First Results of Robots Crawling on a Loose Net in Micro-gravity during a Sounding Rocket Experiment

Leopold Summerer
ESA - Advanced Concepts Team
Keplerlaan 1, NL-2201AZ Noordwijk, The Netherlands,
Leopold.Summerer@esa.int, +31-71-565-6227

Bernhard Putz, Peter Kopacek
Vienna University of Technology - Institute for Handling Devices and Robotics
Favoritenstr. 9-11, A-1040 Vienna, Austria, e318@ihrt.tuwien.ac.at, +43-1-58801 31801

Nobuyuki Kaya
University of Kobe - Dept. of Computer and Systems Engineering
1-1 Rokkodai, Nada, 657-8501 Kobe, Japan, kaya@kobe-u.ac.jp, +81-78 803 6228

Several concepts for the construction of large antennas have been proposed and discussed. This paper presents the first results obtained during a sounding rocket experiment of the Furoshiki-type concept: a large net deployed by spacecraft forms the antenna surface, on which small robots either deploy to perform simple tasks on antenna elements or constitute individual elements of a larger retro-directive phase array antenna. The present paper discusses the trade-off of the robotic options and presents results obtained from robots on the flight experiment.

I. INTRODUCTION

The paper presents the design, trade-offs, development, testing and in-space experiment of the robotic component of a new concept to build large structures in space, especially suited for antennas. The largest structure launched and built in space so far is the International Space Station (ISS), launched in pieces and assembled in low Earth orbit by astronauts and robotic arms. One of the largest solar panels so far used in space is the 32 meter large panel powering the European "Rosetta" spacecraft currently on its journey to encounter comet 67P/Churyumov-Gerasimenko [4] in 2014. Its large solar panels were launched folded and have been deployed in space after launch.

Antennas are either launched using the maximum available space in the launch vehicle fairing or are also constructed deployable when even larger diameters are needed as in the case of the Galileo spacecraft.[5] This example also shows that these folding and unfolding mechanisms are complex and subject to relatively high risk.

An alternative to folding concepts are inflatable structures. While studied and developed since several years, these have still not yet found their way into many space applications.

For large antennas, like those required for microwave Earth observation antennas in geostationary orbit or microwave power transmitting antennas of solar power satellites [1, 3, 6], new techniques are needed to achieve much lower mass to surface ratios than possible with current technology. Virtual large apertures by formation flying spacecraft and fully autonomous self-assembly of individual elements have already been proposed. [7]

The *Furoshiki* concept recently proposed by Kaya seems a promising way of achieving the required large apertures with relatively low mass, very good up-scaling potential and potentially limited control needs.[2, 8] In essence, it consists of a two dimensional tether, a net, containing all the required antenna elements. Stabilisation might be achieved by a slow rotation or via small satellites spanning the net.

II. SOUNDING ROCKET EXPERIMENT

The Japanese space agency JAXA has conducted a sounding rocket experiment intended to test several key technologies of antennas using the *Furoshiki* concept:

- the deployment of a net in a microgravity environment;
- the stabilisation of a net in a microgravity environment via the use of one axis controlled, thruster powered daughter sections;
- the reception of a pilot signal at individual antenna elements (mounted on the daughter sec-

TABLE I: S-310 Sounding rocket characteristics

length	7.1 m
diameter	0.31 m
mass	0.7 t
altitude	210 km
payload	50 kg

tions) and the collective retro-directive signal retransmission and

- the movement of autonomous small robots on a net in microgravity.

The present paper describes the results obtained from this last part of the experiment. For the results of the other parts of the experiment, it is referred to [9, 10] Such robots could serve as individual, autonomous antenna elements that position themselves on the net, communicate with each other and eventually dynamically reconfigure on the net to allow for an adaptive antenna geometry. During this first experiment, only two robots were tested with the tasks of demonstrating the possibility to move on a loose net of unknown shape and local pattern in a microgravity environment.

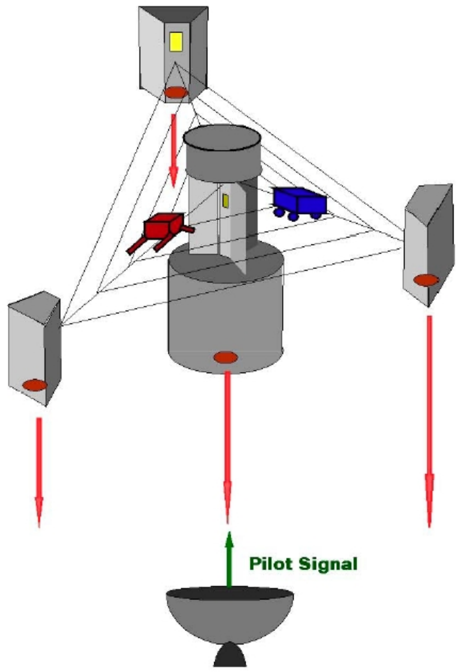

FIG. 1: Schematic representation of Furoshiki experiment.[2]

III. DESIGN OF SPACE ROBOTS

A. Boundary Conditions

The experiment was launched by the Japanese sounding rocket S-310 (Fig. 2, Table I). The 7.1 m high, 0.7 ton heavy rocket can lift a 50 kg payload up to 210 km altitude. Once in microgravity on its parabolic trajectory and separated from the rocket body, it would is de-spun before the experiment separates into several elements: Three "daughter" sections will separate from a central "mother" section by extending a very thin net between them into a triangular shape as schematically represented in fig. 1. Once the net deployed, the release mechanism opens, the two robots receive the start signal and have to move autonomously out of the mother section on the net.

In order to not induce undue disturbances to the net that is only loosely spanned by the 5 kg massive daughter sections, the mass of the robots must not exceed 600 g. Furthermore they need to be fully autonomous, including their own power supply and locomotion control system. Moreover, each robot needs to fit into a $9 \times 9 \times 5$ cm box inside the mother section, from which they are required to autonomously move out after reception of the start signal and release of the holding mechanism. The holding mechanism and the electric contacts for the start signal and battery charging are shown in fig. 3.

B. Schedule

The entire project was initially scheduled for 18 months. However, delays of the launch date finally have increased the time from start of the project o the actually launch to a still challenging 30 months. The robots were designed and built by the Institute for Handling Devices and Robotics of the Vienna University of Technology. The tight time schedules required the use of early, rapid prototyping in parallel to the system studies. Three different designs reached prototype level, two of which were tested in microgravity conditions during parabolic flight experiments in Nagoya, Japan. The three designs are briefly described in the following section.

C. General Design Trade-off

An initial trade-off of different mobility options on a free floating net in microgravity excluded options relying on

vision: The the background behind the very thin net might be the sun, deep space, Earth, clouds

FIG. 2: The Japanese sounding rocket S-310-36 before launch

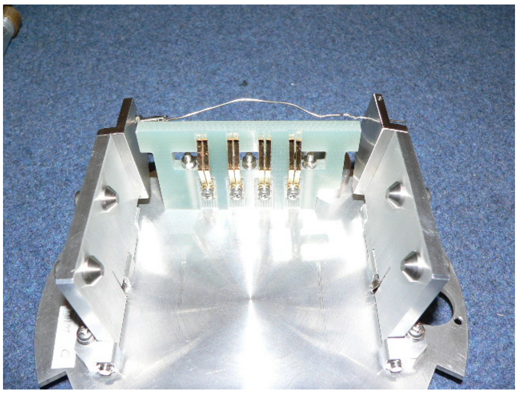

FIG. 3: robot release mechanism

etc and the thin stings of the net might not be visible and recognisable.

assumptions on net surface pattern: Given the high uncertainty of the deployment mechanism and eventual perturbations, the robot could not rely on a certain maximum deviation of the net surface and structure from a nominal flat net under tension. The mechanism needed to be able to cope with large waves and perturbations of the net.

slow mechanisms: The total flight duration limits the time for the robots to perform their movements to a few minutes. Therefore slow mechanisms had to be excluded.

The initial trade-off retained two basic design approaches: a "sandwich"-type robot and a gripping, insect-type robot. Both retained options were designed to retain contact with the net under all foreseeable operational conditions in order not to pose any danger to other mission elements in case of failures.

The very limited operation time of only a few minutes, uncertain behaviour and dynamics of the net during its expansion and the extremely thin and flexible net in front of an uncertain background (Earth, Sun, deep-space) have led to the preference of robustness and reliability over on-board intelligence and vision-based movements.

D. ***RobySpace***

The sandwich type robots try to take advantage of the major apparent complications of the general setup: the very thin and extremely flexible net. The concept is based on two sections, one at each side of the net, hold together by magnetic forces. The very thin net distances the two sides by only $0.5 - 1\ mm$ and the passage of knots can occur uncontrolled as long as the maximal knot distance is smaller than the robot itself.

The whole electronic and locomotion components are placed in the upper part. The electronic part is built up in open architecture. The motion unit controls the motors by a desired trajectory. This desired trajectory (as well as other demand behavior like acceleration and etc.) has to be transferred to the motion unit. The radio module is connected to a microcontroller, which selects and processes the incoming information. Afterwards a bus provides the processed information to the motion unit.

The electronic part consists of a single board for power electronic, communication and a microcontroller. The task of the microcontroller is to control both DC motors and analyze the radio data. This board is universally useable and in circuit programmable by the serial port. Furthermore it contains a high-speed synchronous serial interface, which gives the possibility to connect several microcontroller boards for different tasks. The electronic part consists of the following components:

- XC167 microcontroller from Infineon with internal RAM (8 kByte) and Flash (128 kByte)
- Voltage supply by switching regulators with high efficiency
- High speed dual full bridge motor driver
- Infrared transmission module
- Bi-directional radio module for the frequencies 433, 869 or 914 MHz

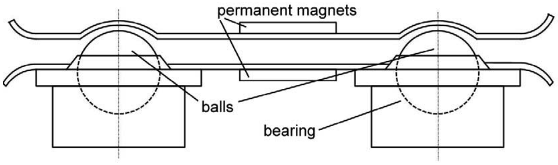

FIG. 4: *RobySpace I*: initial concept of two sections

- Status indication by six bright LED's in different colors
- Serial synchronous interface for communication with further modules, e.g. XScale board.
- Lithium-Ion rechargeable battery (1200 mAh, 10.8 V).

For locomotion two PWM controlled DC motors are used with the following specification:

- Minimotor Type: 1524 06 SR
- Output power: 1.70 W
- Speed up to: 10000 rpm
- Stall torque: 6.68 mNm
- Encoder resolution: 512 ppr

It was not easy to select the right magnetic force to connect both parts. In case the force is too high the motors have not enough power to crawl. In case the force is too low, the two parts separate too quickly in case of any net-resistance. Also the tension of the net structure plays an important role. In case the net has not enough tension the robot might twine the net.

RobySpace uses simple ball-point joints and guiding dips on the passive part of the sandwich structure in order to prevent relative sliding of the two parts.(Fig. 4) While several ground tests on horizontal and vertical nets have been successful, the first parabolic flight campaign demonstrated that the resulting forces in the direction of the movement due to friction by the net were separating the two section far enough to overcome the attractive magnetic force and the robot lost several times the net.

In order to overcome this problem, a completely different design was pursued in parallel, not relying on two parts connected via magnetic forces but holding to the net with small leg-like grippers.

E. *RobySpace Insect*

The *RobySpace Insect* concept substitutes the magnetic adhesion with multiple gripper-legs. Since the dynamics of the web and thus the location of the nodes is unknown and visual information as input for intelligent grabbing not available, the grabbing mechanism needed to rely on 1. a higher number of legs, 2. the maximum distance between two stripes of the net under deformation needs to be smaller than the the distance of two successive legs with one in its grabbing phase and 3. redundancy and exaggeration of the grabbing movement in order to make sure that even a deformed net would not be lost. The resulting mechanisms is shown schematically in Fig. 5 and implemented in Fig. 6.

The major changes with respect to *RobySpace* are done in chassis and locomotion. The robot consists of only one part. The height of the robot is half the height of *RobySpace*. The same electronic parts are used. Six pin type grippers on each side of the robot (one on right-hand side, another on left-hand side) are responsible for the holding and the movement of the robot on the net. Always at least two grippers on each side hold the net. Before one gripper releases the net, the following gripper catches the net and move forwards.

While a mechanisms to sensor and mitigate net mingling was implemented (in case of mingling, the robot would go slightly backwards and then try again to move forward), the inclusion of an additional sensor to measure if the legs had actually caught the net or not were abandoned mainly due to time and complexity.

During the first parabolic flight campaign *RobySpace Insect* succeeded well. During tests the robot moved a distance of 2 m within 10 seconds without loosing the net. Nevertheless, two major problems of *RobySpace Insect* were identified:

Getting out of the rocket box Due to the long gripper legs it is very difficult to move out of the small box. The possibility that the robot gets stuck inside the box or on parts of the rocket frame is very high.

Low tension of the mesh Because of the huge mesh dimension the relatively small daughter satellites are not able to generate a high tension for the mesh. The motion of the robot influences the shape of the mesh locally which increases the danger of getting stuck during the gripper motion on the upper part of *RobySpace Insect*.

These two problems led to a third prototype: *RobySpace Junior*.

F. *RobySpace Junior* - Flight version

RobySpace Junior refined the magnetic adhesion system of *RobySpace* by adding additional guiding fea-

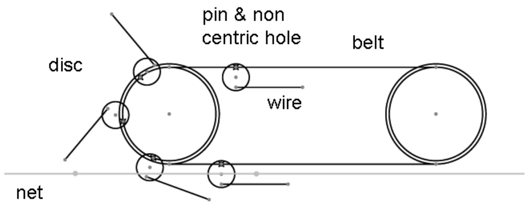

FIG. 5: Grabbing mechanism of *RobySpace Junior*

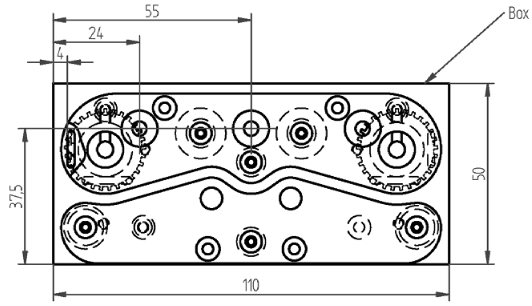

FIG. 7: *RobySpace Junior* concept of two sections

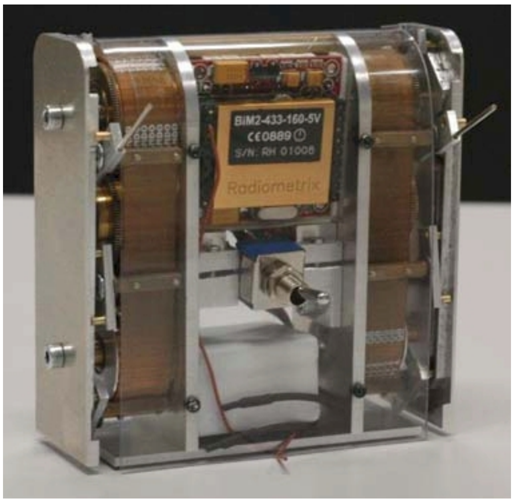

FIG. 6: Prototype of *RobySpace Insect*

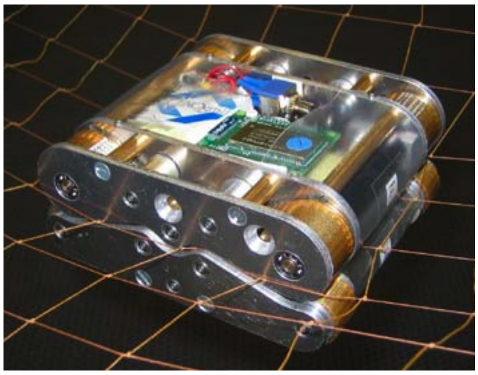

FIG. 8: Prototype of *RobySpace Junior* on the net

tures to the profile of the connection plates and thus preventing any lateral relative sliding movement and strongly restricting the sliding possibility in movement direction.

The locomotion system was also completely redesigned in order to handle very loose, very low tension nets and minimise the friction between the robots and the net. The simple dips of *RobySpace* got replaced by two driven belts in the upper section, mirrored by passive belts in the lower section. (Fig. 7)

The electronic system and software are the same as of *RobySpace Insect* but *RobySpace –Junior* uses Bluetooth communication.

All three prototypes are capable of changing directions and walking to predefined positions on an undistorted net. Direction changes are made by different speeds of the left and right moving belts/leg driving belts. *RobySpace Insect* however can only move in forward directions due to the way the grabbing mechanism has been implemented.

IV. ASSEMBLY, INTEGRATION AND TESTING

The robots, were assembled at the Vienna University of Technology, where the communication, temperature and locomotion tests were performed. The microgravity tests were done in Nagoya, Japan during two parabolic flight campaigns early 2005. The flight model was then constructed and underwent vibration and shock tests according to launch condition data of the S-310 rocket at the ESA Mechanical Systems Laboratory (MSL) at ESTEC in March 2005. In April 2005, it was sent to Japan for preliminary integration, mechanical and interface testing.

It became clear after these tests that there was the possibility to use also the second robot slot and thus test two robots instead of only one. Furthermore, the robot box in the mother section was slightly smaller than planned. These two facts required some changes in the design concerning the robot width, the communication architecture and the sliding interfaces with the holding box.

TABLE II: Specifications of *RobySpace Junior*

Dimensions	
total:	$105 \times 93 \times 47$ mm
Mass	
total:	605 g
Power	
battery type:	rechargeable Li-ion
capacity:	345 mAh; 11.2 V
energy density:	240 Wh/l; 126 Wh/kg
Locomotion	2 DC micromotors
force:	2.5 mNm
speed constant:	3660 rpm/V
power	max. 2×3 W
mass:	41 g
max. velocity	0.4 m/s
max. ang. velocity	10 rad/s
chosen speed:	0.07 m/s
Communication	
Bluetooth (c)	class 1 v 1.1 SSP comp.

A. Reduction of robot width

During launch the robots are fixed inside the rocket payload bay to the mother section of the experiment with a holding mechanism consisting of two side plates with cones. The two plates are connected by a wire; a wire cutter is coupled to the start signals of the robots, releasing the holding plates that are opening to the sides with bottom mounted springs. This arrangement had to be changed several times due to little space between the released plates and the outer rocket structure. This results in a reduced (usable) width of only 93 mm compared to initially specified 99 mm.

This reduction of the width was possible by a rearrangement of the inner components of the upper (active) part of *RobySpace Junior*. Reducing the width of the passive part was straight-forward by reducing the still empty space between the two driven belt mechanisms, that would later be able to accommodate a camera for active vision based navigation and the antenna section in case of use of the robots as antenna elements.

B. Changes in the Communication architecture

The communication between the robot and the mother section has only two main tasks:

- Starting the robot in autonomous mode
- Receiving telemetry data for post test analysis

The bluetooth protocol is used for wireless information transfer with following general settings:

- Serial Interface Configuration: 57600 baud, 8 data bits, 1 stop bit, no parity, no flow control
- Robot is sending ASCII signs if it is turned on
- every command consists of 10 Bytes

The commands have to be send all the time i.e. every 20 ms (for commands "AutoMode" and "StopMotors" this is not necessary). The robots use the *BlueWafe* (c) modules from *Wireless Futures.*

The following two possibilities to initialize a connection between the mother module and the robots were studied:

1. Establishment of the connection with special commands from the rocket system over the serial connection
   This would have the advantage of the system having complete control over connection (establishment, reading state information, disconnection, reconnection etc.). This option required however a reprogramming of the entire communication software
2. Establishment of the connection with the *"wireless cable mode"* of the mother module
   The module has to be programmed only once, because these settings are stored in flash memory and are persitent through power cycles. After switching the module on, it automatically tries to connect to the robot. In order to start the robot, the system would need to wait a few seconds after switching on the communication module to be sure it would be connected before sending the 10 bytes of the start signal over serial interface to the module. The advantage of this option is that the connection is automatic and continuously tried until successful and does not require any special software. On the other hand, the system does not have complete control over establishment of the connection - the module automatically tries to connect continuously until the connection is established.

The second option was chosen due to its robustness and ease of implementation within the short time between the preliminary integration testing and the final integration. At the same time, an efficient and easy solution was necessary to expand this architecture to two robots. It was not possible to use a second dedicated bluetooth module in the mother section for the second robot. All electrical lines were already occupied and changes to the mother section part of the rocket payload were no longer possible. Further there was no support of the module manufacturer to implement a novel multipoint bluetooth connection. The

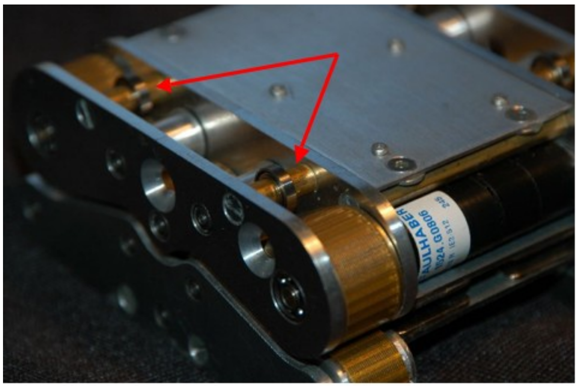

FIG. 9: Mounted low-friction bearings on *RobySpace Junior*

only way to handle this problem was via a software multiplexer, which would allow to still use the "wireless cable mode". The disadvantage was the loss of the ability to communicate with both robots at the same time, i.e. telemetry data will not be available over the entire experiment time but only in time-divided slots. Furthermore, the two robots had to be started in sequence and not in parallel. A time-shift of five seconds was chosen. The starting procedure was not affected by this change.

C. Low friction design

The mechanical verification and integration tests in Japan revealed a new problem: The distance between the robot and the lower and upper plates of the holding box was only 1 mm. Since there was no guarantee that the mother section would not tilt with respect to the deployed net, the robots risked being pressed to the top or bottom plate of the box by the moving net. In addition, the only force the robot could rely on for its movement out of the mother section box was some minimal tension of the net exerted by the daughter sections. Initial small accumulation of the net between the two robot parts was thus likely, resulting eventually in a slight accumulation of net between the parts still within the box. This would reduce the already very small distance between the robot and the upper and lower plates of the box up to the level when the robot would be pressed against the plates and the resulting friction would prevent it from leaving the mother section box.

To avoid this effect two improvements were necessary. First, additional roller bearings were installed on the robot to reduce the friction in direction of motion as shown in fig. 9. These roller bearings were installed directly on the launch site and could only be added to one of the two robots. Second the net inside the mother section was replaced by a small cloth

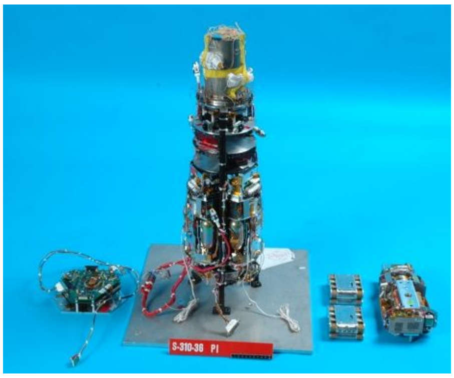

FIG. 10: Different parts of the furoshiki experiment

since the net represented too high a risk of getting entangled on one of the mechanical or electrical parts installed in the bay (e.g. cables, screw heads etc) and being accumulated between the robot parts.

One of the advantages of the *RobySpace Junior* design is its ability to accommodate to a wide range of materials for the net. Tests were made with very different type of nets and cloth materials. In principle, the robot is also able to move directly on flexible solar foils.

V. LAUNCH AND RESULTS

After the final integration at the Uchinoura Space Center in Japan, the sounding rocket S-310 was launched on January 22, 2006. The launch sequence was as planned, the payload bay was de-spun and stabilised, the daughter sections were released simultaneously and deployed the 130 m^2 large net from the mother section which remained at its centre.

Fig. 10 shows the different parts of the experiment partially mounted before their integration into the payload bay of the launcher. Fig. 11 shows the entire experiment including the two robots and the net integrated into the payload bay of the launcher just before the mounting of the fairings. Fig. 13 shows only the robotic compartment of the payload bay with the two *RobySpace Junior* robots and the net ready for launch.

The entire experiment was filmed by three video cameras, two of which mounted on the mother section in direction of the two daughter sections towards which the two robots were intended to crawl and one on the third, uncontrolled daughter section in direction of the mother section and intended to film the deployment of the entire net.

For the discussion of the results of the net deployment and stabilisation as well as the retro-directive antenna experiment, it is referred to [9, 10]. Concern-

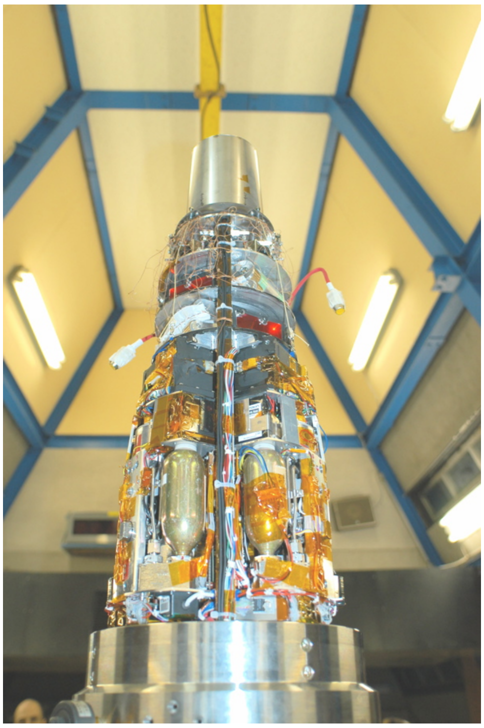

FIG. 11: Payload bay fully integrated before mounting of the launcher fairing

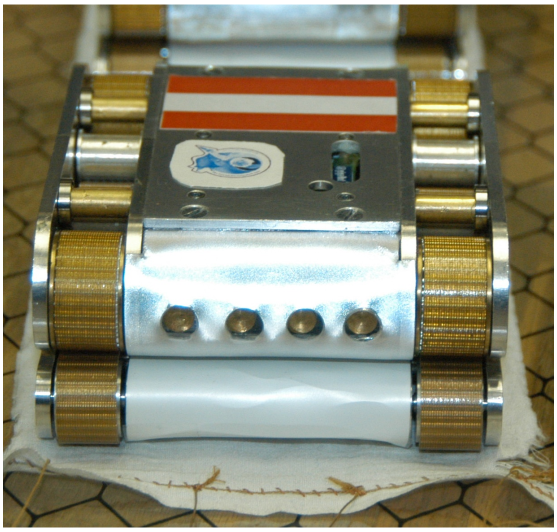

FIG. 12: The ball-bearing equipped flight models of *RobySpace Junior* before integration into the mother section

ing the robotic part of the entire experiment, data from the locomotion system of both robots as well as a short video-sequence showing one of the robots crawling on the net were obtained. Due to tilting of the mother section, the communication signal between the mother section and the ground station (and thus the data from the robots) was lost several times.

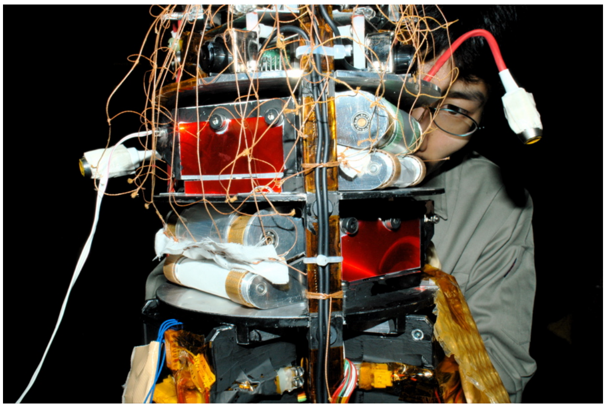

FIG. 13: Two *RobySpace Junior* robots fully integrated in the payload bay before launch

Based on the analysis of the retrieved data, it is clear that

- the connection was successfully established with both robots,
- both robots have received the start signal and started moving,
- the robot with the additional ball bearings has left the mother section as planned and crawled for at least 25 seconds on the net. It crawled on the net with only small resistance (constantly high voltage level and constant velocity over more than 25 seconds), indicating a relatively smooth net without entanglement at least at the section of the robot path,
- the second robot started moving nominally for about four seconds, during which he should have been able to leave the box. After four seconds, the resistance suddenly increased sharply, the motors stopped, tried to move backwards and then forwards again. From the available data, it is not clear if this might have been caused by a defect release mechanism, by a too high friction resistance between the robot and the box or another resistance (e.g. entangled net at robot exit). Based on the test experience, given the smooth exit of the robot with the ball bearings, and the tilting of the mother section with respect to the deployment plane of the net, the friction between the robot and the holding box seems the most plausible cause,
- in addition to the locomotion system status data of the first robot, its controlled movement on the net is further proven by the video data. The robot clearly appears on the net between two losses of the transmission signal for several seconds in one of the cameras. (Fig. 14)

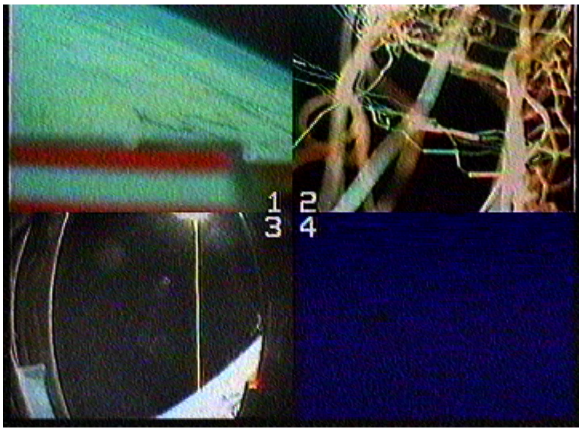

FIG. 14: Screenshot taken from the onboard cameras. The upper left quarter shows the camera image with the appearance of the *RobySpace Junior* robot with the ball-bearings. The upper right quarter shows part of the net in direction of the second daughter section. The lower left quarter shows the image taken from the camera onboard the uncontrolled daughter section, showing at its left side part of the (tilted) mother section.

VI. CONCLUSIONS AND OUTLOOK

The paper presented the results obtained from the robotic part of the *Furoshiki* experiment launched on 22 January 2006 on a Japanese S-310 sounding rocket. The experiment has proven the validity of a locomotion system based on magnetic adhesion on a very loose net in microgravity. The entire robotic part of the experiment was designed, built and tested by a small, dedicated university team on a very small budget and within extremely tight time schedules.

The data have also shown important avenues for improvement and further development. Given the very complex dynamics of a net in micro-gravity, visual data proved paramount for the result analysis in addition to standard system and telemetry data. Ideally, a camera would be placed inside the empty lower, now fully passive part of the robot together with a more powerful communication system. In this case, continuous coverage of the robot movement would be assured, not only relying on the mother section cameras. While the current design has proven the general viability of the concept, neither mass not volumes were optimised. Substantial mass reductions are still possible.

The limitations of a sounding rocket experiment (short experiment time, the robots were released relatively late thus fully affected by the poor communication link due to tilting and the net instability) did not allow to test the full potential of the concept. Ideally, the next step would be to demonstrate the concept in orbit. This could be done as small piggy-back payload.

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