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Miniaturized Multifunctional System Architecture for Satellites and Robotics

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Abstract

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This thesis describes and evaluates the design of nanospacecraft based on advanced multifunctional microsystems building blocks. These systems bring substantial improvements of the performance of nanosatellites and enable new space exploration, e.g. interplanetary science missions using minute space probes. Microsystems, or microelectromechanical systems, allows for extreme miniaturization using heritage from IC industry. Reducing mass and volume of spacecraft gives large savings in terms of launch costs.

Definition and categorization of system and module level features in multifunctional microsystems are used to derive a spacecraft optimization algorithm which is compatible with commonly used concurrent engineering methods.

The miniaturization of modules enables modular spacecraft architectures comprising powerful multifunctional microsystems, which are applicable to satellites between 10 and 1000's of kg.

This kind of complete spacecraft architecture has been developed for the NanoSpace-1 technology demonstrator satellite. The spacecraft bus uses multifunctional design to enable distributed intelligence and autonomy, graceful degradation, functional surfaces, and distributed power systems. The increase in performance of the new spacecraft architecture as compared with conventional nanosatellites is orders of magnitudes in terms of power storage, scientific payload mass ratio, pointing stabilization, and long time space operation.

This high-performance system-of-microsystems architecture has been successfully employed on two space robotic concepts: a miniaturized submersible vehicle for Jupiter's Moon Europa and a miniaturized spherical robot. The submersible is enabled by miniaturization of electronics into 3-dimensional, vertically integrated multi-chip-modules together with new interconnection methods. These technologies enabled the submersible vehicle tube-shaped design within 20 cm length and 5 cm diameter. The spherical rover was developed for long range and networked science investigations of interplanetary bodies. The rover weighs 3.5 kg and is shown to endure direct reentry on Mars, which increases the ratio between the landed mobile payload mass and the initial mass in Mars orbit by a factor of 18.

Keywords: Multifunctional design, Spacecraft, Robotics, Microengineering, MEMS, Exploration, Distributed intelligence, Mission Design

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Dedicated to my wife Karolina

"When faced without a challenge, make one"
Peter's Law no. 12 by Peter Diamandis

List of papers

I Nanospace-1: the Impacts of the first Swedish Nanosatellite on Spacecraft Architecture and Design, F. Bruhn, J. Köhler, L. Stenmark, Acta Astronautica, vol. 53, pp. 633-643, 2003. (Invited paper)

II NanoSpace-1: Spacecraft Design using Advanced Modular Architecture, F. C. Bruhn, P. Rathsman, L. Stenmark, submitted to AIAA Journal of Spacecraft and Rockets, 2005.

III Spacecraft Design Optimization – A Multifunctional Microsystem Module Implementation Method, F. C. Bruhn, J. Köhler, L. Stenmark, G. Thornell, submitted to AIAA Journal of Spacecraft and Rockets, 2005.

IV Distributed Communication Architecture in Spacecraft System-of-Microsystems – A Preliminary Analysis, F. C. Bruhn, Sven-Erik Jansson, P. Nilsson-Zandkarimi,, J. Köhler, O. Redell, Submitted to Journal of MEMS, 2005.

V MEMS Enablement of Miniature Autonomous Submersible Explorer, F. C Bruhn, F. D. Carsey, J. Köhler, M. Mowlem, C. German, L. Stenmark, and A. E. Behar, IEEE Journal of Oceanic Engineering, vol. 30, pp. 165-178, Jan 2005.

VI A preliminary Design for a Spherical Inflatable Microrover for Planetary Exploration, F. C. Bruhn, J. Warell, C-I. Lagerkvist, V. Kaznov, J. A. Jones, L. Stenmark, Accepted in Acta Astronautica 2005.

VII Extremely Low Mass Spherical Rovers for Extreme Environments and Planetary Exploration Enabled with MEMS, F. C. Bruhn, K. Pauly, V. Kaznov, 8^{th} Int. Symp. on Artificial Intelligence, Robotics and Automation in Space, 16-20 September, Munchen, Germany, 2005. (Invited paper)

The contribution by the author to the papers included in the thesis is as follows:

I Significant part of the planning. Major part of evaluation and writing.

II Major part of the planning and evaluation. All of the writing.

III Major part of the planning and evaluation. All of the writing.

IV Major part of the planning and evaluation. Substantial part of the writing.

V Major part of the planning and evaluation. Substantial part of the writing.

VI Substantial part of the planning, evaluation, and writing.

VII Substantial part of the planning. Major part of evaluation. Significant part of the writing.

Contents

Introduction

Microengineering is one of the newest tools available to the space community. Several technology leaps have been taken in space design over the years and microengineering may represent the largest step ever. Microengineering, or microstructure technology (MST), or microelectromechanical systems (MEMS) initiates an even larger revolution than the introduction of surface mounted devices (SMD). MST represents a potentially better approach since it provides the possibilities for multifunctional designing, i.e. MST is not a specific tool like SMD, but rather a broad method to add electronics, mechanical functions (e.g. structure load carrying, valves, micropumps, filters) and thermal handling.

As with any new technology in the space business, flight qualification and flight heritage is important. These two areas are difficult to fulfill because of the conservative thinking of space managers around the world. One major goal of this thesis is to present technologies and ideas that can help bridge the MST "valley of death", i.e. the phase where devices and systems matures from breadboard to flight systems [1].

MST has been successfully applied to numerous applications on Earth and in space [2-5]. However, these systems are often on device level and require a hybrid, or fully traditional setup around the device to work.

Dr. Siegfried Janson *et al.* of the Aerospace Corporation, USA went a long way in 1993 when they laid out the goals of spacecraft built from silicon using MST techniques [6]. Janson's *et al.* vision has not yet come true, but the work of Dr. Johan Köhler in his PhD thesis, "Bringing micro-systems to space" sets the scene for highly MST dependable spacecraft. Köhler's thesis addresses the implementation of MST, and in particular multifunctional microsystems (MMS) in spacecraft design [7].

My thesis will discuss in detail the implementation of MMS in spacecraft and space robotic design, evaluation of new space mission opportunities, and general system aspects. Detailed design of a next generation high performing nanosatellite is discussed in Papers I, II, and III. Paper I is included to summarize the work that was done before I started my research and to identify the interesting areas of research. Further information regarding spacecraft classification and technology readiness levels is given in the appendices. Additional work on enabling technologies and applications is discussed in Papers IV and V.

In the pursuit of demonstrating the wide applicability of the toolbox denoted MMS, designs of a robotic vehicle for Jupiter's icy moon Europa and networked exploration of our Moon and Mars have been investigated and evaluated in Papers VI, VII, and VIII.

The main track of this thesis is on the definition, design, evaluation, and construction of NanoSpace-1 (NS1) recently renamed Micro-Link 1 (ML-1). This is a technology satellite test-bed for disruptive technologies, and in particular multifunctional microsystems. NS-1 is a 10 kg spacecraft, hence classed as a nanosatellite by definition (appendix 2). It is designed with the aim to be a relatively low-cost platform enabling recurring spaceflight opportunities for space qualification and evaluation of MMS modules and MST devices. The major research and development driver has been an internally enforced goal of designing a 10 kg spacecraft with the relative performance of order-of-magnitude larger satellites. This thesis shows that it is possible to meet the system and performance envelopes of larger spacecraft with effective nanosatellites forged on the development and advances of multifunctional microsystems.

The research in this thesis is devoted to system level designs and integration of complex systems. The scope of the papers included in this thesis is presented in Table 1. Here, the application level runs down a hierarchical ladder from Mission level through spacecraft, subsystem/function, to the basic devices. The results achieved can be categorized in conceptual work, design and analysis, going from overview into detail and understanding.

Table 1: Scope of the thesis papers

	Concept	Design	Analysis
Mission	I, VII	I	VII, V, VI, VII
Spacecraft	I, III	III	II, VI, VII
Subsystems/function	III	III, V	III
Device		III	III

System design with respect to microsystems

This thesis is devoted to developing, defining, evaluate, and applying Multi-functional MicroSystems (MMS) in various applications. Since no MMS system has yet evolved above Technology Readiness Level (see appendix 1) 4 to 5, it is difficult to estimate the quality of the technique, although an assessment is done in Paper II and Paper IV. Quality in this context means long time stability and degradation, impacts of unforeseen problems, etc…

Benefits of MMS

A multifunctional design differs from traditional subsystem-oriented design in that there are no subsystems *per se*, but rather implementations of functions. In a functionally-designed spacecraft or system, the design process emphasizes the identification and specification of functional requirements using the usual front-end systems engineering procedures. However, the identified requirements are never specifically allocated to a physical subsystem. Instead, the various required spacecraft functions are implemented in suitable building blocks without regard to traditional spacecraft subsystem boundaries. This means that single components or multiple subsystems can be implemented in the same building block.

In the MMS concept, functional modules are used to implement higher-level mission-specific functions or to fulfill mission requirements. In particular, introduction of MMS will enable redistribution of functionality from single expensive platforms to high-performing nano/microsatellites. The MMS concept is developed to be a generic design concept that is easily adaptable to different missions and requirements. Subsystem functions are distributed across multiple MMS modules. Each MMS can also be a structural element ("building block") that contains embedded electronics, conductors, and thermal control. Traditional subsystem boundaries (and their associated penalties) no longer exist.

Three important definitions are defined for the overall functionality of a MMS based system [Paper I, II, and III]:

- Adding functional modules as required
- Swapping/adding MMS
- Replacing selected functions/modules on a satellite design

The second definition to allow swapping of MMS modules are the most difficult to fulfill since the wiring in a spacecraft is usually different for each module. The implementation of MMS offers extreme miniaturization and weight savings from the reduction or even elimination of black boxes, wire harnesses, dead volumes, heavy radiation shielding, and connectors.

Figure 1 illustrates the MMS concept strategies and techniques for miniaturization and optimization. The toolbox available for MMS is divided into six major areas, which are equally important.

Functional modularization is the trade of traditional subsystems versus distribution of functions over one or several modules.

High-level integration is the level of integration in each module of MMS "block".

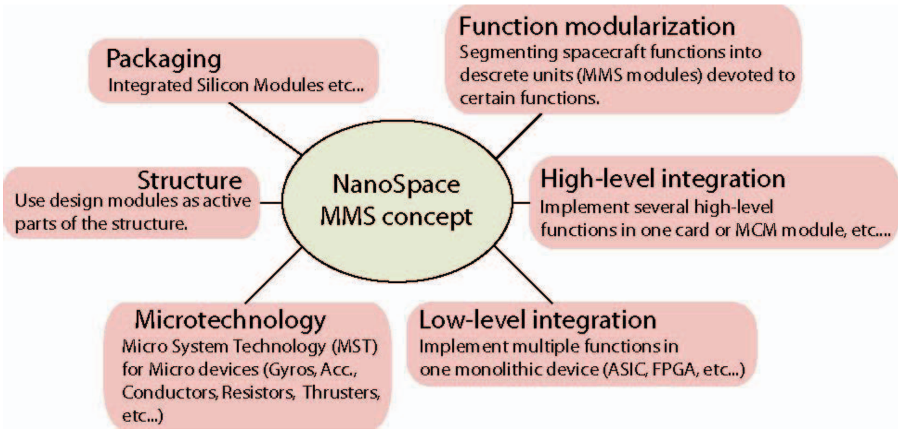

Figure 1. Illustration of the MMS concept strategies and techniques. The consequence of creating spacecraft building blocks that approaches all six areas is high performance. This is enabled when every single building block is given properties from not only mechanical or electrical aspects, but rather from new packaging material, miniaturization of electronics, integration of advanced thermal properties, being part of the senabl tructure, ing high-level integration in the package, etc.

Packaging, functional modularization, high and low level integration, microtechnology and structure are necessary parts of a successful general module building block. An ultimate solution should always be to design a module that makes use of all six areas.

This can be illustrated in the following way: assume that one would like to miniaturize a printed circuit board that has a common communication interface, a protective casing, a connector, and some electronics. Applying Fig. 1 the miniaturized system should provide a casing, accommodate a connector, contribute to the structure, have the original functionality, and integrate the electronics.

Figure 2 shows a graphical representation of a multifunctional microsystem (MMS) module that fulfills these requirements and also incorporates a general design that makes sense from a production point of view. The module is separated into three main blocks, where the bottom Communication module is standardized and the top Protection module partially standardized. This example module consists of three sub-modules which are thin-film soldered or bonded together. The middle module incorporates the electronics in a 3-dimensional layout stretching over one or more silicon wafers using internal vias [8].

Defining subsets or subparts of MMS modules speeds up the development and assembly and thus reduces the manufacturing costs. The trade-off is that the full level of flexibility will not be reached unless a new development cycle from scratch is triggered, but this in turn is relatively expensive. My suggestion is that, at least initially, this option is left open mainly for mission specific modules.

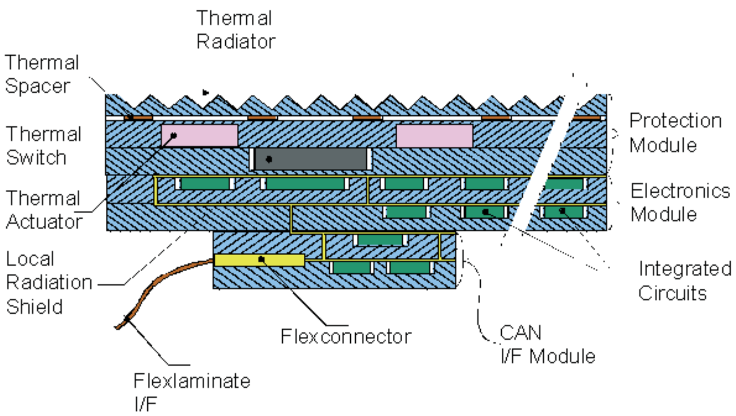

Figure 2. Multifunctional Module system consisting of three parts. At the bottom is a standardized interconnection and communication interface, in the middle an electronics module, and at the top a space environment protection module.

Low level integration considering trade-offs to integrate many small discrete functions into a larger device. Typical incarnations of this are the replacement of many discrete components into application specific IC (ASIC's) or field-programmable gate arrays (FPGA's).

Microtechnology is an extremely vital part as this tool enable miniature multifunctional modules integrating multiple functions.

Structure is regarded as an extension of microtechnology, where a good design can give added system value by allowing the module to act as a load carrying element.

Packaging is important to for enabling proper integration and interfaces of all the previous areas. The MMS modules must be compatible with a number of packaging methods where the most common one is using silicon wafers as the bulk material.

A balanced concept that makes sense and touches on each strategy in figure 4 has obvious benefits, and can be defined as a multifunctional microsystem (MMS).

Thus, a fully optimized MMS would make use of the best low-level integrated monolithic devices, package them in the best high-level package together with mechanical functions using microtechnology, and finally be part of the satellite structure.

However, while each of these techniques and strategies has its own advantages, none by itself is truly enabling for implementing the next generation of high-performing nanosatellites. Particularly important, as for any modularized system is the trade-off between performance, scalability, and technology lifetime. The MMS modules are manufactured as complex bonded silicon structures and cannot, by its nature be easily changed. Therefore, MMS require process maturity and exceptionally skilled planning to meet the technology lifetime requirement.

Related work

The Multifunctional Structure (MFS) approach by Lockheed-Martin and others clearly illustrates a tremendous progress in this field, although not yet coming to a design strategy that incorporates all techniques [9-10]. MFS is a very similar technology to the MMS that aims to reduce or completely remove the cables and connectors. The walls of the spacecraft are covered with a flexible film which holds the conductors for MCMs and other components. MFS touches on many of the strategies presented in Fig. 1, although it doesn't not go to the extreme high-level integration that MMS does. Many circuits in the MFS concept are socketed, or mounted in groups onto a carrier, which would then be placed on a corresponding socket, in order to be replaceable. In this way are parasitic masses and volumes removed.

A similar approach with larger "sockets" is taken with the MMS concept, by incorporating a flexible film that contains all conductors, on the backside of larger MMS module arrays. On NanoSpace-1, printed circuit boards are used as intermediate shell. On these PCBs are all conductors are located. The MFS concept has been verified on the NASA Deep Space-1 mission. The MFS uses a structural panel as mounting device; the panel also incorporates integral thermal control. The panels can incorporate capillaries and a capillary pump loop to liquid cool areas with high power densities. The MMS technology is really a mixture of all techniques mentioned above.

Calculations made by the US. Air Force Research Laboratory (AFRL) on the STRV study using MFS shows a typical reduction of 70-90% in mass and volume and more than 30% in power [11]. Calculations performed by the author using MMS technology on a submersible vehicle for the Jovian Moon Europa shows an increase in packing density of 25 times [12].

A truly functional design methodology represents a complete paradigm shift in spacecraft design. MMS capitalize on the volumetric benefits of encapsulating traditional and necessary components (e.g. propellant tanks, batteries, etc...) in a functional shell.

Using the possibility to use the structure for implementation of high-level systems, such as power regulation, battery recharging, distribution and thermal control is very important in order to get a balanced concept. MMS further allows for commercial-off-the-shelf (COTS) to be implemented, although it requires naked dies to be used for high-level integration, but on the other hand semi-conductor manufacturers are making their components readily available as naked dies in addition to the traditional packaging. Surrey Satellites Technology Limited have successfully demonstrated the use of COTS in space and also demonstrated some initial degree of modularization [13]. However, Surrey's approach has been more oriented on sales than technology enhancements and they still rely heavily on traditional Printed Circuit Boards (instead of microsystem integration).

A major difference between the proposed MFS concept or a higher order system approach based on MFS the Reconfigurable Multifunctional Architecture (RMA) concept compared to MMS as it is implemented in the ÅSTC distributed system-of-microsystems is that the common bus is routed differently [14]. In the systems-of-microsystems there are one thin flexible panel on each side of the spacecraft and also across that interconnects all modules to the power bus and the Controller Area Network (CAN) bus (Paper IV).

In the MFS concept the common bus is typically positioned on the same multifunctional structure as the satellite functions and interconnections are made using small flexible hinges at each corner, where two building blocks intercepts. The MMS concept is more flexible since it has "free" and independent modules, whereas the MFS require a larger panel, to be mounted and connected.

There is a slightly larger overhead with the MMS interconnection scheme in terms of more and smaller modules, but this can effectively be minimized if the flexible film is positioned in an intermediate shell, working between the outer shell and the core elements, as demonstrated on the NanoSpace-1 spacecraft (Paper II).

Don Hunter from the Jet Propulsion Laboratory has pursued a concept called Integrated Avionics System (IAS) which in nature is quite close to MMS [15]. IAS is a design philosophy that provides a low-mass, modular distributed or centralized packaging architecture which combines ridged-flex technologies, high-density COTS hardware and a 3-dimensional mechanical packaging approach. IAS shares some of the thoughts from the MFS concept described above. Although IAS focuses on reduction of mechanical interfaces, an electronics comparison with MMS can be made. IAS is designed to work as load-carrying elements of a spacecraft. This is done effectively through interconnection between the flex plates that forms the base of IAS. Since IAS is formed around several flex panels it is also possible to form a box shape. The typical size of a MMS module for the NanoSpace-1 spacecraft is 68x68x3mm where in the IAS case the typical dimensions are similar, 50x50x12.7mm.

A major difference is that the IAS is mounted inside an aluminum frame while the MMS is constructed around silicon wafers. This has a significant impact in implementation possibilities since the MMS is a solid structure that can be formed using micromachining for various functions, while in the IAS case, much space is non-occupied. This results from the fact that IAS using flex boards with surface-mounted components in a layered configuration inside the IAS frames. 3-dimensional packaging is creating by interconnecting the flex boards internally. MMS systems can reduce even further by packaging everything closer together using micro machining. The silicon wafers used in MMS are also better heat conductors that flex boards and are therefore more suitable to handle higher heat fluxes. If needed, local micromachined heat pipes or micropumps can be incorporated in the MMS concept.

Limitations

The single most important issue to MMS design is manufacturing limits and process yields. Köhler *et al*. have performed preliminary analysis of the process yields for manufacturing of multifunctional microsystems modules [7].

There are several differences compared to traditional yield modeling and yield management approaches, as described by Roos, Atchison, and Manson [16, 17]. MMS design for space applications will have limited series which in turn will give a low number of samples to verify for yield. MMS also involves a complex internal structure with many various process steps and process types.

A comparison can be made to modern semiconductor manufacturing with large volumes such as CPUs or FLASH memories. First, the semiconductor manufactures uses similar process types and process steps throughout the entire line and does not involve many different functions. This fact together with automated process lines allow for traditional yield management to be applied and intensively analyzed as the ramp up in production creates massive amounts of wafers. Second, the semiconductor manufacturers have well developed simulation tools that help minimize systematic yield problems. Third, reduced yield losses can be through development and quality assurance of equipment and processes. Fourth, two major drivers are important when building a CPU or a FLASH memory, namely the clock frequency and the number of transistors. The number of transistors in turn determines the power consumption and thus, the maximum clock frequency and the manufacturing complexity.

Analyzing yield effects in MMS is quite different since the series are small and there are no complete software to simulate the complex processes and mixtures of functions. The existing software also has problems to simulate the three-dimensional structure that is inherited in the MMS design. Since space is a constrained market there are not massive amount of development funds which together with many different process types lead to a substantial systematic yield problem on top of random yield effects. Reducing the systematic yield errors are extremely important for MMS and requires massive quality assurance implementations [7]. In our comparison with the semiconductor industry were few parameters dominate the performance, an MMS have many parameters and functions which substantially raise the yield complexity. Specifically a MMS module does require bonding of several and most often structured silicon wafers. The bond interfaces are extremely critical and necessary in order to verify the functionality in the MMS since many functions are distributed over several wafers.

Space environment

The space environment will put requirements on the MMS modules in terms of radiation hardening and micrometeorite impacts [18]. The importance of this is strongly related to commercial aspects. The largest markets for spacecraft are in Low-Earth Orbits (LEO) and in Geo-Equatorial Orbits (GEO). However, these orbits have very different characteristics. GEO orbits are close to the upper Van Allen belt and therefore generate much higher radiation doses that the system must tolerate.

In response to this, the MMS development can be divided into three categories which corresponds to market opportunities and requirements by the science community. These three segments are defined according to this:

1. Low Earth orbit (low radiation from Van Allen belts)
2. Interplanetary travel and small interplanetary bodies
3. High doses from radiation belts

The modules should be designed according to Fig. 2, i.e. in a way so that radiation shielding can effectively be added without introducing a completely new design of the whole module. This can be done by allowing for extra silicon wafers with shielding material to be added on-top of the modules. An example on this is the s-band antenna design by Kratz *et al.* [19]. In this design paraffin heat storage is added. This can be modified for various thicknesses in order to increase radiation protection. In this context it can be noted that the first set of modules that will fly on NS-1 will be designed for

Low Earth Orbit (segment 1) and moderate radiation doses. Changing a module design for segment 1 and adapting it for segment 2 and 3 typically involves adding radiation shielding: however, in some cases where highly energetic particles have a high probability of causing single event latch-ups (short circuits) one may also have to take precautions by adding radiation hardened electronics.

The mass penalty

Space travel and space exploration are difficult and require large rockets. Around this fundament is all government sponsored launchers forged. A few are challenging this fundament, especially in the United States. Companies like Space-X are anticipating smaller and more capable spacecraft. Also the European Space Agency (ESA) is working on smaller launchers, namely the Vega launcher.

Going into space is typically a 1:100 weight ratio, i.e. for every kg in orbit it requires 100 kg propellant and support structures on the surface of Earth. The American space shuttle has a lift of mass of about 2000 metric tons, or 2 million kg. The obvious way to reduce cost taken the mass penalty ratio into account is to lower the launch mass. However, many systems have a minimum size defined by connectors and traditional setups.

Reduce mass to cut cost

The idea of reducing mass to cut cost is really tempting since it should be feasible to have smaller launchers. Smaller spacecraft should also be quicker to assemble and can possible allow for clusters to be deployed in a single launch [20, 21]. However, reducing the spacecraft mass typically means cutting scientific value of the spacecraft due to decreased payload capability. This can be exemplified with the Surrey Satellite Technology Ltd (SSTL) SNAP-1 bus [22] and Munin developed by the Swedish Institute of Space Physics (IRF) in Kiruna [23, 24]. Both have been successfully launched and operated in space.

A short comparison between SNAP-1 and the Ångström Space Technology Centre's NanoSpace-1, Paper II, shows large differences, mainly due to electronics development over several years, and microsystems implementations. For instance, the total delta-V of the spacecraft can be increased from 3.5 to about 100 m/s. The power capability in nominal mode increases from 5-6 W to 64 W. The battery capacity increases from 10 Whr to 172 Whr. Furthermore, many systems on the NanoSpace-1 satellite are redundant. It is quite clear that the scaling down of traditional spacecraft reduces performance and scientific value while implementing MST on all levels can keep relative performances and provide extraordinary spacecraft.

Deploying highly integrated and MST-enabled spacecraft will increase the development costs, and make the paradigm void the belief that smaller spacecraft is significantly cheaper. The savings in launch costs are still valid but the development costs of these technologies drive the cost. No complete spacecraft has been built using MMS derived architecture yet and therefore the costs are only estimations. The best cost estimate today for development on the NanoSpace-1 spacecraft puts it at about 100 million Swedish Kronor (SEK) ~ 10 million Euro.

Modularity for cutting cost and gaining performance

Many systems on Earth utilize modularity and distributed intelligence to lower cost and increase performance, e.g. most cars today use a serial communication link with smart "nodes". For instance, the signal lights of a car is turned on by sending a serial command to each light, which in turn will blink until further notice that they should stop. In each of the lights a smart node is employed that allowing the light a certain degree of freedom and distributed intelligence.

The introduction of modularity and systems distribution has long been desired in spacecraft design. The conventional and conservative space design rules together with the requirement to keep mass as low as possible have effectively restricted these approaches. This is mainly because the conservative ways of designing spacecraft tend to require that each node or subsystem should be packaged in a protective cover and be equipped with bulky connectors.

Distribution of intelligence and distributed sensors are widely implemented into space robotics [25, 26]. This is mainly due to complex wiring, which can be significantly reduced using serial data communication and smart nodes. The Scorpion and ARAMIES robots developed by ESA and the University of Bremen are excellent demonstrators where distributed intelligence has been applied [27, 28]. A backside of this approach is that each node gets fairly large when using traditional technologies. Introducing MST and vertically integrated multi-chip-modules can significantly reduce the sizes of interconnects and electronics and subsequently significantly decrease the mass involved. The SCORPION robot has 24 distributed mechanical nodes or joints, were each joint comprises connectors, a dc-motor, motor driving electronics, a processor, and communication transceivers. Reducing each node by 50-70% is within reach using MMS which would make a large difference on this multi-node system. Furthermore, the mass would scale even better since the supporting robotic body and mechanics can then be made lighter.

Enabling powerful and low weight spacecraft and robotic vehicles

General aspects on MMS modules and spacecraft design

For any successful implementation of MMS to make a profound step forward in spacecraft design, at least the following properties must be accommodated (Paper III):

- Enabling low weight high performance support systems
- Enabling low weight high performance scientific payloads
- Enable a scalable and modular design
- Enable autonomy and distributed intelligence

Scalable design is highly wanted due to several reasons. First scalable designs will enable a larger market for the products. If a specific multifunctional Microsystems module can work over a range of spacecraft sizes, from nanosatellites to large spacecraft, the number of potential customers' increases. Creating a scalable design however requires careful planning. Three major issues have to be considered (Paper I), the lifetime, the performance, and the technology lifetime of a MMS module, i.e. the time before the module must be updated due to new technology or higher demands in processing capabilities. The performance of the module is deeply connected to the scalability and the classification of the module. Classification means mission specific or general type in modules. General types of modules are better economically but may not make sense for specific application. It is anticipated that at least one module is mission specific for MMS enabled spacecraft.

Modularity is also important when looking at the business case for MMS modules. The reason why is that the complexity involved in the manufacturing of MMS modules does not allow all conventional subsystems to be miniaturized. Many systems would also require a process complexity that simply cannot be accomplished today. Therefore, by adding a modularization requirement we can ensure that larger systems can accommodate and minimize the overhead introduced with each module. This is closely related to scalability of the system and states that any module should be fully functional in itself and not depend on any other (except for power and data communication).

This can be exemplified with power generation and conditioning modules. One or more power generating modules may be used on the same spacecraft. The modularity requirement states that they must be able to work on their own without being aware of the others. This again relates to the fact that it may be impossible to build a power generation module that can sustain a large spacecraft directly, and, thus the complete power generation function would have to be built up from smaller units. At the same time it is desired that the systems make use of the benefits of having more than one power generation modules on-board. Paper I and II define an algorithm included in each power module for balancing load. Thereby the characteristics of modularity, and scalability is preserved.

Autonomy and distributed intelligence are also closely related to both scalability and modularity. For any system to be modular it must comprise a communication system. These systems are widely used on Earth, the largest one being the Search for Extra Terrestrial Intelligence (SETI) software that runs of thousands of computers world wide. The problem is that distributed systems require large bandwidth which is undesired due to power constraints on spacecraft. In order to reduce the need of bandwidth, two methods are employed: introduction of group addressing in the on-board communication protocols (to reduce the number of packets that need to be transmitted) and implementation of autonomy in several nodes [Paper IV]. Allowing nodes to have autonomy reduces both the software complexity of the central on-board computer and the bandwidth requirements. Paper II, IV, and V discuss distribution and autonomy of spacecraft functions.

The economical gains of creating low weight spacecraft are two-fold. The cost of launching a spacecraft is significantly reduced and with the current large launchers, the small size and low mass of nano-satellites makes it feasible to launch many satellites together, further reducing the launch cost per satellite. This opens up possibilities for new mission scenarios where clusters or constellations of “nano” spacecraft can synthesize functions previously requiring much larger spacecraft. However, since individual nanosatellites may have performance capabilities comparable to those of micro- and small satellites, it is possible to create “super clusters” or “super constellations” within flight mass constraints. The importance of satellite constellations for both Earth and Space Science has been summarized in a number of papers in the past [20, 21].

NanoSpace-1 - the MST technology demonstration frontier

Paper I summarizes the preliminary steps and ideas around implementing a fully MST enabled spacecraft. NanoSpace-1 (NS1) is targeted to show MST enabled spacecraft systems on a broad scale, with the ambitious goal of miniaturizing the complete spacecraft and not only individual devices. The DARPA / Aerospace Corporation PicoSat program have been aiming for this in several launches but had severe budget constraints and was forced to limit the design to individual MST devices [29].

The NS1 spacecraft serves several goals. First, it should be a complete testbed for advanced spacecraft microsystems, second it should be a solid recurring technology testbed platform that has standardized interfaces that allow easy implementation of systems from all over the world.

Fig. 3 shows the structural test model of NanoSpace-1 which was built at the Ångström Space Technology Centre. The photograph shows the real size of the spacecraft with a regular pen as reference. The spacecraft comprises the same functionality as a traditional spacecraft of about 200-300 kg.

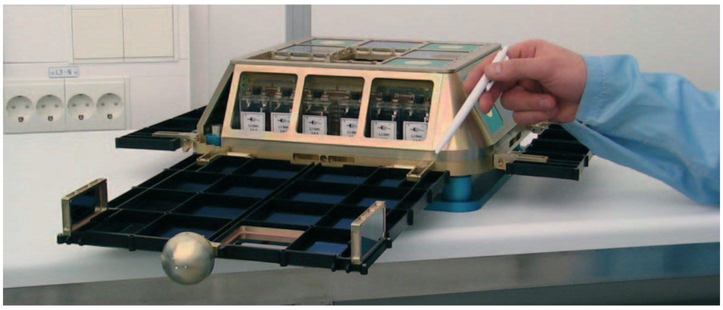

Figure 3. NanoSpace-1 structural model with a regular pen as reference.

The NanoSpace-1's scalable and modular spacecraft architecture is enabled with advances in the following important areas:

- A new distributed and load balancing power system [Paper II].
- New philosophies for handling of several active and autonomous on-board computers (OBC) [Paper II, IV].
- Enhancement of the SMART-1 CAN application layer bus protocol by adding group addressing. (Now implemented on Swedish Space Corporation's PRISMA satellites due to be launched in 2008) [Paper IV].
- Distribution of intelligence which significantly reduces software complexity [Paper II, V].

- Miniaturization of standardized Controller Area Network (CAN) & ESA SpaceWire (SpW) user interfaces [Paper IV].
- New MST interconnection methods.
- Division from traditional subsystems into multifunctional entities called modules, i.e. physically limited modules which can house one or several functions [Paper II, III].
- General miniaturization of all systems using MST [Paper II].

Figure 4 shows a cross-section of the NanoSpace-1 (NS1) spacecraft. The figure illustrates the important aspects of a modular MST-enabled vehicle. The spacecraft is divided into three layers, an inner core containing radiation sensitive modules such as on-board computers, mass storage memories, and guidance, navigation and control. Layer two is an intermediate shell which in this configuration represented by flexible printed circuit board substrates that distribute the communication bus, power and various signals. Layer three is the external shell, which houses all modules that need access to the surroundings. Typical modules in this layer are communication, sun sensors, star trackers, GPS receivers, etc. Modules located on the external shell should include thermal handling. Benefits from the implementation of silicon as the bulk packaging material can be drawn from a thermal design point. As silicon is a good heat conductor virtually the whole spacecraft acts as one single heat pipe.

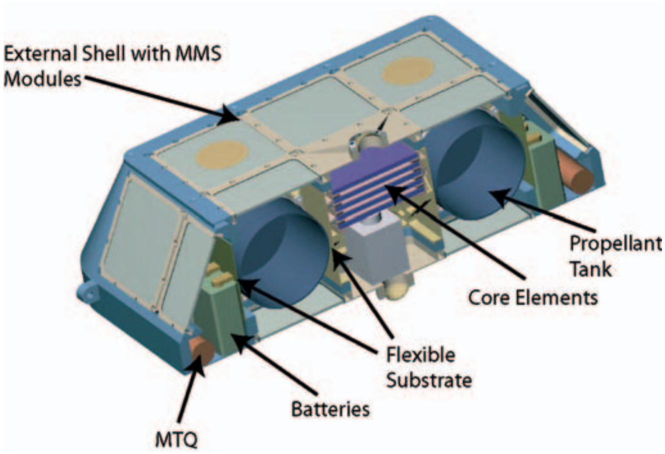

Figure 4. Cross-section of the NanoSpace-1 spacecraft.

Not only the thermal design is significantly enhanced using MST derived technology, also important features such as signal to noise ratios, processing and memory speeds are significantly increased. This is due to the relatively short signal distances inside each module package.

A scalable, modular and high performance spacecraft bus

During the development of NanoSpace-1, 13 main modules have been identified and motivated (Paper II). The modules are derived being applicable over a range of satellite configurations, including today's larger spacecraft. The breakdown of the spacecraft bus into smaller packages, or modules has been made with respect to the following criteria:

- Manufacturing complexity and available equipment
- Scalability and modularization, option to easily reconfigure
- Technology lifetime
- Commercial value/interest

The modular design of MMS in its current form requires classical components such as propellant tanks, batteries, aluminum structure frames, magnetic torquers, etc. to be complete. This is illustrated in Fig. 4.

A set of these 13 modules can form the base of many high performing nanosatellites or larger spacecraft. NanoSpace-1 is realized using a total of 41 modules taken from this set (plus an extra science module) and with a mission specific scientific module. The relative performance is not yet determined for all modules. They are 13 complete spacecraft bus system modules. In the section on system design aspects we showed that each module may in itself be built up from a number of standardized blocks.

Advanced robotic applications enabled with MMS

Not only satellites benefits from the MMS development. Significant enhancements to space robotics is possible for obvious reasons. Mass is a very important driver in interplanetary exploration since the landed payload ratio on other bodies in the solar system is a fraction of launch mass. Putting 700 kg in Mars orbit requires roughly 1500 000 kg launch mass. Reducing the weight of an interplanetary robot to Mars with 1 kg saves 2.2 tons in launch mass.

Two robotic applications have been studied in this thesis: a submersible explorer vehicle for Jupiter's icy Moon Europa and a Spherical rover for planetary bodies with sufficient gravity.

Miniature Autonomous Submersible Explorer

The Miniature Autonomous Submersible Explorer (MASE) concept was proposed by Behar *et al.* [30] and addresses miniaturization and selection of suitable instrumentation and the design of a novel miniaturized vehicle based on requirements from Astrobiology for small, cheap and disposable submersibles for extreme environments (e.g. narrow bore holes connecting to sub surface lakes, acid lakes, hydrothermal systems, etc.). A vehicle of this scope benefits greatly from miniaturization, packaging of electronics and instrumentation into 3-dimensional multi-chip-modules (3D-MCM). The MASE vehicle was designed to fit inside other vehicles (e.g. deep ocean mother ship, Cryobot, torpedo, etc.) and must therefore be extremely miniaturized [31]. The size of the vehicle is 23 cm in length and 5 cm in diameter.

Figure 5 shows a CAD drawing of the MEMS enabled MASE (MEMSEMASE) concept. MMS was applied successfully to the on-board electronics design, enabling extremely compact fiber optical communication, motor drivers, camera, navigation, and on-board processing capabilities.

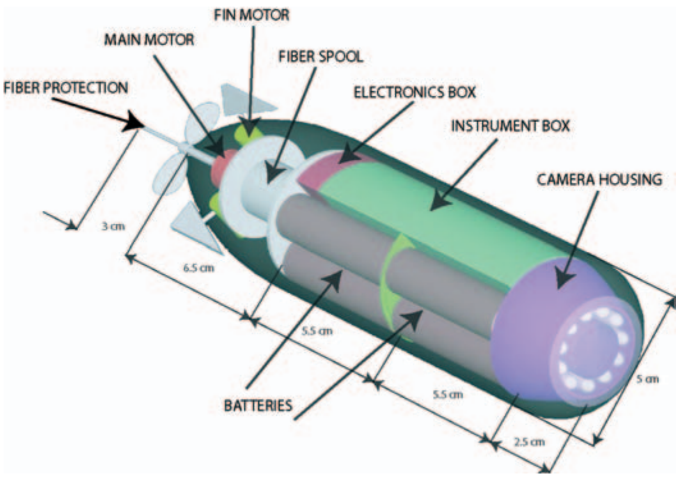

Figure 5. An illustration of the Miniature Autonomous Submersible Explorer (MASE) vehicle proposed by *Behar et al*.

The MMS modules designed and developed for NanoSpace-1 have a square shape. A submersible that will stand high pressure and be fluid compensated is often designed like the MASE with a cylindrical shape. Figure 6 shows the layout chosen for the silicon MMS module implementation on MASE.
There are many interesting applications on Earth for a submersible like MEMSEMASE. The vehicle is small enough to go into deep boreholes or autonomously investigate narrow trenches or submersed caves.

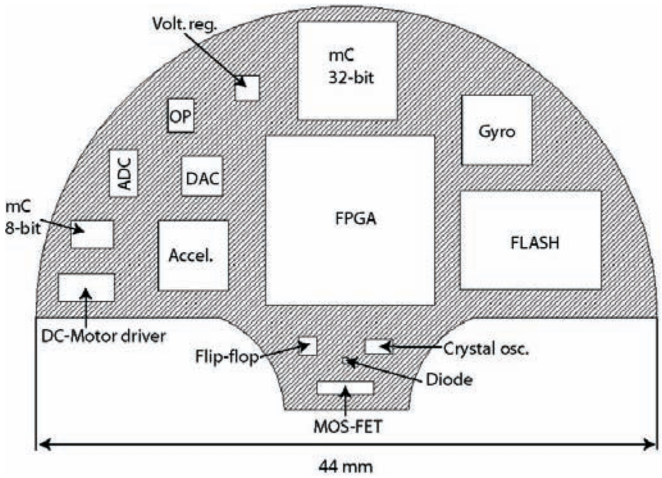

Figure 6. Illustration of the silicon MMS implementation in MASE.

Spherical Mobile Investigator of Planetary Surfaces (SMIPS)

The Spherical Mobile Investigator for Planetary Surface (SMIPS) concept was studied in response to a light weight rover for exploration on the Planet Mercury. The introduction of Multifunctional Micro Systems (MMS) design solutions gives the robot high performance per weight unit. The untraditional spherical shape makes it easily maneuverable and thus provides a platform for scientific investigations of interplanetary bodies. Figure 7 shows an artist impression of the concept.

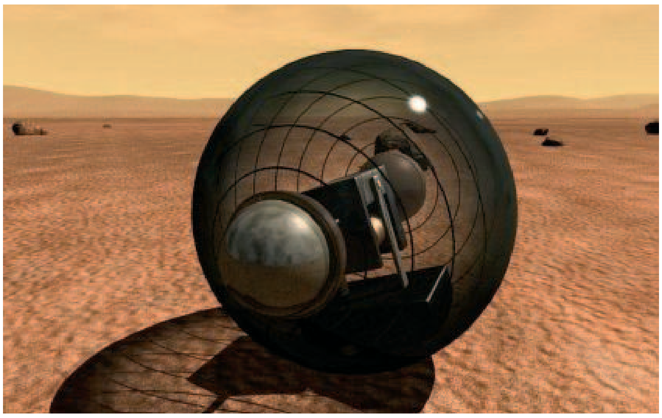

*Figure 7. A*rtist impression of the Spherical Mobile Investigator of Planetary Surfaces (SMIPS) enabled with MMS. Courtesy of Per Samuelsson.

SMIPS shall be seen as a compliment to larger, wheel-based rovers which have the ability to have moving arms on the body. The main application of SMIPS is to perform long range reconnaissance for interesting areas or to collect small samples in multi-sample return or analysis missions. An important application for the future may be remote visualization at human outposts on the Moon or on Mars. Wheel-based rovers will always consume more energy than SMIPS, paper VI and VIII shows that the spherical shape together with a simple locomotion principle is extremely robust.

The enabling technologies for SMIPS in terms of MMS are a multifunctional shell comprising solar cells and instrumentation. Microsystem technologies also allow clever design of s-band communication. The importance of reducing the mass and compressing electronics are two-fold for this particular system. First, reducing landed mass reducing the size of the launcher, or enables several vehicles to be deployed at the same time. The locomotion principle behind SMIPS is a simple relative movement of internal masses, thus utilizing the gravity to propel the vehicle. Putting the center of mass closer to the ground significantly increases the performance of the vehicle as it can traverse larger obstacles. It is therefore important to reduce the size of everything so that the center of mass can be lowered.

What about spacecraft on chip and Pico Satellite Design?

Dreams of a spacecraft on chip (SoC) are pursued by several institutions [ref, surrey 5th Round T]. My opinion is that this is to novel and doesn't really have any real applications. A spacecraft on chip solution can be seen as an MMS module where in principle all 13 modules defined for NanoSpace-1 should be housed. It can also be seen as an ultimate application specific integrated circuit (ASIC). The thermal and complexity aspects of such system, together with the inherited drawbacks of not being scalable and modular put the SoC into an extremely narrow niche market. It is not clear to me today what this would be.

When it comes to Picosatellites (see appendix 2). There is probably a good market for these systems in certain niches and the thermal aspects have a good potential to be solved. Perhaps Spacecraft on Chip and Picosatellite development can be merged to create extremely miniaturized spacecraft. However, the SoC still require very complex processing and my suggestion is to use MMS. This should be much more economical since the MMS concept allow for ASIC's and small System of Chip solutions to be integrated in 3-dimensional packages with very good thermal handling. MMS holds the potential on paper to cover the needs of the space community for at least the coming 15-20 years and will scale from large to picosatellites.

Summary of papers

Summary of Paper I: Nanospace-1: the Impacts of the first Swedish Nanosatellite on Spacecraft Architecture and Design (invited)

This paper summarizes the initial design concept for the NanoSpace-1 spacecraft. It highlights the identified problem areas associated with multi-functional microsystems (MMS) design. The conceptual structure of the spacecraft is presented together with initial results from subsystem development.

Modularity and scalability is discussed in conjunction with decision trade-offs regarding reliability and redundancy.

Presentation of the central ideas for developing multifunctional microsystems and distributed intelligence, modularization, and functional division are identified as vital part of the suggestion methodology.

Summary of Paper II: NanoSpace-1: Spacecraft Design using Advanced Modular Architecture

Advances on the NanoSpace-1 satellite from airbrush and preliminary designs through Phase-B design are presented in this paper. The Advanced Modular Architecture is detailed and new design tools are presented.

The paper discusses a complete satellite design using MMS technologies. Important features such as scalability, distribution, and modular systems are discussed. Advanced Modular Architecture is shown to provide systems level implementation of graceful degradation, and fractional and multi-way redundancies using the tools of MMS.

Summary of Paper III: Spacecraft Design Optimization – A Multifunctional Microsystems Module Implementation Method

Spacecraft design using a discrete set of multifunctional modules is presented together with an algorithm for spacecraft optimization. The reasons for deciding and selecting various modules or configurations are presented together with definitions how MMS modules should be expressed in terms of functions. A simple design example verifies the algorithm operation.

Summary of Paper IV: Distributed Communication Architecture in Spacecraft System-of-Microsystems – A Preliminary Analysis

This work presents a new distributed communication architecture for spacecraft, compatible with multifunctional microsystems. A new application layer for the Controller Area Network (CAN) bus is defined, evaluated and implemented in hardware.
A standardized CAN interface is designed and developed which will enable easier access and implementation on the spacecraft platform for science payloads.

Summary of Paper VI: MEMS Enablement of Miniature Autonomous Submersible Explorer

This paper details the design of a miniaturized submersible vehicle designed for harsh underwater environment. The vehicle is very small and fits inside other vehicles. MMS enabled an increase from 2 to 6 scientific instruments and also incorporation of a high resolution real-time camera. The vehicle communicates through a bi-directional fiber optical link, which with MMS have the potential to transfer 2 W of continuous power.

Summary of Paper VII: A preliminary Design for a Spherical Inflatable Microrover for Planetary Exploration

The preliminary design of a low-weight spherical interplanetary rover is presented. Analysis of key technologies such as communication antenna positioning, multifunctional shell, and navigation is detailed.
Important conclusions on mission design and feasibility of new scientific mission scenarios are shown presented.

Summary of Paper VII: Extremely Low Mass Spherical Rovers for Extreme Environments and Planetary Exploration Enabled with MEMS (invited)

This paper discusses how the Spherical Mobile Investigator for Planetary Surfaces (SMIPS) can be effectively used on Mars by using direct reentry to lowering or removing the mass requirement on a Lander.

Appendices

TRL definition

The Technology Readiness Level (TRL) scale was pioneered by NASA and is used throughout the space community to assess the level of maturity of a device or system.

The definition of TRL is given here as a reference for the reader of this thesis. The TRL scale is dived into three regions, low TRL (1-3), mid TRL (4-6) and high TRL (7-9).

Table 2. Technology Readiness Level definition

TRL1	Basic principles observed and reported
TRL2	Technology concept and/or application formulated
TRL3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL4	Component and/or breadboard validation in the laboratory environment
TRL5	Component and/or breadboard validation in the relevant environment
TRL6	System/subsystem model or prototype demonstration in the relevant environment (ground or space)
TRL7	System prototype demonstration in a space environment
TRL8	Actual system completed and flight-qualified through test and demonstration (ground or flight)
TRL9	Actual system "flight-proven" through successful mission operations

Spacecraft naming definition

Spacecraft are usually named according to a mass definition. However, the mass ranges may vary from publication to publication. This thesis uses to following nomenclature.

Table 3. *Spacecraft nomenclature based on weight definition*

Weight range [kg]	**Name definition**
0-0.1	Femtosatellite
0.1-1	Picosatellite
1-10	Nanosatellite
10-100	Microsatellite
100-500	Smallsatellite
>500	Large satellite

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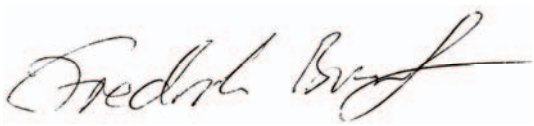
Uppsala, October 25, 2005



Sammanfattning på svenska: Miniatyriserad multifunktionell systemarkitektur för satelliter och robotik

Min avhandling beskriver och utvärderar nanosatellitdesign uppbyggd av avancerade mikrosystem. Mikrosystemen höjer nanosatelliternas prestanda åtskilligt, och öppnar nya möjligheter för utforskningen av rymden i form av exempelvis interplanetära vetenskapliga missioner med pyttesmå rymdprober. Mikrosystem, eller MEMS som de kallas med en amerikansk förkortning (mikroelektromekaniska system), gör extrem miniatyrisering möjlig med hjälp av arvet från elektronikindustrins processer för integrerade kretsar. Miniatyriseringen och den därmed förknippade stora minskningen av massa och volym, sparar stora kostnader för uppskjutning av rymdfarkoster.

Jag har definierat och kategoriserat olika egenskaper och funktioner på system- och funktionsnivå i härledningen av en smidig optimeringsalgoritm för mikrosystembaserade rymdfarkoster (t. ex. satelliter). Designalgoritmen är kompatibel med de *concurrent-design*-metoder som används i gängse satellitdesign idag. Miniatyriseringen av de multifunktionella modulerna (MMS, *Multifunctional Microsystems*) ger möjligheten att konstruera modulära satellitarkitekturer bestående av kraftfulla, högpresterande moduler, användbara för farkoster mellan 10 och 1000-tals kg.

MMS systemen är en blandning av bland annat elektriska, termiska och strukturella funktioner som byggs upp i moduler. Modulerna består av flera ihopfogade kiselskivor som tillsammans bildar en tredimensionell packningsteknik. I princip kan man säga att denna avhandling behandlar uppdelningen och anpassningen av olika system till dessa tredimensionella moduler.

Denna slags systemarkitektur har utvecklats för den svenska teknikdemonstrationssatelliten NanoSpace-1. Farkosten utnyttjar multifunktionell design för att åstadkomma distribuerad intelligens och autonomi, lindrigt förfallsförlopp av prestanda, funktionella ytor och distribuerade kraftsystem. Prestandaökningen som hänger ihop med den nya systemarkitekturen jämfört med konventionella och traditionella nanosatelliter går över en storleksordning med avseende på energilagring, masskvoten vetenskapliga instrument, pekstabilitet och livslängd i rymden.

För denna satellit har även nya metoder för distribution av dataprocessning och kraft definieras och flera system tilldelas autonomi. Satelliten innehar alla funktioner som en jämförbar 200-300 kg traditionell satellit. En detaljerad jämförelse med teknik från år 2000 visar att många system visar en tiofaldig ökning av prestanda.

Tre viktiga begrepp snor sig i en röd fläta genom avhandlingen: Modularitet, skalbarhet och bibehållen prestanda.

Med modularitet menas att systemen är oberoende och fristående men samverkar då de kopplas ihop. Till exempel ska kraftsystemet fungera utan att det på förhand vet hur många kraftkällor det har. I modularitet ligger även att moduler ska kunna byta plats. Detta ger upphov till individuella byggstenar som var och en har en egen marknadspotential och som tillåter snabb montering av nya satelliter. För första gången kan man prata om kraftfulla satellitsystem som kan monteras på ett Henry-Ford-liknande löpande band.

Det andra begreppet är skalbarhet. Här avses att modulerna fungerar på en 10 kg satellit lika väl som på större, och att modulernas respektive individuella prestanda kan läggas ihop för att fylla skarpare kravspecifikationer.

Det sista ledordet är bibehållen prestanda och detta är ett krav som dominerar hela arbetet. Det innebär att de utvecklade miniatyriserade systemen ska ha samma prestanda som deras större förlaga.

Den höga prestanda som blir möjlig genom denna system-av-mikrosystem-arkitektur har också använts för designen av två rymdrobotkoncept: en miniatyriserad undervattensfarkost som ska simma omkring under isen på Jupiters måne Europa och en sfärisk rullande robot.

Undervattensfarkosten bygger på elektronikminiatyrisering med hjälp av tredimensionella vertikalt integrerade multichipmoduler tillsammans med nya anslutningsmetoder och kopplingar. Detta gör att hela farkosten ryms inom 20 cm längd och cylinderdiameter på 5 cm.

Den sfäriska roboten utvecklades för vidsträckt vetenskaplig utforskning i nätverk på främmande planeters respektive ytor. Roboten väger 3,5 kg och klarar av ett direkt inträde genom Mars atmosfär, vilket ökar kvoten mellan den landade mobila massan och massan i marsbana med en faktor 18, jämfört med konventionella marsbilar.

Arbetet bakom avhandlingen är genomfört vid Ångström Rymdtekniskt Centrum i samarbete med Nasa Jet Propulsion Laboratory, Kungliga Tekniska Högskolan, Surrey Space Technology Ltd, samt Rymdbolaget för att säkerställa att de designade systemen är kompatibla med befintliga system idag.

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