Using Microtechnologies to Build Micro-Robot Systems

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ABSTRACT

Within the frame of the ESA Technology Research Programme "Micro-Robots : Components & Control", an industrial team consisting of Astrium, Mecanex, EPFL and IMM has studied the impact of micro/nano technologies (MNTs) as applied to Space Automation & Robotics (A&R) systems. The term "Micro-Robot System" (MRS) is defined in this context as a space A&R system making significant use of MNT. The results of this prospecting study support ESA in assessing the state-of-the-art of MNT relevant for A&R systems, in defining and promoting applications and in directing possible future R&D work.

1. INTRODUCTION

MNTs are commonly regarded as key technologies of the future. Today, a variety of different MNT components are commercially available, or will soon be introduced. Since there is a clear need to reduce mass, complexity and cost of space systems it seems obvious to introduce this technology into spaceflight. Within the field of space A&R systems the application of MNT potentially offers new capabilities and opportunities such as new types of missions, which are not feasible or unaffordable with conventional technology, or more frequent mission opportunities.

Potential applications for MRSs are for instance :

- Robots for exploration and scientific survey of celestial bodies
- Robots to support future human planetary exploration
- Robots for future use at the International Space Station (ISS)

This paper describes briefly the main activities performed in this study. Three selected "MRS Reference Applications" are described in more detail.

The work consisted of the following tasks:

- a review of the state-of-the-art of MNT applicable to space A&R systems was performed
- a map of European competence centres in MNT was established
- potential applications for MRSs were identified and reference applications which were defined in more detail were selected
- possible shortcomings of MNT for the potential MRS applications were identified and recommendations to overcome these shortcomings have been made.

Afterwards, three of the most promising MRS reference applications were selected, namely :

MICROS : A miniaturized free-flying platform for inspection, environmental monitoring and EVA support tasks at the ISS.

MANTA : A micro-aerial vehicle for local/regional exploration of the Martian surface and atmosphere.

Nano-Rover Swarm : Local surface exploration of planetary bodies via a swarm of very small rovers.

Breadboard models including key MNT items related to the two latter concepts have been built. A breadboard model of the first concept was produced during another activity.

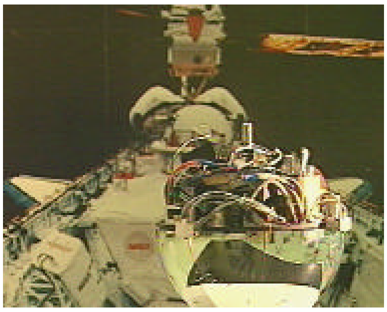

Figure 1. *MICROS, Astrium GmbH*

Figure 2. *MANTA, Astrium GmbH*

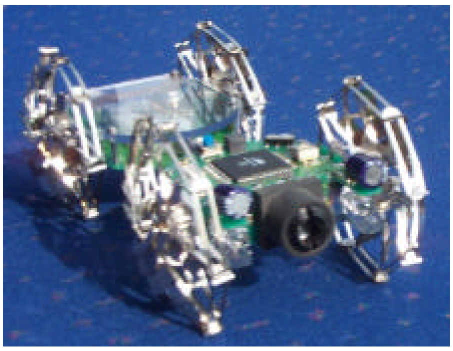

Figure 3. *Nano-Rover, EPFL*

In addition, a first programmatic estimate of the development effort required to turn MANTA and the Nano-Rover into mature products for space applications was made.

2. STATE-OF-THE-ART MNT ITEMS

An extensive review of the state-of-the-art MNT covering existing items as well as items under development has been performed. Micro-fabricated components have nowadays achieved a state of maturity that promise large mid-term benefits for space applications in terms of cost reduction and extended functionalities. The existing technology base and the broad potential of terrestrial applications allows the consideration of space applications in essentially all types of subsystems of space vehicles and all types of payloads.
A variety of micro-fabricated actuators and sensors have been developed for terrestrial applications as well as for their specific use in space such as a miniaturized sun sensor and micro-machined gyroscopes.
These components have been fabricated via different technology routes and thus take advantage of the variability of today's micro-technologies. Thus the space engineer is encouraged to think in micro-technologies and to further stimulate the exploitation of the potential of micro-technologies for space applications.
The feasibility of micro-technology for use in micro-robots has already been proved in a variety of prototypes. As an illustrative example, Figure 4 shows a version of a miniaturized excavator as a demonstrator for the integration of various miniaturized micro-components into a manipulator. Figure 5 shows a sugar cube sized rover with sensors, a low-power µ-controller, motors, and communication able to navigate autonomously through a labyrinth.

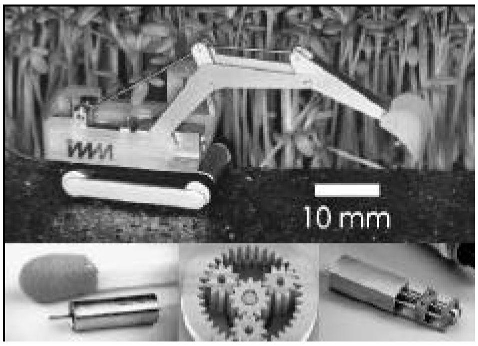

Figure 4. *Miniaturized Excavator, IMM*

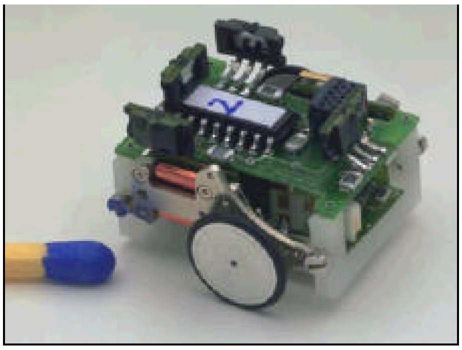

Figure 5. *Alice, EPFL*

The results of the MNT survey, including a list of European competence centres dealing with MNT, have been summarized on a public accessible web site called "MICROCOSA". (web address : dmtwww.epfl.ch/microcosa)

3. POTENTIAL MRS APPLICATIONS

A review of existing and foreseen applications of space A&R has been performed and as many credible applications as possible which could benefit from MNT have been identified. At the beginning of the process of collecting innovative MRS applications, a breakdown structure was established. This structure has been broken down into five levels starting with the main categories :

A) Supporting Low Earth Orbit Systems

B) Supporting Systems in other Earth Orbits

C) Solar System Exploration

An example of the breakdown is given below.

No.	Level 1	Level 2	Level 3	Level 4	Level 5
A	Supporting Low Earth Orbit Systems				
A1		International Space Station (ISS)			
A11			ISS System Servicing		
A111				External Servicing	
A1111					Fixed, Local Servicing
A1112					Mobile Servicing
A1113					Free-Flying Servicing
A112				Internal Servicing	
A1121					Fixed, Local Servicing
A1122					Mobile Servicing
A1123					Free-Flying Servicing

Table 1. MRS Applications Breakdown (Example)

It was the aim to define at least one MRS application for each end level of an individual breakdown line. After a first brainstorming, about 50 different applications were listed. This list was reduced to 28 applications by deleting all those that were considered unfeasible as well as those, which were considered as incomplete systems but as subsystems. In coorperation with the ESA and with the help of detailed evaluation criteria, six so-called MRS reference applications were selected. The selected applications are those, which promise from todays point of view the highest benefit in terms of feasibility potential, usefulness, innovation potential, and reuseability in other applications.

4. REFERENCE APPLICATIONS

The selected MRS reference applications are :

- "Elephant Trunk"
  flexible, multi-task manipulator
- MANTA
  microaerial vehicle for local/regional Martian surface and atmospheric exploration
- Micro - Eye
  inspection tool for infrastructure elements
- MICROS
  free-flying platform for external inspection, environmental monitoring and EVA support
- Pico - Rover Swarm
  local surface exploration of planetary bodies with swarms of nano-rovers

- Windball
  wind-propelled robot for regional surface and atmospheric exploration of Mars

More detailed concept descriptions were established for these six applications.

Breadboard models including some key MNT items for the MANTA and the Nano-Rover concepts have been built. A MICROS breadboard model and simulator was produced within the framework of another activity.

4.1 MANTA

MANTA (**MA**rs **N**ano/micro-**T**echnology **A**ircraft) is intended to extend scientific mission capabilities and provide an additional tool to aid the exploration of Mars. The deployment of a category of aircraft, termed autogyros, can considerably enhance mission objectives. Apart from helicopters, it is the only type of fully-controllable vehicle which can take-off vertically from and make point landings on unprepared surfaces. Therefore, MANTA will be in a position to explore locations outside the range of rovers or astronauts, e.g. craters, deep valleys, natural caves, etc.

More specifically, MANTA will be able to perform the following tasks on Mars:

- surface reconnaissance
- surface material in-situ analyses / return
- atmospheric measurements (density, temperature, wind speed, etc)
- IR and visible video imaging

The use of micro/nano-technology is a key issue in the realization of the MANTA concept and enables the vehicle's size and mass to be minimized. MANTA's low mass coupled with its small size makes it not only an ideal tool for inclusion in early precursor missions (e.g. "piggy-back") but also an outstanding tool for a future permanent base on Mars, since it has been sized to be passed through a small airlock, i.e. vehicle maintenance, repair and exchange of scientific equipment can be performed in the pressurized environment of the base, or inside a large manned rover. In the latter case, MANTA can be regarded as a useful addition to the astronaut's tool kit.

Examples of flight profiles which can be flown by MANTA are depicted on the following Figures. These figures also show types of search patterns which can be combined with the multiple take-off and landing capability of the aerial vehicle.

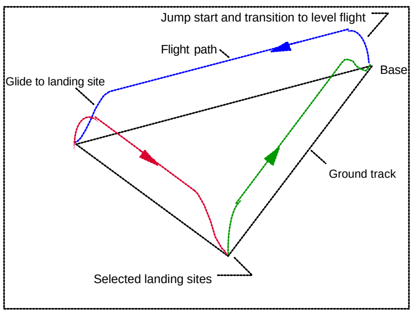

Figure 6. *Flight Profile to Selected Landing Sites*

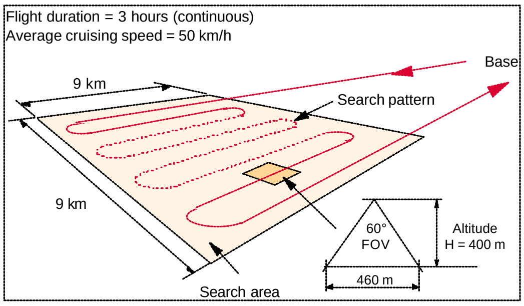

Figure 7. *Aerial Survey (area)*

The aerial vehicle will be able to perform missions with a total flight duration of 3 hours at speeds up to a maximum of 100 km/h. During the mission, MANTA will be capable of performing multiple take-off and landing cycles, thus enabling the vehicle to explore selected sites in more detail.

The proposed MANTA concept is an autogyro capable of vertical take-off and forward flight. Its design is based on well-established and flight-tested aerodynamic and flight control principles, main features and characteristics are given in the following Figure and Table respectively.

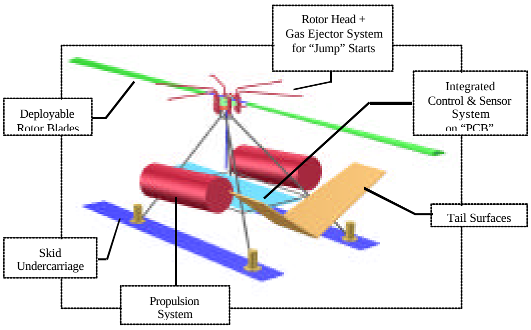

Figure 8. *MANTA Concept*

Total mass	2,5 kg
Rotor diameter (deployed)	1500 mm
Stowed dimensions (L x W x H)	800 x 500 x 380 mm
Airlock clearance diameter	600 mm
Maximum mission duration	3 h
Maximum speed	100 km/h
Normal cruising speed	60 km/h
Range at maximum speed	100 km
Glide path (power off)	1 : 6 (estimated)

Table 2. *MANTA Characteristics*

Based on preliminary aerodynamic estimates and wind tunnel tests, a full-scale MANTA mock-up as shown in Figure 9 has been established. This mock-up is equipped with the following key MNT items :

- a micro-camera plus a special 360° panoramic optic
- S/W to convert the 360° picture into a rectangular one

In addition to these items the mock-up is equipped with all H/W needed to transmit the video data to a conventional PC.

4.2 MICROS

MICROS represents a miniaturized multi-purpose, multi-mission MRS system, which shall perform inspection, EVA support, and P/L operation tasks in the close vicinity of the ISS and ISS visiting vehicles (between 1m and 200m).

MICROS is equipped with three video cameras for inspection purposes and with standardized interfaces for the attachment of additional micro-instuments or sensors.

The spacecraft is compatible with the EVA constraints and airlock dimensions and will be serviced (battery, tank, sensor exchange, etc.) inside the ISS by IVA astronauts. It is stored in an ISS storage rack during the non-operational periods.

The MICROS S/C with a diameter of about 230 mm and a mass of about 6 kg can only be realized by the utilization of micro-technology products to the maximum extent possible today.

Within its on-orbit lifetime of approximately 5 years the spacecraft shall be in a position to perform at least one mission per month with a minimum mission duration of 8 hours, i.e. the mission time covers one complete EVA shift of 6 hours and the vehicle is able to support the EVA crew during their mission.

Furthermore, MICROS is considered as the basis for a family of free-flying MRS systems, e.g. small manipulator arms could be added or vehicles for internal ISS use could be derived from the basic MICROS vehicle with some modifications.

The MICROS system consists of following elements :

- MICROS spacecraft
- Monitoring & Control Station (MCS) inside the ISS or Shuttle
- Airborne Support Equipment (ASE)
- Ground Support Equipment (GSE)

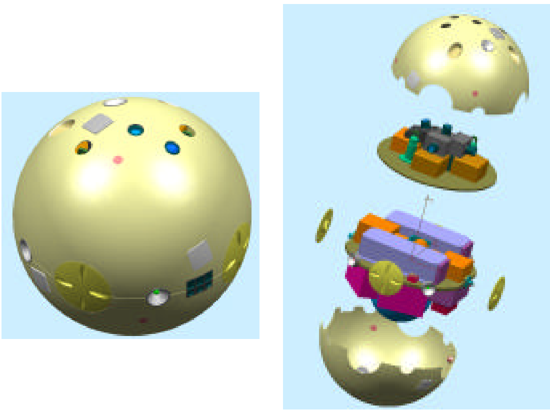

Figure 9. *MICROS Configuration*

MICROS is a "ball" type spacecraft with a soft outer cover and a rigid inner structure. The soft cover may be realized by foamrubber or by a thin, flexible metal mesh with cuttings and perforations as required (e.g. for thrusters, camera head etc.) and is detachable to allow access to the internal equipment for maintenance purposes. For reference purposes the "flexible mesh" design solution has been selected.

The spacecraft main body will be designed nearly without any protrusions to avoid crew injuries and damage to the ISS surfaces.

The inner structure consists of two light-weight, horizontal plates, which allow the accommodation of the required subsystems and P/L equipment. The distribution of the subsystem equipment into the three resulting floors is mainly driven by aspects like equipment dimensions and available volume under the outer cover, placement of the centre of gravity near to the geometrical centre and not by functional dependencies and relations between the different boxes.

Within the frame of ongoing R&D activities at Astrium GmbH a MICROS model with the full functionality of a real system has been built, together with a 5 degree-of-freedom air bearing facility (2x translation, 3x rotation). This forms the MICROSim facility. This facility is used for the MICROS system software development and verification as well as for combined hardware/software check-out and human operator training.

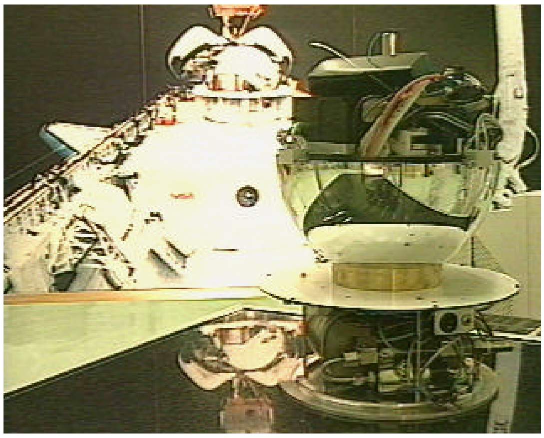

Figure 10. *MICROSim Facility*

The MICROS model contains all subsystems and components found in a real micro-satellite: an on-board data handling system, a TTC unit, an attitude control system with 3 reaction wheels and 3 fibre optic laser gyros, a propulsion with 16 cold gas thrusters, and power subsystem, as well as 3 video cameras and the necessary S-Band transmitters. The Air Bearing Facility has been designed to allow translational motions along the in-plane axes as well as full rotational motion around one axis and limited rotational movements around the other two axes. Therefore, it is necessary to have two air bearing facilities whereby one consists of a hemispherical structure and its counterpart and the other of an aluminum baseplate and the corresponding air bearing table. In order to achieve a maximum operation time for both air bearings emphasis has been put on the accuracy of the surfaces and a minimum air gap. The result is a combined high precision air bearing facility with a surface accuracy in the nm-range that has not been available on the market up to now and which is absolutely independent from external compressors due to internal N_2 tanks. An external Position Recognition Subsystem detects the MICROS position on the air bearing table (dimensions: 800 x 1600 mm) with an accuracy of 5 mm. This has been realized using a CCD camera mounted 1.8 m above the air bearing table and a ring of 6 LED's which is fixed on the air bearing facility. Highly sophisticated software algorithms have been developed using the camera information to calculate the position on the air bearing table with an update rate of 10 Hz and with the required accuracy. An open S/W architecture, implemented on a PC acting as ground station, allows it to test different control loops and to simulate different flight phases. In addition to these features the Attitude Control subsystem allows man-in-the-loop video navigation by CCD cameras. The video data are transfered by a S-Band transmitter to the ground station (PC) and displayed on the monitor.

Figure 11. *MICROSim Components*

4.3 NANO-ROVER SWARM

The present MNT allows to build fully autonomous MRS weighing under 100 g, with a typical size of 10 cm. Their high level of functionality is provided by the systematic use of MNT components for every subsystem including the payload. The main objectives of nano-rover swarms are surface explorations on planets and other celestial bodies under the aspect of a very high overall mission reliability. Two typical mission scenarii of multiple autonomous nano-rovers are described below.

- Exploration near a lander by a swarm of MRS
- Mobility extension at short range of bigger mobile systems through the use of MRS as autonomous subsystems.

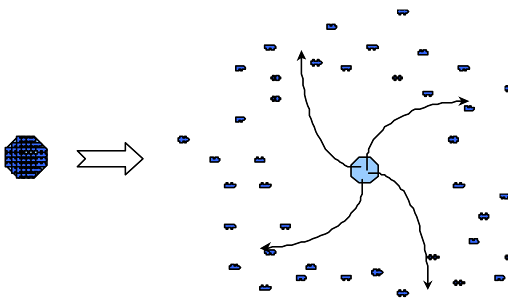

Figure 12. *Dispersion (ejection) of the Nano-Rovers*

In the first scenario, a high number of Nano-Rovers are ejected from a lander on the ground. Their locomotion and control system allows them to redistribute themselves on this surface to cover homogeneously the area or take a particular shape on the ground. Each Nano-Rover makes local measurements and works as a radio transmitter for the other. This allows the building of a distributed network of sensors to provide simultaneous measurements in real time. When data collection is finished, the lander can transmit them back to earth (possibly via an orbiter).

In the second scenario, the mission description is very similar, but the lander is substituted by a mobile system. It can be a robot for long range exploration or even a manned vehicle.

A very interesting application is the combination of MRS with flying systems. In this case, MRS can be used around the landing site, as previously, but they can also be dropped in flight. This allows access to very difficult areas such as deep and narrow canyons or craters. At the end of the MRS mission, the flying system can retrieve the MRS or only the data by radio, if a landing is not possible.

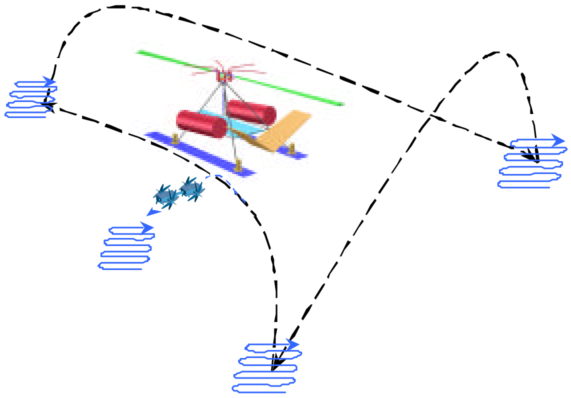

Figure 13. *Combination of Flying System / Nano-Rovers for long and short Range Mobility*

The selected Nano-Rover concept, as depicted in the following figures, is based on two articulated modules linked with a beam that allows torsion and horizontal flexion but avoids vertical flexion. It provides a push-pull effort for obstacle climbing and an excellent terrain adaptation for the four motorised wheels.

The wheels are made of flexible blades which offer high climbing abilities by providing a hybrid locomotion of rolling and walking. Preliminary computer simulations showed that this configuration is energetically interesting when the size of obstacle and the wheel size become comparable. The Nano-Rover is operational on both sides to be insensitive to tumbling over and is modular enough to allow the implementation of various functions. Ideally these functions should be able to provide a real co-operation between the different rovers during the mission.

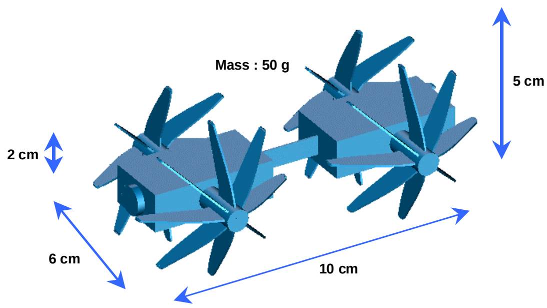

Figure 14. *Nano-Rover Dimensions*

The on-board control provides the path planning and the obstacle avoidance through the analysis of data produced by a frontal micro-camera and ensures the radio transmission of the payload sensors. It is interesting to note that the micro-camera is shared by the MRS and its payload. In other terms, it can be used as sensor for the locomotion but also as high resolution imager.

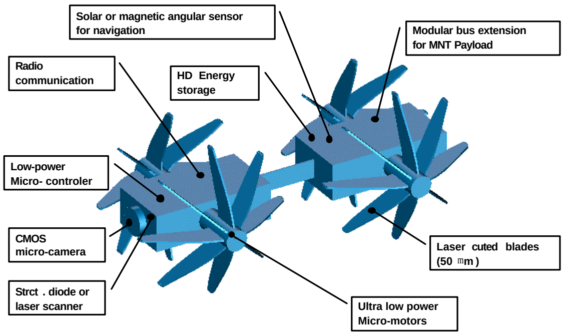

Figure 15. *Nano-Rover Subsystems & Components*

For this Nano-Rover concept a breadboard as presented in Figure 3 has been built. The breadboard contains the following key MNT items :

- low power micro-controller
- transmitter (communication with a PC)
- micro-camera (CMOS)
- micro-motors

In addition to these items all other H/W (e.g. batteries) and S/W components required to operate the rover are provided.

5. CONCLUSIONS

MRSs can be built with currently available MNT. The selected MRS reference applications are innovative and promise advantages (mass & volume reduction, cost reduction, new types of missions etc.) compared with conventional space A&R systems. But a high development effort is required to turn MRSs into mature products for space applications. The MNT aspects have to be considered in particular.

The survey of the state-of-the-art MNT products has shown that there are a lot of items, which might be of interest for potential MRS or general space applications. But, more than 90% of these items are not yet space-qualified. There is no question that MNT products should be used for space systems, as subsystems incorporating such products exhibit qualities that are desirable in a space environment. Many of these items / subsystems are orders of magnitudes smaller than those currently in use. The power and thermal requirements for MNT items are a fraction of the items they can replace. They exhibit robustness to shock and vibration environments many times greater than current space components. Consequently, the use of MNT could be a way to reduce drastically the costs of future space A&R missions.

The cost of developing MNT products especially for space applications can be very expensive and the space community will, only in exceptional cases, be in a position to afford this. In fact, the cost of developing and certifying MNT items for use in space may cost more than the systems they are meant to replace. Moreover, the number of MNT units required per year will be relatively small; MNT for space will not realize the economy of scale found in the consumer / commercial market. This fact in combination with the stringent requirements (reliability, radiation, thermal stress etc.) imposed on space-qualified products discourages the MNT industry and other MNT institutions to develop new technologies / items for space application.

Industry will not develop MNT items specific to space applications. The already existing but not yet space qualified MNT items promising a high benefit for space applications have to be considered. To enjoy the advantages of the existing MNT items new approaches for insertion of these items into space have to be established in cooperation between industry and agencies.

6. REFERENCES

Hill, W., *et al.* "Micro-Robots: Components & Control", Final Report, ESA Contract No. 13622/99/NL/WK