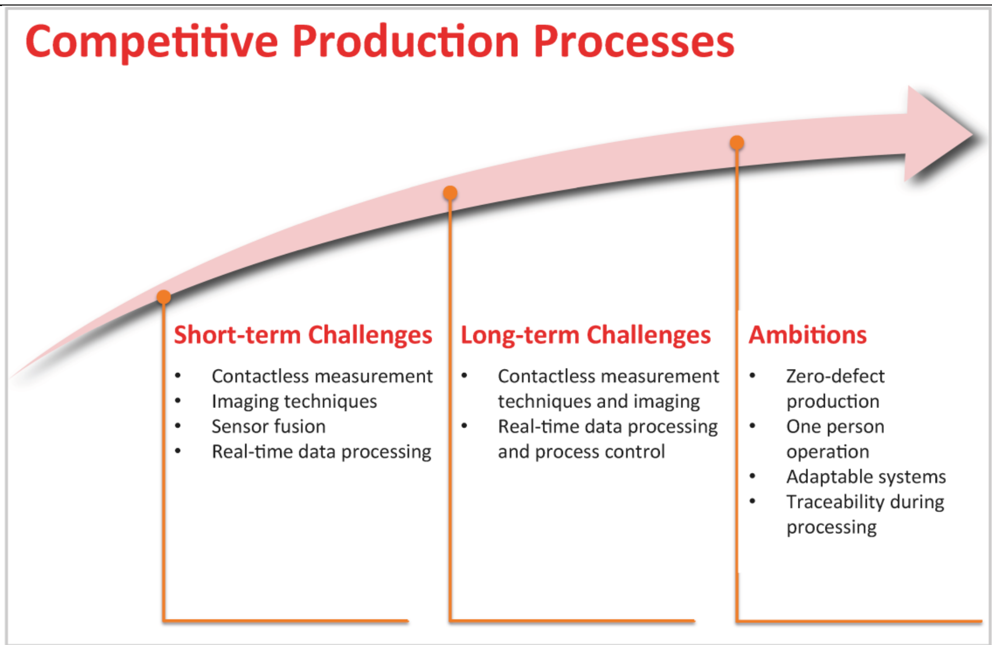

Figure 2.3. Challenges and ambition for advanced instruments for competitive production processes.

3.4 Instrumentation for modern society

3.4.1 Essential contribution to the KIAs, key technology clusters and the NWA

Instrumentation for a modern society contribute to the Dutch governmental missions in the KIA *Energy and Sustainability*, KIA *Health*, the KIA *Security* and the KIA *Agriculture, Water and Food*. Applications of these instruments essential for the governmental missions include non-invasive and remote sensors, personalized devices to monitor blood values, sensor and detection techniques for agriculture and food quality, fast diagnostic systems, smart antennas, autonomous transportation systems, and many more.

For applications of these instruments the following Key Technology clusters are essential:

- Life Science technologies
- Digital technologies
- Chemical technologies

The MJPs linked to this theme are MJP 10 *Nano4Society*, MJP 21 *Photonics for society*, MJP 26 *System architecture and system integration* and MJP 34 *Smart Industry*, MJP 71 *Measurement and Detection technology* and MJP 72 *Evidence Based Sensing*,

3.4.2 State-of-the-art

Several Dutch companies hold a strong position in the commercialization of large medical instruments, fast diagnostic systems, safety and security systems, among other applications of advanced instrumentation application. The very well developed IT infrastructure offer Dutch companies and institutes a head start position on the application of integrated sensors systems and Big Data analyses. Also, the big science projects in which R&D in the Netherlands (such as the space projects as conducted by ESA/ESTEC and the SKA developments by ASTRON) and the involvement of industry provide the necessary conditions for a successful interaction between R&D institutes and commercial high-tech companies.

3.4.3 Future developments

Improved sensing technology is required to address several of the grand societal challenges. Advancement in instrumentation technology is essential for countering the expected rise in health costs. Specific patient information is required for personalized medicine, advanced screening and more efficient diagnosis and treatment. Miniaturization of instrumentation and large-scale production methods will help bring diagnostics and treatment to the patient home and local care centers. Monitoring and quantifying safer and greener transportation requires operational monitoring systems, asking for more advanced methods for example to monitor CO_2 production. Climate action and other environmental policies and measures require good information on climate and environmental parameters on a global and local scale, requiring new remote sensing and in-situ instrumentation. Global as well as local monitoring of the human environment is a crucial component in ensuring a safe, healthy and secure society. Application of novel instrumentation techniques is crucial for safeguarding our food safety and providing better transparency on food quality. Better instrumentation is crucial for improving agriculture and land use whilst preserving environmental quality. Novel sustainable sources of energy require extensive development of new instrumentation, for example in nuclear fusion, in which the Netherlands have a strong position. Not only better and more accurate instrumentation is needed to tackle the future societal challenges, but also strong advances the interpretation of sensor data by, e.g., improving scientific modeling and computing, the combination of data, the automatic interpretation of data and the autonomous derivations of relevant correlations using AI techniques.

3.4.4 Questions and Milestones

The short-term and long-term challenges and ambition of our roadmap for Societal instrumentation are depicted in figure 2.4. The questions in instrumentation to be addressed in the context of the grand societal challenges focus around non-invasive, remote or in-situ instrumentation for:

- Health, e.g. replacing wet chemistry and microbiology methods with physical measurement instrumentation;
- Safety and security by smart camera’s and sensors.
- Environmental monitoring from space and aerospace;
- Food, agriculture and horticulture;

Here, robust, intelligent and autonomous systems are short term focus, as well as new technology for non-invasive and non-destructive diagnostics. Together with advances in miniaturization, longer term goals form non-invasive replacements for health monitoring and diagnosis, either remote at home or in a hospital environment, advanced instrumentation for food product inspection, and remote sensing techniques used for climate, safety and security applications. Considering the already strong position of the Netherlands, the roadmap has the ambition to become technology leader in non-invasive medical instrumentation and to play a dominant role in remote sensing and instrumentation for food and agriculture inspection.

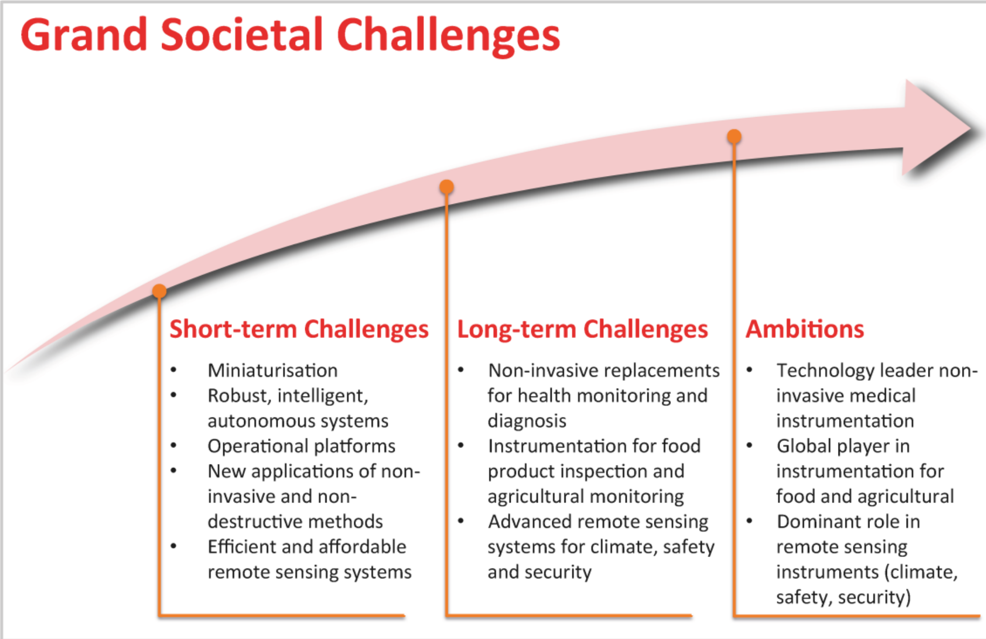

Figure 2.4. Milestones and ambitions for societal instrumentation.

4 Key technologies of the roadmap

To address the challenges of the sectors of the roadmap Advanced Instrumentation, co-creation of key technology areas is required. In the following sections, the main key technology clusters *Measurement and detection technology, Photonics, Advanced production systems and process technology,* and *Digital technology* are addressed and the required developments to address the challenges of Advanced Instrumentation are summarized. Additionally, the links to the HTSM grand challenges and NWA routes are identified.

4.1 Measurement and detection technology

The key technology *Measurement and detection technology* focuses on device optimization, system design and system integration. This includes: sensors, actuators, system technology, FE, BE Electronics, ASICS, miniaturization, MEMS, array- & matrices of sensors, components & circuits, nanotechnology, mechatronics. Measure and detection technology is crucial for all the HTSM grand challenges, but the most obvious links are with *Health* measurements and monitoring of health using home devices and Internet of Things, miniaturized systems for sensing and interaction in our daily environment, and bioelectronics in and on human bodies, including targeted drug delivery by nanotechnology) and *Sustainability* (quality control (agri)food).

4.2 Photonics

The key technology cluster of *Photonics and Light* focuses on light from X-rays, UV, VIS, IR, to THz and cosmic gamma's, detectors and light sources, table-top alternatives for synchrotrons, "handling" of light and photons (e.g. for quantum technologies and lithography), laser technology, spectral technologies, imaging (ESA, remote sensing, vision), optical components (immersed gratings), radiation sources & detectors (CERN), beam handling, radiation hygiene, proton therapy, RF-technology; design for maintainability and for optimal life time control.

4.3 Advanced production systems and process technology

The key technology *Advanced production systems and process technology* focuses on handling of (nano-)fluids, manipulation of atoms & molecules, handling of hazardous matter, (micro-) assembly technologies, light-weight constructions, sensing & control for unmanned aerial vehicles (UAVs), (nano-)satellite design and seismic control, challenging mechanical and thermal designs.

4.4 Digital technology

The key technology cluster *Digital technology* focuses on advanced scientific processing of data, the efficient handling of large amounts of data, model-based fusion of data sources, the automatic interpretation of scientific and sensor data, automatic generation and testing of hypotheses or data storage, data mining, pattern recognition, and (multi-) image processing. To realize these advanced computational applications, the efficient use of the underlying computer architecture need to be supported by programming techniques for parallel programming, use of advanced processing equipment such as FPGAs and GPUs, distributed computing, and advanced (unstructured) database.

5 Implementation and collaboration

The highest priority for the roadmap Advanced Instrumentation is to organize the process in which participating industrial partners together with the scientific partners jointly identify R&D priorities for the Netherlands. Due to the nature of this sector, this is not a single theme, but a collection of generic and specific questions to be addressed. Together this should lead to well defined, concrete programs that build on the existing strong areas of instrumentation know-how, capabilities and commercial positions, as well as initiating new ones.

5.1 Implementation in public-private partnerships and ecosystems

Good understanding between Dutch companies, knowledge institutes and universities is essential to:

- Make science and industry share their quest for broad applications of their instrumentation, technology and expertise;
- Make science and industry share their interest in solving problems in their instrumentation.
- Secure a significant role for Dutch industry in large tenders for European scientific instruments and their infrastructure.

There is no clean-cut role of each player. Figure 4.1 visualizes the approximate landscape versus technology readiness level. In fact, this figure will already be different for each of the themes within Advanced Instrumentation. The figure does, however, clarify the prime areas in which each partner operates. The roadmap Advanced instrumentation actively brings together the academia, knowledge institutes and companies (e.g. using MIT subsidies for networking activities). This approach has multiple branches:

- The roadmap team of Advanced Instrumentation actively explores the overlap with other roadmaps by organizing joint 'MKB work sessions' on a regular basis (1 - 2 times/year); the first joint meetings with the roadmaps Mechatronics and

Manufacturing respectively Components and Circuits and Photonics were held in 2014 (with talks, posters and discussions). Each meeting attracted approximately 60 to 70 participants, well-balanced over companies, institutes and academia.
- Discussion between academia, innovation centers / TO2 institutes and companies, at strategic level will be facilitated to invest in technological foresights and clear ideas on the ambitions and future needs on large scale infrastructures (see also AWT report “Maatwerk in Onderzoeksinfrastructuur", p.24/32.
- Regular meetings with dedicated small groups of R&D developers, from academy and industry, will be organized allowing (in depth) meetings on technology development.
- The 'owner' of each of the four application oriented themes in Advanced Instrumentation organizes 'theme sessions'. At this moment the ownership is defined at a top-level: Big Science - academia and institutes; Characterization and Manipulation of Matter - companies, Competitive Production Processes - companies, and Grand Societal Challenges - academia and institutes.
-

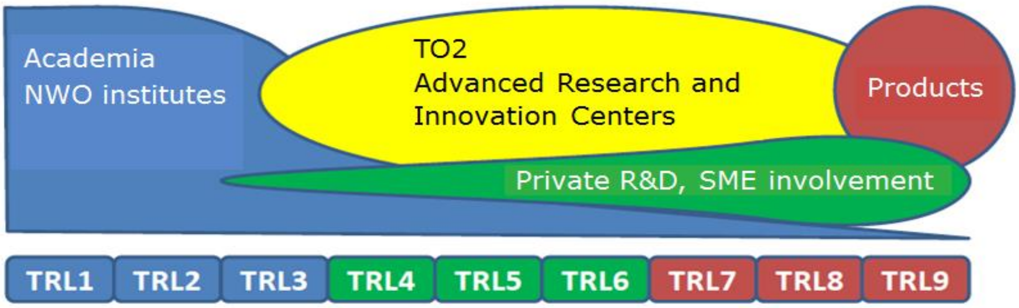

Figure 4.1 Technology landscape with players versus technology readiness level (indicative).

- A permanent committee for large-scale scientific infrastructure has been installed by NWO. NWO consulted KNAW, VSNU, VNO-NCW, NFU and TNO for the composition of this committee. This committee continues to investigate the need of the scientific and broader research community for investments, exploitation and use of national and international large-scale facilities and the chances for infrastructural investments. In December 2016, the committee made an inventory in the National Roadmap for large-scale scientific infrastructure, where relevant infrastructures as ATHENA, ELT, ET, and KM3Net were identified as important structures for future investments and contribution by the Netherlands. The roadmap Advanced Instrumentation will follow the developments by this committee closely and act actively participate in the contribution from Dutch medium and small enterprises to the identified important large-scale infrastructures.

5.2 Participation of the roadmap in programs, platforms and consortia.

As formulated in our Vision statement, to be successful in realizing a significant improvement of return for Dutch industry, a true collaboration between knowledge institutes, industry and policy (OCW and EZK) is required, in which parties are able to play their respective roles from the beginning, the scientific, societal and commercial interest are balanced in the policies, and collaboration is set up such that successful business is possible.

5.2.1 Key technologies

Collaboration to increase societal impact and innovation of technology is stimulated by the government by the National Science Agenda (NWA) and the Knowledge and Innovation Convenant (KIC). The missions and goals set in the NWA and KIC are to be translated in PPS programs and consortia. For this purpose NWO develops interdisciplinary calls to improve collaboration between knowledge institutes and companies, and is open for initiatives that fit the roadmaps of the topsectors HTSM, Chemistry, Energy, and ICT.

NWA-calls include the NWA-ORC, aimed for consortia within the NWA routes. Broad, interdisciplinary consortia that go from fundamental to applied research can apply for funding. There are multiple bandwidths of funding (0,5 -2 M€, 2-5 M€, 5-10 M€), with a minimum co-financing of 10% in cash or in kind.

The NWO funding instruments KIC are divided into four program lines: mission-driven research, partnerships on 'demand', strategic collaborations and practice-oriented instruments. The mission-driven programs are aligned with the KIAs, see Chapter 2.1, set by the government to fulfill the missions. This category is most interesting for this roadmap since 11M€/year is reserved specifically for research and development of key technologies. For these programs a co-financing of 30% is asked in kind or in cash.

5.2.2 Big Science instrumentation

Research on instrumentation development for Big Science research projects, performed by 3TU, NWO or TNO in collaboration with industry, form a major contribution to this roadmap. Roughly 50 public-private collaborations or concrete project plans have been identified for the roadmap Advanced Instrumentation, demonstrating mutual interest for collaboration and co-creation of knowledge. New initiatives will be taken the coming years, and relevant projects are likely to get funded, by the TTW HTSM calls, and also the National roadmap for Large Infrastructures.

A network of Industrial Liaison Officers, ILO-net, affiliated to research institutes and universities with a national coordinating role for international Big Science research facilities such as CERN, ITER, CERN, ESA, ESO and SKA aims to connect Dutch industry to Big Science projects. ILO-net collaborates with the roadmap to inform industry in an early stage of tenders, organize industry events, increase a network and to present Dutch industry at Big Science conferences and trade fairs (such as the BSBF conferences). These activities are organized with the ultimate goal to improve the industrial return for investment for The Netherlands.

5.3 Linkage with other instruments that stimulate innovation.

Below are summaries of highly promising programs and platforms that are being developed in public-private cooperation that are of importance to this roadmap:

- Dutch Optics Center (DOC) – initiated by TNO and TU Delft. DOC is a research center for optics and optomechatronics where topresearchers share facilities, PhD-students are educated and businesses contribute to new knowledge development. The mission of this collaboration is to strengthen Dutch businesses in optics and optomechatronics by increasing high-end production processes, with the ultimate aim to bring the Dutch businesses in optics and optomechatronics to an international competing level. Collaboration with other knowledge institutes is key.

- High Tech Systems Center (HTSC) – TU Eindhoven. HTSC executes research focusing on complex equipment and manufacturing with the emphasis on systems engineering. The center aims to take the lead in the research field of complex mechatronic systems in order to master the 'cyber-physical systems' of the future. The main goals of this broader initiative are: Development and coordination of a nationwide industry-university research roadmap, supported by NWO/STW; Coordination of available courses in the field of High Tech Systems; Establishment of a center of expertise for SMEs and; Development of a Human Capital agenda.
- Molecular Imaging Institute (M4i) – University of Maastricht: M4i is a state-of-the-art molecular imaging institute that brings together a powerful palette of high-end, innovative imaging technologies. The mission of the institute is to perform fundamental, instrumentation and applied studies in molecular imaging as a part of a translational, synergistic, interdisciplinary research program in a leading international center relevant for science, education, economy and society.
- Advanced Research Center for Nanolithography (ARCNL) – UvA, VU, NWO and ASML. ARCNL conducts fundamental research in physics with relevance to key technologies in nanolithography. Their mission is to obtain fundamental insights in physics and to contribute to the production of smart and compact electronic devices.

5.4 Collaboration and leverage with European and multi-national policies and programs

By definition, Big Science-projects are multinational and qualify for (and fit in) the European research strategy. The Dutch membership in organizations like CERN, ESA, ESO, and the International SKA organization should be regarded as the necessary entrance ticket to participate in large international scientific programs; satellites, particle accelerators, nuclear reactors, etc.

- Dutch flanking policies should be aimed at optimizing the opportunities to make use of these large facilities. In this context several levels of funding are preferred:
- Base funding for the NWO institutes, universities and TNO (earmarked for cooperation with industry);
- Competitive funding on a national basis (like NWO's roadmap for large scale infrastructures) or international (EU-programs, Horizon2020)
- Funding for outsourcing to industry (as a supplier respectively to stimulate technology transfer, valorization and expertise, the latter linking to the Human Capital agenda);
- Cohesion policy funds (also known as Structural Funds), which will be implemented through series of projects, including those supporting research and innovation and in cooperation with Smart Specialization Strategies of the regions.

6 Investments

The investments in the roadmap are difficult to accurately estimate since companies and institutes do not use a separate label for investments in Advanced Instrumentation. For this reason, the larger partners could often not provide us with numbers themselves. The roadmap has roughly estimated the investments in the roadmap by consulting the total investments of some of the larger companies, institutes and projects, and substantiating what percentage of this investment would be for the purpose of 'developing advanced instrumentation'. Purely production of instrumentation is not taken into account. The table will be updated when more detailed information becomes available. Note that the error bar in the numbers mentioned in the table below could be substantial. The entries labeled 'pm' are an estimate as no specific information was available.

Roadmap	**2020**	**2021**	**2022**	**2023**
Industry	4.5	5.5	6.5	7.5
TNO	7.0	7.3	7.7	8.0
NLR	0.2	0.2	0.2	0.2
NWO	14.0	14.5	15.0	15.5
Universities	3.0	3.5	4.0	4.5
Departments and regions (excluding TKI)	3.5	3.5	3.5	3.5
Grand total (M€)	**32.2**	**34.5**	**36.9**	**39.2**

European programs within roadmap	**2020**	**2021**	**2022**	**2023**
Industry	2.5	2.8	3.0	3.3
TNO	1.0	1.2	1.4	1.6
NLR	pm	pm	pm	pm
NWO	pm	pm	pm	pm
Universities	3	3	3.5	3.5
Co-financing of European programs	pm	pm	pm	pm
European Commission co-financing	3.0	3.3	3.7	4.0
Grand total (M€)	**9.5**	**10.3**	**11.6**	**12.4**

Appendix

Hundreds of companies are active in the ecosystem of Advanced Instrumentation. These 235 companies are regularly contacted about activities of this roadmap. The companies labeled with an asterisk * (over 50 in total) have been involved during the preparations of this roadmap (by taking a leading role in this roadmap, and/or through participation in the 'kennistafels', and/or by positively responding to the roadmap and/or by actively participating in different roadmap-events).

3D Metal Forming
3D Worknet
Aalberts Industries
Aandrijf Technisch Buro B.V.
ACAL BFI Nederland B.V.
Actemium Lintronics
ADSE
Advanced Solutions Nederland
Aerofilm systems BV
Aerovision
Agilent Technologies Netherl. B.V
Airborne Composite Tubulars BV
AKAPP BV
ALT
Amstel Engineering
Amsterdam Scientific Instruments*
ANSYS BENELUX
Antea Group
Anteryon*
ASI*
ASML
ASTRON
AstroTec Holding B.V.
ATG Europe BV*
Autonational
Bakker Magnetics BV
Benecom B.V.
Boers en Co FijnMetaalGroep*
Boessenkool Machinefabriek BV
Bouman Industrial Supplier Group
Bradford Engineering B.V.
Brandt Fijnmechanische Industrie B.V.
Bronkhorst High-Tech B.V.
Bronswerk Heat Transfer BV
Brookx Company B.V.
Brunelco
CCM Ontwikkelingsmij B.V.
CE masters
Century Dynamics (ANSYS)
Ceratec Technical Ceramics BV*
Coherent Europe
Cosine Research bv*
Cryozone*
Da Vinci Europe
Delft Circuits
Delft Spectral Technologies
Delmic*
Dekra
Deltour
DEMCON TWENTE B.V.
De Koningh Advanced Technology*
Diamond Kimberlit B.V.
DotXControl
Draad Nijmegen BV/Smit Draad
Dutch Society for Precision Engineering
Dutch Space
Airbus Defence and Space NL B.V.*
ECM Technologies
Effect Photonics
EKB Groep Zuid B.V.
Eldim
Element
Element Six
Embed Engineering*
Eonic BV
Etchform BV
FEI
Flexible Optical

Fokker
Fontijne Grotnes BV
Frencken Group
FTD Drachten*
Fugro Ingenieursbureau B.V.*
Futura Composites b.v.
Gen Plant Research
Geodelta
Germefa B.V.
Getronics Workspace Alliance
Gigalink Microwave Connection Engineering b.v.
GIS-PCB
Globe Benelux
Global Interconnection Services*
Goudsmit Magnetic Systems BV
Grontmij
Gusto B.V.
Heeze Mechanics BV
Heinmade*
Heras Nederland
HIT Heemskerk Innovative Technology BV
HITEC Power Protection B.V .
Hittech group BV*
Hositrad Vacuum Technology
Humitemp
Hunter Douglas Europe B.V.
IBM*
IKT*
Imec
ImProvia
INCAA Computers*
Incas3
Innoseis*
Innovam
Innovation Handling*
Innovationquartel
InProcess-LSP
Ipcos BV
Inspiro*
Irmco*
Isteq
Janssen Precision Engineering BV*
KEC*
KE-works
Kin Machinebouw Rijen B.V.
Kluin Wijhe BV
Kok & Van Engelen Composite Structures B.V.
Kryoz Technologies BV*
KxA Software Innovations*
Lambert Instruments*
Landustrie
Larsen Premium Precision Parts
Launch-IT
Leering Enschede Apparatenbouw BV
Lencon*
Lens R&D
Leuveco
Levitech*
LievenseCSO
LioniX BV*
Magneto special anodes B.V.
Major Electronics
Malvern Panalytical*
MAPPER lithography
MassSpecpecD BV
Maxon*
Maxon motor
MECAL
MECON Group*
MI-partners*
MKL Projecten
MKS Baratron
MMC Academie
Mogema
Molenaar Optics
MonetDB*
MTSA Technopower B.V.
Nascent Ventures BV
National Instruments Netherlands B.V.
NEM
Neways Electronics*
Nijkerk Computer Solutions
NLeSC
Norma groep

NOVA NL school for astronomy
NTS-Group
NXP
Oceanz
Okotech
Optics11*
Panalytical*
PBF group B.V.
PDCA
Pfeiffer Vacuum Benelux B.V.
Philips Advanced Metal Solutions/Philips Lighting B.V.
Philips Applied Technologies
Philips Consumer Lifestyle*
Philips Research and Innovation Services*
PM-GROUP*
PM-aerotec
Prodrive B.V.
Prysmian Group Nederland
RGS Development
RiverD International B.V.
Rolan Robotics BV
Royal Haskoning DHV
S[&]T*
Satrax
Schelde Exotech
Sensiflex*
Sensor Universe*
Shockwave Metalworking Technologies BV
Shell*
Single Quantum*
Sioux
Smart Photonics
Software Innovations
SolMateS
Spinque
Stip B.V.*
Stirling Cryogenics BV*
Stratix Consulting
Strukton
STTLS
Sumipro Submicron Lathing BV
Suplacon
Swagelok
SystematIC*
Tata Steel*
TBP Electronics
Tebulo
Technobis*
Technolution
Tegema
Teledyne DALSA
Tencate
Tessella*
Thales Nederland
Tiberion
TKH Group
TMC Electronics, Physics*
Umantec
Urenco Nederland BV
Ursa Minor space & navigation
Uzimet
Vacuum Specials BV
Van Campen Aluminium
Van der Hoek Photonics
Van Halteren
Vancis
Variass*
VDL Groep*
Vecom Group
Veldlaser
Vernooy Vacuum Engineering
Viro Engineering bv
Vitronics Soltec
Vortech*
Vos Mechanical Contracting B.V.
VSL
VTEC lasers and sensors
West Consulting
West End BV
Wijdeven
Witec
Xensor Integration
Xycarb Ceramics B.V.