SPINNING-IN OF TERRESTRIAL MICRO-SYSTEMS AND TECHNOLOGIES TO SPACE ROBOTICS: RESULTS AND TECHNOLOGY ROADMAPS

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ABSTRACT

Systematic miniaturization of Automation & Robotics (A&R) systems can result in more robust, less power-intensive and less expensive systems with increased redundancy and enriched functionality. Due to the large and diverse markets, terrestrial micro/ nano technologies (MNTs) are characterized by high performance, low development cost, reliability and sustainability of capabilities, making them ideal candidates for spinning-in in space A&R systems. These observations motivated this paper that presents (a) the findings of a thorough review and assessment of existing terrestrial MNTs that can be spinned-in to space A&R systems and (b) the systematic application of selected MNT to space A&R systems, resulting in roadmaps for space A&R systems.

1. INTRODUCTION

In this paper we present (a) the findings of a thorough review and assessment of current terrestrial Micro/ Nano technologies (MNT) that have the potential to be transferred to space Robotics and Automation (A&R) systems and (b) the application of selected MNT to space A&R, and the related roadmaps for introducing terrestrial MNT to space A&R systems. This paper is based on a completed ESA research project [1].

The technologies of interest include MEMS devices, nanostructured products and miniaturized mechanisms, collectively referred as MNT. These components can substitute A&R space components and devices aiming at developing systems of reduced mass, reduced volume, minimized power consumption, increased redundancy, greater robustness and enriched functionality; these systems are referred to as miniaturized. The results of the review and the roadmaps presented here allow for the introduction of terrestrial MNT to space A&R, aiming at miniaturized systems. The miniaturization effected by the introduction of MNT is at a (high) system level; the redesigned A&R system may have subsystems replaced by MNT; however to retain the desired functionality, the A&R system might not be smaller (e.g. robotic arms, rovers). The review focused on European technologies; non-European technologies were considered when no alterative was available.

1.1 Motivation

There are several reasons for introducing miniaturization in space. One important reason is that launch vehicles have tight constraints with respect to the payload's mass and volume characteristics and successful miniaturization directly results in an improved, more compact and less expensive system. Clearly, a benefit out of the miniaturization process is that the total resources required for A&R space components (e.g. mass, volume, power) are substantially reduced. Systems such as proprioceptive/ exteroceptive sensors, wireless communications, control units, power generation and transmission units can be integrated into small packages at a system level, allowing for a substantial increase of the permissible payload, reduction in power losses, more efficient thermal management and an overall increase in efficiency. At the same time, integrating several microsystems into a silicon wafer and introducing redundancy by design, results in increased reliability and flexibility, lower risk and greater functionality compared to conventional A&R space systems. Furthermore, this design is subject to economies of scale and reduced cost. An additional advantage of the use of MNT technology is that it is a field in which Europe has a competitive advantage and is worth enforcing it.

Space Automation and Robotics is an area of significant importance to future missions, in the form of autonomous orbital or planetary agents (e.g. rovers), in assisting astronauts and performing inspections (e.g. free-flying robots) and in robotic arms inside or outside of a module. For example, miniaturization resulting from the introduction of MNT to a rover can enable planetary exploration missions by increasing the available payload space and overall functionality and efficiency.

Space systems usually employ technologies and products that have proven and tested for many years, but with specifications below similar terrestrial products. It is common for space systems to lack radical innovations because the space industry is very conservative, especially due to the harsh space environment, which requires special designs for packaging, shielding and radiation hardened electronics. Therefore, spinning-in terrestrial, novel and improved MNT to space A&R, will significantly improve the performance of space systems.

1.2 Background

Elements of miniaturization have been already introduced in some space systems, which may not be strictly A&R systems but provide useful insights. A successful example is the miniaturization of satellites, such the well-known Cubesat standard, a 1kg, 10x10x10 cm picosatellite [2]. Examples of missions employing Cubesats are ESA's SSETI Express (2005), University of Toronto's CAN-X1 (2003), CAN-X2 (2008), MOST (2003) and Delft University of Technology's Delfi C3 (2008). Other recent missions using nanosatellites are NASA's NanoSail-D (2010) and O/OREOS (2010) [3]. NanoSail-D successfully deployed a 100-square-foot polymer sail. O/OREOS is the first nanosatellite to operate at the exosphere to conduct astrobiology experiments weighs 5.5 kg and will use a propellant-less mechanism for de-orbiting. NASA has also launched AERCam (1997), a small free-flying monitoring system (16 kg, 2 cameras, avionics, 12 thrusters). Its follow-up is the Mini AERCam. Another example is the SPHERES experiment, there small robots capable of formation flying and rendezvous; the experiment was conducted on ISS in 2007 with partial success.

Several A&R systems have been already flown is space, such as DLR's ROTEX (1993), CSA's SRMS (Canadarm) and SSRMS (Canadarm2) and NASA'S Robonaut 2 (2011), the first dexterous humanoid robot in space. JAXA's Hayabusa mission (2003) included a small rover (weight 591g, 120x100 mm). ESA's ERA, Eurobot and the Dextrous Hand Robot (DexArm) are under development. NASA's Sojourner rover (11kg) and the current Mars Exploration Rovers (MER) Spirit and Opportunity (about 180kg each) are well known examples of successful rover designs. Spirit and Opportunity both incorporate a robotic arm for instrument deployment. NASA's next Mars rover is Curiosity, scheduled to launch on December 2011. Curiosity will be twice as long (about. 3m) and five times as heavy as the current MERs [4]. The next Mars rover mission will be conducted jointly by ESA and NASA and will include two rovers, NASA'S Max-C (65kg) and ESA's ExoMars (270kg), however the mission is still under review [5]. A comparison between the masses of these Mars rovers shows that their weight is increasing due to the increased scientific needs and objectives. However, this weight increase is limited by the launch vehicle's capabilities and the cost/launch is analogous to the total weight.

The general consensus is that although the development of Microsystems capable of replacing modules and of highly integrated small robots presents numerous challenges, it is highly desirable. Although there have been examples of successful miniaturization in space, the introduction in A&R of miniaturization technologies remains limited. A&R space applications are numerous and versatile, as can be seen from this very brief review. The proposed study of terrestrial Microsystems and their space applications is expected to contribute to the introduction of micro systems in A&R, an area considered essential in future ESA missions.

1.3 Methodology

The methodology to achieve the identification of suitable terrestrial MNT components and the roadmaps for their introduction to space A&R was the following, divided in three tasks.

The first task was an extensive research on the state of the art of terrestrial MNT technologies with the aim of identifying micro-nano technology products that could replace current space A&R systems and could result in improvements in mass, volume, power consumption, computational power requirements and functionality. The research included novel terrestrial products which showed great potentials for space A&R. The research was conducted using a broad range of resources; internet, magazines, journal & conference papers and ESA's "Micro Nano Technology Component Technology Board Dossier". The information was filtered and categorized according to technical and programmatic criteria, resulting in a preliminary selection of MNT components.

The second task was an extensive review of current A&R space technologies with the aim of identifying the areas that would benefit the most from the introduction of MNT. The selected A&R scenarios were also analyzed according to their subsystems. The results of this analysis were the main candidates for replacement in A&R systems and the parts where the maximum positive effect could be identified. Various sources were used, including the Internet, journal & conference papers, information published by the various space agencies and ESA's "Automation and Robotics Technology Dossier". The first and the second task were conducted individually and simultaneously but not in isolation, so to facilitate an efficient research for MNT candidates for space A&R.

The third task was the application of the selected MNT components to the problematic areas identified in the second task. This synthesis yielded (a) the most prominent replacements by MNT per subsystem and (b) the recommended roadmaps to facilitate the systematic implementation of these replacements to space A&R.

2. TERRESTRIAL MNT

It is important at this point to define the term micro-nano technologies (MNT). "Microtechnology" covers devices using parts within 1 mm and 1 μm, while "Nanotechnology" describes different types of research where at least one of the characteristic dimensions can be expressed in nanometers. In Europe, a microsystem (MST or Microtechnology) is defined as: "...an intelligent miniaturized system comprising sensing, processing and/or actuating functions. These would normally combine two or more of the following: electrical, mechanical, optical, chemical, biological, magnetic or other properties, integrated onto a single or multichip hybrid" (Microsystems, 4th Framework IT, Sept. 1996). In Japan, Micromachines are composed of functional elements only a few millimetres in size, which are capable of performing complex microscopic tasks. (Micromachine Centre, 1996). In referring to MNT in the context of this paper, the EU definition is used, while the Japanese one is taken into account in a broader sense. Additionally, the notion of MNT technology encompasses miniaturization technology, e.g. novel technologies for integrating motion control units into actuation motors and compact power systems.

2.1 Benefits of terrestrial MNT technology

The process of transferring terrestrial technology to space is called "spinning-in". Spinning-in non-space technologies for space is happening in many ESA program and a number of ESA initiatives for promoting spin-in already exist. However, a more systematic approach for identifying solutions to space problems by exploiting the potential of non-space research and technologies was required. Spinning-in terrestrial technology to space is important for four main reasons:

Performance: Ground applications are often more demanding than space applications (e.g. micro-electronics, micro-nano technologies in medicine, automation, software in embedded systems, etc.), therefore non-space solutions will allow addressing challenges not addressable by gradual evolution of space technology.

Development cost: The institutional and commercial investments on non-space technology exceed by orders of magnitude those of space.

Sustainability of capabilities: A strong mass market assures the enhanced maintenance of engineering skills, process and facilities. It is important to ensure European access and independence in critical technologies.

Reliability of MNT, MEMS and miniaturized components has been assessed extensively during the last five to ten years in a wide range of terrestrial applications.

2.2 Sources

The sources used to provide the MNT state of the art applicable to space A&R were the following. ESA's MNT CTB Dossier was used as a starting point and reference document for information (up to 2007) on the major MNT technologies, products and companies that have been used by or are candidates for space systems. The Internet was used to access universities', research intuitions' and companies' sites and information on their products, technologies and skills, focusing on novelty, enriched functionalities, technical specifications, level of maturity, indented development for the forthcoming years and application in the terrestrial domain. There was also direct contact with companies and institutions of interest, either by conversations over the phone, by frequent email correspondence or by field trips. A major part of the study was based on the use of related literature and a thorough study was conducted on technological and scientific magazines and books, scientific communities and networks for information on novel projects and technologies at the early research stage, commercialized products, specifications and research results. Another source was ESA's EMITS system, which contributed to the understanding of specific technological needs of space A&R and offered pointers on where MNT technology could be most valuable.

2.3 Selection criteria

The selection of the terrestrial MNT component was guided by a set of *technical* and *programmatic* criteria [6, 7, 8]. The technical criteria examine the feasibility of making the selected MNT components compatible with the space environment and functionality requirements of A&R and the programmatic criteria are used to assess the maturity of the technology.

The technical criteria are: *(i)* Applicability to space A&R, *(ii)* Launch conditions, *(iii)* External space environment (LEO, Mars, Moon, Near Earth Asteroid), *(iv)* Required technical lifetime. The programmatic criteria are: *(i)* Development maturity, *(ii)* Development risk, *(iii)* Development cost to reach sufficient maturity, *(iv)* Development time to reach sufficient maturity

To ensure the compliance of each MNT component to the technical criteria, each was assessed for its applicability to the space A&R systems that were studied and their identified needs and problems. Devices that were purely for scientific experiments were excluded, since they are part of the scientific payload. For each selected MNT the following factors were taken into account to ensure compliance with the technical criteria: suitability of the device's operating principle and design for space environment, robustness and extended operational lifetime, thermal shocks, vibrations, radiation and vacuum conditions. An additional criterion is the maximum operating voltage, which is limited at approximately 2kV for space applications due to electrical insulation specifications.

For the programmatic criteria it is important to consider that terrestrial MNT devices are characterized by high volume production with well defined quality control practices from the initial design to the final product.

This results in reliable and profitable production lines, with a reduced risk of errors and faulty products. However, because this is terrestrial technology and despite the high level of maturity, most of these MNT products do not fully comply with the strict specifications for space certified components. A terrestrial component that has been extensively tested and has been verified by being used in the industrial or commercial sector would require an additional 10% cost for spinning in. If the terrestrial component or technology has not been extensively tested, the cost of technology transfer to space increases above this 10% and proportionally to the number of tests required. Nonetheless, this emphasizes the importance of spinning-in terrestrial technology to space, instead of developing a new component.

It should be noted that there is currently no general qualification process for space approved MNT, it is done on a case-by-case basis and usually there is no volume production. The general standards for European space activities can be found at [9]. Therefore, terrestrial MNT components must be ascertained on a case-by-case basis, taking into account each individual design.

2.4 Results of the survey

The search covered a broad range of terrestrial technological areas: automotive, process control, consumer electronics (entertainment, home appliances, etc.), environmental, power generation and distribution, motion control electronics, defence and biomedical.

The outcome of the search and selection process was the identification of more than 100 components/ technologies that are candidates for space A&R. The identified components span a broad range of technologies, e.g. nanostructured materials, piezoelectric actuators and sensors, energy generators, liquid lenses, image processing units, composite materials, electroactive polymers, novel actuators, MEMS. The complete list can be found at [10]. The description of each component includes: physical principle, specifications, space compliance and technical and programmatic maturity.

The selected MNT components have been classified according to their potential functionality with respect to space A&R systems: Power (incl. Thermal), Structure & Materials, Motion control & Force, torque and pressure sensors, Propulsion, Attitude & Orbit Control Systems (AOCS), Actuation, Optical Systems, On-board Data Handling (OBDH) & Communications. This categorization aims to facilitate the efficient selection of components required for the design of a novel, miniaturized space A&R subsystem. In this way, a systematic approach for identifying solutions to space problems by exploiting the potential of non-space research and technologies is provided. Figure 1 depicts the identified MNT components per subsystem.

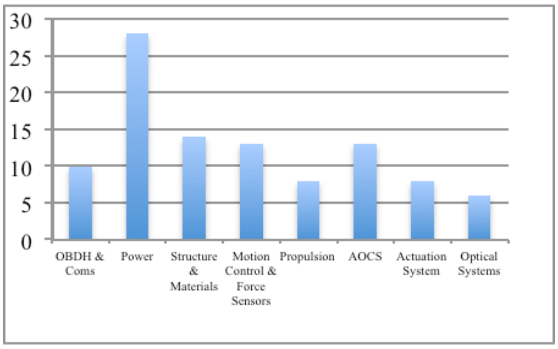

Figure 1. Statistics of results per Subsystem.

The research provided valuable information regarding the trends of MNT technology. The number of products per A&R subsystem highlights the technological areas where MNTs exhibit the greatest growth and have high maturity. AOCS, motion and force control are those that most MNT industries target. As a result, a plethora of MNT candidates exist that can replace or augment in a reliable and cost effective manner A&R components such as IMUs, INS, motion controllers, force, pressure and torque sensors. Power management is another area that increasingly employs MNT for compact designs and higher efficiency. Thermal management also uses MNT components, although few products are currently commercially available. The key breakthrough in many technological areas is expected from nanotechnology and nanostructured materials, but these technologies are not mature yet. For power storage devices and power conversion technologies nanotechnology is expected to increase batteries' energy capacity and discharge and for photovoltaic cells and fuel cells to increase their efficiency and reduce their weight However, nanostructured, reinforced materials, that improve the thermal conductivity, mechanical strength and electrical conductivity of structures are already available. The research also demonstrated that there are technological fields (e.g. communications, optical devices) whose components cannot be easily replaced due to physical constraints (antennas require specific dimensions for reception and transmission, lenses require specific aperture).

3. SPACE A&R

3.1 Classification and problems

For the purposes of this work it was necessary to classify space A&R systems according to their functionality and working environment. The following A&R scenarios were examined: Rover explorers/ other means of locomotion, stationary surface explorers, orbital explorers, aerobots/ balloons, satellite servicers and robotic manipulators inside or outside orbital constructions. Payloads were excluded because a scientific instrument has its own specialized requirements, usually affected by the targeted scientific objective. Planet penetrators, moles and underwater robots were also not reviewed as they are still in a very early phase. Human-class systems and Earth-orbiting satellites were excluded.

The selected A&R were analyzed per subsystem, see Sec. 2.4, to identify potential problems and limitations. The criteria were the following: mass, volume, functionality, electrical, and computational power requirements. The effect of each subsystem on the system was also taken into consideration. Table 1 presents the main problems identified for each class per subsystem.

Table 1. Characteristic problems in space A&R

Class	Subsystem	Problems
(i) Rovers/ Other Means of Locomotion	Power	Solar cells: efficiency-dust Large and heavy batteries
	OBDH	Low computational power
	Navigation	Slow in rough terrains Computational Restrictions
	Mechanisms	Efficiency of DC motors Integration of electronics
(ii) Stationary Planetary Explorers	Power & Mechanisms	Same as (i)
	Propulsion	If retros: mass and volume
(iii) Orbital Planetary Explorers	Power	Solar cells: efficiency Large batteries
	AOCS	Power consumption Computational demanding Low redundancy
	OBDH	Low computational power
	Propulsion	≈ 50% of mass and volume
	Structure	≈ 20% of total mass Enhanced properties required
(iv) Aerobots/ Balloons	Structure	Space restrictions Corrosive environments
	Power	Eff. of flexible solar cells Large batteries
	Propulsion	Use mainly of propellers.
(v) Satellite Servicers (Orbital Servicers)	Power	See (iii) Solar panel at proximity ops
	AOCS & OBDH	See (iii) Add. reqs due to servicing ops
	Sensors for rendezvous and docking	Massive sensors High power consumption
	Manipulators	See (vi - viii) Add. comp. power req.
(vi - viii) Manipulators	Structure	Large mass Cabling
	Sensors	Integration of sensors
	Actuation	Eff. of DC motors Integration of electronics
	End Effector	Lack of standard design Dexterity Sensory information
	Add. requirements depend on environment (e.g. low or zero-g, radiation, etc)	

Some identified problem areas were common among the selected A&R systems. Table 2 presents the subsystems with the greatest effect independently of the class.

Table 2. Subsystems with largest effects

Mass & Volume	Computat. Power	Electrical Power
Power	OBDH	Power
Propulsion	AOCS/Navigation	Motion*
Structure	Manipulators	Thermal

*Motion includes propulsion & locomotion (wheeled/ other).

The identification of the common problems and the subsystems with the greatest effect on the whole system highlights the areas that will be most benefited and is therefore essential for the selection and spinning-in of the selected MNT components and the development of the associated roadmaps.

3.2 Selection of Representative Classes

Due to the similarities in terms of subsystems and problems between the A&R scenarios, two representative classes were selected, taking into consideration the identified similarities, problems, variety of operational environments and the priorities of space agencies. Addressing their problems using MNT also provides the guidelines for the other classes.

The first class is Rovers, the most common exploration system. Their design and results are adaptable to classes (ii), (iv). The second class is Orbital Servicers, because they combine manipulators and orbital systems and there is an increased interest for servicing systems. The results for Orbital Servicers can be adapted to classes (iii), (vi-viii).

4. MOST PROMINENT REPLACEMENTS

4.1 Introduction

The outcome of the search and the selection process was the identification of more than 100 technologies candidate for space A&R, classified according to their potential functionality with respect to space A&R. Of those 100 components, 11 major technological areas and representative components are presented here and in Section 5. These 11 components are presented as demonstration, to highlight certain technological areas and according to their expected impact. It is an objective of this paper to facilitate a greater interest on spinning-in terrestrial MNT components and to highlight prominent technologies. In cases where patented technologies were found, efforts were made to present alternatives.

4.2 Interesting Replacements

The selected technologies and components are presented in Table 3. These improvements by these technologies affect both space A&R classes selected in Section 3.2.

Table 3. Replacements, characteristics and technology.

Technology	Characteristics	Replac.
Piezo-transformers (Noliac–DK) *Alternatives: Solar Cell – Step-up converters (Intivation – NL)*	Voltage Converter High efficiency No EMI and EMC	DC/DC converters
WISA Power (ABB-DE)* *Alternatives: Thermogenerators (EnOcean–D), MicroPower (Tyndall–IR)*	Wireless Power Supply;	Cables inside A&R systems
TE Peltier Coolers (Micropelt-D) *Alternatives: Carbon nanotubes (n-Tec – NW, Nanocyl - BE)*	Fast Cooling Small footprints Higher power density	Active cooling
Motion Tracking Instrument (IMEGO – SW) *Alternatives: MS900D (Colybris – CH)*	Small size Rugged device Shock tolerant	IMUs and INSs
Liquid Lenses (Varioptic – FR) *Alternatives: FluidFocus (Philips – NL)*	Variable focal length No moving parts Fast response Optical Image Stabilization.	Camera Lenses
3D Camera (Mesa Imaging – CH) *Alternatives: icycam, CMOS low-light imagers, CMOS high-speed imagers (CSEM – CH)*	Automatic calculation of distance No intensive computational systems needed	Cameras with S/W calculating depth
PolyPower (Danfoss – DK) *Alternatives: DuraAct (PI and INVENT GmbH – D)*	Based on Electroactive Polymers Technology; Actuator & sensor;	Sensor, actuator, or as vibration suppressor
Wire in Composite (BeruF1 – GB) *Alternatives: Carbon nanotubes (n-Tec-NW, Nanocyl-BE, Sandvik-SE)*	Embed PCBs, cables , sensors etc. into the structural material	Current structural materials, bulky cabling
EyeQ System-on-Chip (Mobileye – NL) *Alternatives: Icyflex processor (CSEM – CH)*	Real-time visual recognition and scene interpretation	Current ICs and software processors
WiseNET – Ultra low power wireless sensor technology (CSEM – CH) *Alternatives: Wireless Sensor Networks (Tyndall – IR)*	Ultralow power RF SoC with on chip micro-processor , SRAM and sensor	Sensors with cables
Linear Actuator (KATAKA – DK)*	Compact Very rigid Working principle	Special Actuation req.

* Not an MNT, but still an interesting concept found.

5. ROADMAPS

5.1 Introduction

The efficient, systematic introduction of terrestrial MNT technologies to space A&R is achieved by the implementation of roadmaps. The roadmaps and recommended replacement by terrestrial MNT are presented for both the selected classes in Section 3.2. However, during the research, the selection of the two classes had an important role in providing a reference point regarding the effectiveness of the replacements.

There are still some areas where terrestrial solutions cannot yet improve the capabilities of the space systems. The efficiency of space solar cells is higher than the terrestrials, since solar energy is the main energy resource in space and this technology is already advanced. Hydrogen Fuel Cells are still not a viable solution for autonomous systems, mostly due to their volume. There are currently no advances in magnets and materials that would result in novel motors that produce same or higher torques, while having same or smaller dimensions and require less power than those currently in use.

5.2 Roadmaps

The roadmaps are presented in Table 4 and consist of combinations of replacements that provide a target technology with a major impact. It is difficult to estimate the timeframe of space qualification for each product, as it is not yet a streamlined process. However, the presented technologies are already mature. The roadmaps are presented here for both space A&R classes, unless noted otherwise. The roadmaps presented affect all A&R systems

Sensor Islands: Sensor Islands, or Power and Computational Autonomous Remote Sensors, is a highly pursued research area. This concept is very important because it would increase the autonomy and flexibility of systems. A sensor island is characterized by: (a) Receiving or harvesting power with minimal cabling (e.g. Power SoC – Tyndall (IR), (WISA Power-ABB(D)), (b) High integration of electronics, (c) Computational autonomy, data fusion and signal processing without need to send or receive any data, except the final measurement or infrequent patches (e.g. icyflex Processors and S/W Configuration Mechanisms – CSEM (CH)), (d) Wirelessly communicate with a central computer for the overall control (e.g. Wisenet – CSEM (CH)) and (e) Integrate sensors of different functionalities.

Structure: The main efforts concentrate on developing structural elements with advanced capabilities. Robust but lightweight materials like CFRPs (Carbon Fibre Reinforced Plastics) are already in use; however their capabilities can be significantly increased by ejecting specialised nanoparticles. This can be combined with techniques for embedding sensors and cables inside the structure, thus lowering mass penalties and thermal losses and increasing flexibility and protection (e.g. Wire in Composite (WiC) – BeruF1 (GB)). The technology of Electroactive Polymers (EAP) and Piezoelectric elements can also be used in structural elements as sensors and/or actuators (e.g. Polypower – Danfoss (DK), DuraAct – Invent (DE)), e.g. as vibration suppressors.

OBDH: The main aim is the development of a decentralized architecture, based on elements of the Sensor Island, but concentrated on processing power. Dedicated image processors would lower the computational burden (e.g. EyeQ DSP – MobilEye).

AOCS: Terrestrial MNTs offer great opportunities in this area. There are products with small footprints and low consumption which offer superior functionalities for common used elements, such as GPS, gyroscopes and IMUs (e.g. Butterfly Gyro – IMEGO (SE), GPS – U-Blox). This also is valid for electronics and micro-controllers, where 64bit solutions could increase the computational power (e.g. Icycam – CSEM (CH), EyeQ – Mobileye). The use of Sensor Islands would increase the capabilities of this subsystem.

Navigation/ Rendez-vous/ Docking: This roadmap combines elements of other roadmaps in terms of power supply (e.g. Piezo-transformers – Noliac (DK)), Optical Sensors (e.g. 3D Camera – Mesa Imaging (CH), High Speed CMOS Sensors – CSEM (CH)) with aid of advanced lenses (e.g. Liquid Lenses – Varioptic) or sensors which can assess relative speed or distance with great accuracy (e.g. Ground Speed Sensors – BeruF1(GB)). Additionally fast data processing is necessary in a decentralized architecture (Sensor Islands) using dedicated processors (e.g. EyeQ DSP – MobilEye, icyflex Processors – CSEM (CH)). 3D cameras that do not require excessive computational efforts to derive automatically the depth (e.g. 3D Camera – Mesa Imaging (CH)) improve the navigation.

Actuators: This roadmap highlights the importance of higher integration of sensors (e.g. Position Sensors – Posic (CH), Torque Sensor – CSEM (CH)). It also presents novel concepts for linear actuation with minimal requirements, a rather difficult matter in space technology (e.g. Linear actuator – KATAKA (DK)).

Table 4. Main Roadmaps for the development of novel technologies for space A&Rs

Roadmaps	Requirements	Current Technologies	Intermediate Techn.	Final Technology
Sensor Island	Packaging-Shielding 64 bit Technology	WISA Power (ABB) icyflex processors (CSEM) WiseNET (CSEM)	Depends on required sensors	Sensor Island
Structure	Packaging	WiC (BeruF1) Active Vibration Damping (Danfoss, PI) Piezo-transformers (Noliac)	Sensor Islands Modular CFRP components with inside cabling	Novel Chassis with active elements and high protection
OBDH	Packaging-Shielding 64 bit Technology	WiseNET (CSEM) Icyflex processors (CSEM) EyeQ DSP (Mobileye)	Sensor Island	Distributed Architecture
AOCS	Packaging-Shielding 64 bit Technology	Piezo-transformers (Noliac) IMU (Imego) Icyflex Processors (CSEM)	Sensor Islands	Multifunctional distributed AOCS systems
Navigation	Packaging-Shielding 64 bit Technology Characterization of Liquid Performance in Space	Piezo-transformers (Noliac) Icyflex Processors (CSEM) 3D Camera (Mesa) Speed Sensor (BeruF1) EyeQ DSP (Mobileye) Liquid Lenses (Varioptic) Hi-Speed CMOS (CSEM)	Decentralized cameras with DSP and Variable focus Sensor Islands	Decentralized packages for Navigation/ Rendezvous and Docking purposes with data fusion by many sensors
Actuators	Packaging-Shielding	Piezo-transformers (Noliac) Position Sensor (Posic) Linear Actuator (KATAKA) Torque Sensor (CSEM)	Larger Integration of motors Sensor Islands	Linear and novel rotational actuators with large integrations

5.3 Benefits by the use of Roadmaps

The beneficial impact on space A&R as demonstrated by the roadmaps is high on functionality improvement, is medium to high on mass and volume reduction, is medium to high on computational requirement reduction and is low to medium on power requirement reduction and increased efficiency. In particular:

Mass and volume: Smaller devices replace current systems, which also enables the use of more than one similar devices increasing redundancy and data accuracy. More space is freed for payloads.

Power Consumption: MNT devices consume less and provide more clever and efficient power management (Incl. better cabling protection). This also means smaller panels and batteries, thus lowering mass and volume.

Computational Power: Using decentralized architecture and sensor islands, the efficiency of computational resources is increased.

Functionality: MNTs extent the mission capabilities of space A&R, while increasing redundancy; in the same volume more similar subsystems can be implemented.

Table 5. Benefits for Space A&R.

Roadmaps	Advantages	M	V	P	C	F
Sensor Island	Fewer Cables, Efficiency, Redundancy	**	**	***	***	***
Structure	Less weight, Better Protection, Higher Power Efficiency	*	*	**	*	***
OBDH	Redundancy, Less Computational Burden	*	*	**	***	***
AOCS	Lower Power Consumption, Redudancy, Less Computational Burden	***	***	***	***	***
Navigation	See AOCS, Higher accuracy	***	***	***	***	***
Actuators	Lower mass & volume, higher efficiency, design flexibility	*	**	**	*	***

6. CONCLUSIONS

More than 100 MNT components and relevant technologies were found that could be spinned-in in space A&R. The majority of the components are European, which leads to conclusion that Europe and can be to a large extent technologically independent. These MNTs can significantly benefit space A&R systems in terms of mass, volume, power, computational power, functionality and increased redundancy and also have better specifications compared to current space products. The A&R subsystems of AOCS, motion and force control are the ones most targeted by terrestrial MNT. Power and thermal management can also employ MNT for more compact designs and higher efficiency. Nanotechnology and nanostructured materials are still at a research level, with the exception of reinforced materials which can implemented in the overall structure.

Two base scenarios were selected for the introduction of MNT and the development of the roadmaps: (a) an Exploration Rover, (b) a Satellite Servicer with a Robotic Manipulator. The highest beneficial impact from the introduction of MNT was at the AOCS, Structure and Navigation subsystems. The subsystems that have a medium impact from the replacements were the OBDH and Actuators/Locomotion while the lowest impact was at the propulsion, thermal and communications subsystem. The most promising and feasible roadmap is the Sensor Island, which is crucial to the overall improvement. The roadmaps can be applied to all space A&R, therefore any spin-in efforts for a particular system can be transferred to other systems. Additionally, the simultaneous implementation of MNT in more than one subsystem increases the overall benefit due to the fact that all subsystems exhibit synergies with each other. In conclusion, this work demonstrates that there are mature technologies in the European research community and market that can greatly augment space A&R, without altering their basic requirements and function.

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