A Unified Ground Control and Programming Methodology for Space Robotics Applications — Demonstrations on ETS-VII

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Abstract

The paper outlines the main features of DLR's ground control station for space robotics applications. It combines sensor-based task-level teleprogramming with the features of tele-operation and shared autonomy. The teaching by showing approach is the key to a easy-to-use programming interface at different levels of space robot controlling. This approach has led to a modular task-directed programming scheme, which provides a very flexible architecture to adapt the application-specific requirements to a given controlling scheme. To demonstrate the power of our system, we describe the results of the GETEX experiment, which was performed in April '99 at the first free-floating space robot on NASDA's ETS-VII satellite[1].

Introduction and Overview

Over the last years, DLR has focussed its work in space robotics on the design and implementation of a high-level task-oriented robot programming and control system. The goal was to develop a unified concept for a flexible, highly interactive, on-line programmable teleoperation ground station as well as an off-line programming system, which includes all the sensor-based control features partly tested in the ROTEX[2] scenario. But in addition it should have the capability to program a robot system at an implicit, task-directed level, including a high degree of on-board autonomy. The current system provides a very flexible architecture, which can easily be adapted to application specific requirements. To get the robots more and more intelligent, the programming and control methodology is based on an extensive usage of sensors, such as cameras, laser range finders, and force-torque sensors. It combines sensor-based teleprogramming (as the basis for on-board autonomy) with the features of teleoperation under time delays (shared control via operator intervention). Applications in a well-known environment, e.g. to support or even replace an astronaut in intravehicular activities, can be fully pre-programmed and verified on-ground – including the sensory feedback loops – for further sensor-based execution autonomously on-board. The desired tasks can easily be composed in a virtual world by a payload user, who has normally no expertise in robotics. As man machine interface, a sophisticated VR-environment with DataGlove and high-performance graphics is provided as well as a simple Java/VRML applet. This is a very intuitive programming interface, based on internet standards, for controlling a space robot by an ordinary PC from anywhere in the world. Otherwise service tasks, such as assembling and maintenance ISS modules or catching and repairing a failed satellite requires a high amount of flexibility in programming and controlling. This stems from the fact that most of the activities cannot be foreseen. Because the remote environment will not be known sufficiently or uncertain for exact modeling. To handle both application fields we have developed a 2in2-layered architectural model, which represents the programming and control structure from the „how-to-do" to the „what-to-do" level in a hierarchical order.

The flexibility of the system, to control nearly each kind of space robotics applications, has been shown in several applications: starting with ROTEX where the sensor-based control features were successfully verified, the development reached a first milestone in spring 1999 where the Japanese ETS-VII space robot was controlled from the ground by our system. First, the power of the task-oriented sensor-based programming approach was shown, demonstrating the vision&force control scheme by executing a prototypic peg-in-hole task fully autonomously on-board. All the operations were pre-programmed in the simulation environment on-ground, including image processing and vision controller parametrization. Second, we have extensively studied the dynamic interactions between robot and carrier with the attitude control system switched off. By conducting several dynamic motion experiments on the ETS-VII satellite, we could thoroughly verify our dynamic motion model, which has been integrated into our programming and control system.

Our cooperation with NASDA w.r.t. to the dynamics verification was one important step towards a free-flying service satellite. For more details see [3]. In our lab the semi-autonomous telemanipulation feature of the ground control and programming system is used for the ESS (experimental servicing satellite) scenario, where a free-flying telerobot is supposed to approach, inspect and repair a malfunctioning satellite, e.g. the TV-Sat-1, where after launch one solar panel had not opened. A special in-house-developed capture tool containing 6 laser range finders, a wrist-mounted force-torque sensor and stereo camera allows, in combination with the dynamics behavior prediction, fully autonomous servoing, insertion and capturing of apogee motors which are typical for any geostationary satellite.

Currently, we apply our programming and control methodology to an ESA funded mars rover study, where the autonomy of the flight system has been increased even further due to the very large time delays.

Programming and Control Methodology

The goal for the development of our high-level programming system was to design a unified concept for a flexible, highly interactive, on-line programmable teleoperation station as well

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as an off-line programming tool, which includes all the sensor-based control features as tested already in ROTEX, but in addition provides the possibility to program a robot system on an implicit, task-directed level.
A non-specialist user – e.g. a payload expert – should be able to remotely control the robot system in case of internal servicing in a space station. However, for external servicing high interactivity between man and machine is demanded. For that reason the design of our programming system is based on a 2in2-layer-concept, which represents the hierarchical control structure from the planning to the executive layer:

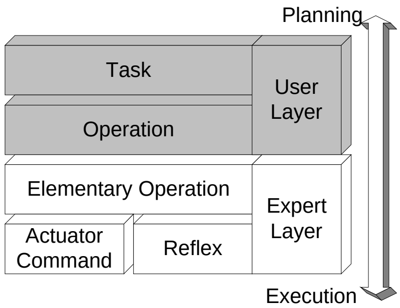

Figure 1 2in2-layer-model

On the user layer the instruction set is reduced to **what** has to be done (planning level). No specific robot actions will be considered at this task-oriented level. On the other hand the robot system has to know **how** the task can be successfully executed, which is described in the expert layer (execution level). For details see[4].

Expert Layer
At the lowest level of our programming and control system the sensor control mechanism is active. These so-called *reflexes* guarantee the local autonomy at the remote robot's site by using sensory data processing algorithms in an extensive way. The teaching by showing paradigm is used at this layer to show the reference situation, which the robot should reach, from the sensor's view: in the virtual environment we store the nominal sensory patterns and generate appropriate reactions (of robot movements) on deviations in the sensor space. This programming layer is completed by the Elemental Operation (*ElemOp*) level.

User Layer
Wheras the Reflex and ElemOp levels require the robotics expert, the task-directed level provides a powerful man-machine-interface for the robotics user. An *Operation* is characterized by a sequence of ElemOps, which hides the robot-dependent actions. For the user of an Operation the manipulator is fully transparent, i.e. not visible. To apply the Operation level, the user has to select the object/place, (s)he wants to handle, and to start the Object-/Place-Operation. For that reason the programming interface is based on a virtual reality (VR) environment, which shows the workcell without the robot system. Via a 3D-interface (DataGlove or SpaceMouse) an object can be grasped and moved to an appropriate place. The execution of the generated *Task* can be started by doing a specific VR-hand gesture.

The GETEX experiment on ETS-VII
From April 19-21, 1999 DLR's telerobotic and programming system was used to control the robot arm on the Japanese ETS-VII satellite. The main goals of the German ETS-VII Technology Experiments (GETEX) were

- to verify our telerobotic *ground control* station for remote control of a free-floating robot, in particular
- to perform a peg-in-hole experiment, using VR methods and the „*vision&force*“ control scheme, by closing sensor control loops directly on-board (force) and via the ground track (vision), thus proving our sensor-based autonomy features,
- to conduct experiments with relevance to the behavior of ETS-VII in *free motion mode* and thus to verify the existing 6 dof dynamic models for the interaction between a robot and its free-flying carrier satellite.

For details concerning the experiment setup see [5].
All the experiments were available live at the Internet via Video transmission and a VRML simulation which showed the current robot and satellite status in an impressive way[6]. In principal it would have been possible to control the task execution via our Java/VRML interface from any point all over the world regardless of time delay.

Peg-in-hole experiment, using VR methods and the „vision&force“ control scheme
After teaching the desired peg-in-hole task in the VR environment, i.e. pick TBTL (TaskBoard TooL), see Figure 2, and placing it into HOLE A, see Figure 3, the execution was started and performed fully automatically on-board:
To get the TBTL, we first carried out a visual servoing task. For that task we used the markers mounted all over the TaskBoard.
Originally, these markers should guide the operator to teleoperate the TCP into the accurate grasping position over the TBTL or another part mounted on the TaskBoard. For each camera lens of the stereo pair, three corresponding markers have to be aligned as well as the middle have to be centered within the outer ring (see Figure 4). Now, we used these operator-markers for controlling the robot autonomously over the TBTL grasping position.
To extract the markers from the video image we used a blob-finding algorithm, described in the following: due to the extreme contrast inside a marker (bright spots on a black background, see Figure 4) as well as strong fluctuations of illumination, the grayscale image of the task board is reduced to a standardized ternary image (black/gray/white).
This conversion is based on an illumination estimation derived from intensity histograms of a limited image history and the last set of verified markers, if there are any.
Furthermore the identification of new marker locations is performed in tree stages:

1. Noise and drop outs of adjustable size will be eliminated by adaptive standard filters (e.g. convolution methods).
2. Each spot of appropriate form, size, and structure, which is fully included, will be extracted out of ternary image.
3. Both measured features of each spot and a scalable marker model are used for a statistical conformity analysis of measured and predicted background intensity distribution.

Figure 2 Pick TBTL

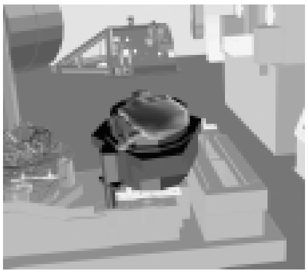

Figure 3 Place TBTL

The necessary reference features as well as the marker models for the outlined selection are estimated starting from the last valid marker set (if any), the elapsed time, and the intensity distribution of the current grayscale image. The detected markers are tagged in the grayscale image.
Because this algorithm delivered more „markers“ as desired, e.g. due to bad lighting conditions, we selected the markers interactively and checked the resulting control command before sending it to the real robot. All the control algorithms we applied in the real environment were parametrized and tested on our ground station, which provides the necessary sensor simulation as well as sophisticated graphical tools for VR visualization.
We developed an approach that doesn't need any calibration. The control law may be written as

$$v_c = \alpha\, C\, (s-s^*)$$

where (s-s*) is the vector-valued deviation between the current and the nominal sensory pattern indicating the displacement of the current robot pose x from the nominal pose x*. v_c is the velocity command, α represents a scalar dynamic expression, at least a real constant, determining the closed control loop behavior, and C represents a projection operator used for mapping the sensor space onto the (cartesian) control space. C is determined by neural network learning[7] or using analytical methods[8].
Here we have applied the analytical method for determination of *C*, which is represented by the pseudoinverse of the Jacobian matrix of the *m* deviations in the sensor space w.r.t. the *n* deviations in the control space. For that we moved the robot's TCP a little bit around in all *n=6* degrees of freedom, recorded the corresponding sensor values and generated the Jacobian from the resulting difference quotients.

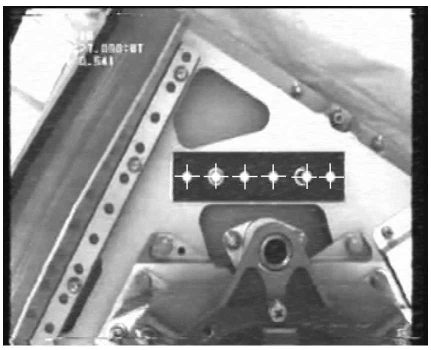

Figure 4 View out of the left hand camera, showing the tracking markers for visual servoing

$$J_{i,j} = \left.\frac{\partial y_i}{\partial x_j}\right|_{x^*} \quad i = 1..m,\ j = 1..n$$

We performed the experimental determination of *C* in our simulation environment as well as in the real one. The result was nearly the same, due to the accuracy of our camera calibration, that we applied in the simulation. The intrinsic camera parameters have been estimated using an in-house developed camera calibration tool, the external could be easily extracted from the available CAD data.
To illustrate the accuracy, the respective simulated and measured pixel coordinates are shown in Table 1. They differ only in the subpixel domain.

	X1	Y1	X3	Y3	X4	Y4
real	273.80	240.17	365.70	240.35	411.60	240.37
sim	273.94	240.38	365.81	240.56	411.71	240.59

Table 1 measured and simulated pixel coordinates

The goal for the control system was to find the markers in the live video image and to generate the appropriate straight path command to move the robot into the desired target pose. To verify the vision-based sensor control loop, we moved the TCP intentionally into a position different from the target pose (a few centimeters in all translational directions and about 20 degrees in z-rotation). After 3 cycles, the target pose was precisely reached. To fulfil the *vision&force* control scheme, the force control loop, implemented on-board, was activated and supervised.

Dynamic Motion Experiments

A major part of the GETEX experiment time was allocated to the so-called "Dynamic Motion Experiments", which consisted of a series of manœuvres carried out by the manipulator while the attitude control system of ETS-VII was switched off.
For space robotic systems that are neither position nor attitude controlled the angular momentum conservation law leads to a rotation of the spacecraft by an amount that results from the mass and inertia properties of the manipulator links and the spacecraft. It is generally assumed that no external forces act on such free-floating robots[9,10]. The free-floating mode of operation is of interest for space robots not only for the reason that attitude control fuel may be saved which augments the robot life-space, but also will be of importance during repair missions.
As long as the tasks performed with the robot are described in robot-fixed coordinates, the fact that the satellite position remains uncontrolled has no influence. If, however, the task is described with respect to an orbit-fixed co-ordinate system, as it would be the case for example for the capturing of another defective satellite, the robots satellite motion has to be taken into account (see Figure 5). The equations relating the TCP motion to the manipulator joint motion, which for robots with an inertially fixed base are purely kinematic equations, therefore become dependent on dynamic parameters in the case of free-floating space robots due to the fact that the momentum equations are used to describe the satellite motion.

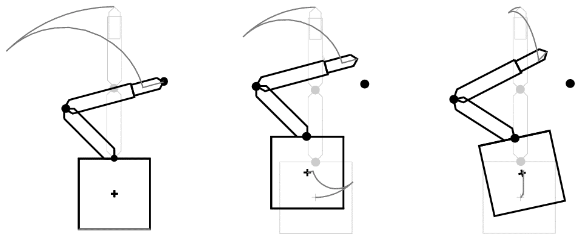

Figure 5 The influence of the satellite attitude control mode on the path described by the robot end-effector - the same joint motion is carried out by a robot with a fixed base (left), an attitude controlled robot (middle) and a free-floating robot (right).

This influences the path planning methods which have to be applied. On one hand, singularities, that is joint configurations in which the robot is not controllable in Cartesian coordinates, are no longer a function of the robot kinematics only, but become dependent on the dynamic properties of the robot, too. Therefore, iterative methods based on the direct kinematic equations have to be used instead of the inverse kinematics equations. Moreover, the angular momentum equation makes the system nonholonomic[11], which means that the satellite orientation is not a function of the current joint configuration only, but also a function of the chosen path.
Two different paths starting at the same initial configuration of the robot, and leading to the same final configuration, will therefore result in different amounts of satellite rotation – and thus in different final inertial TCP positions, too. As a consequence, nonholonomy offers the possibility to do a re-orientation of the satellite using manipulator motion only, by simply carrying out a closed-loop manœuvre in joint space.
Whatever path planning method is applied to free-floating robots is necessarily highly model-based. The parameters of the dynamic model have therefore to be known quite well. While this poses no problem for the geometric parameters and for the mass and inertia of the manipulator, the mass and the inertia of the spacecraft are subject to important changes during the lifetime of a servicing satellite. This is especially the case if the spacecraft is performing capturing or rendezvous/docking like operations.
One goal of the GETEX experiments has therefore been to identify the mass properties of the satellite after one year and a half of activity in orbit. Further objectives were the verification of the dynamic models and to obtain some insight into the nature and importance of the disturbances acting on a robotic satellite on low Earth orbit. Additionally, the mission aimed at gathering data for the future design of controllers that combine the manipulator motion control with the satellite attitude control. To meet all these objectives, a variety of different manœuvres were executed by the manipulator while the attitude control system of ETS-VII was switched off.

Experiments

In the GETEX experiment the following manœuvres of the manipulator on-board the ETS-VII satellite were performed:

- point-to-point manœuvres
- manœuvres to determine a variation of the attitude of the satellite
- optimized manœuvres to minimize satellite base motion or manipulator joint motion (minimum energy manœuvres)

During the first half of the experiments the satellite attitude control system was switched to "free-floating mode", allowing a free-floating condition of the system within an attitude range of a few degrees. Since during normal operation mode the satellite was given a nominal angular rate equal to the orbital rate, such that it would always point in the same direction towards Earth, also during the free-floating motion experiments the angular rate of the satellite was unaltered, as the satellite kept rotating due to its inertia.
The experiments were performed in five slots of twenty minutes, where the first ten minutes were in free-floating mode and the last ten minutes were with the attitude control system (AOCS) switched on.
Each slot consisted in the following procedure:

- unwinding of the momentum wheels using attitude control thrusters
- reduce the residual angular velocity of the satellite to a lower value by winding up again the momentum wheels
- AOCS switched to free-motion mode
- perform manoeuvres
- AOCS switched to momentum wheel motion control mode
- repeat manoeuvres.

Results of the experiments

The following discussion will refer to the first representative slot of experiments, for which the manoeuvres shown in figure 7 were performed in succession. The figure shows the end-effector motion (continuous line) simulated with an ideal free-floating model (free of external actions). Note that the first is a point-to-point manoeuvre while the second is a closed-loop manoeuvre.
Real end-effector motion with respect to the satellite was found to coincide with the simulated motion. The satellite attitude motion during the free-floating condition was found to differ from the simulated motion, as shown in figures 8a and b. The figures show the Euler parameters describing the satellite attitude relative to the orbital frame in function of time.

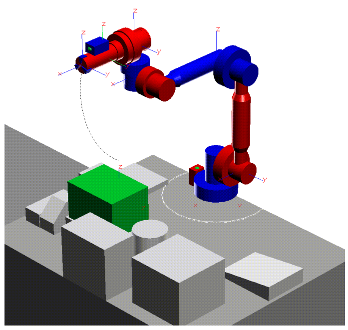

Figure 7a Point-to-point manoeuvre

Of interest is also the angular momentum of the reaction wheels which is shown in figure 9 for all the duration of the first slot. The figure shows that the momentum during the free-floating condition time of the experiment (910-1360 seconds) had some small non zero value, due to the second phase in the above mentioned sequence.

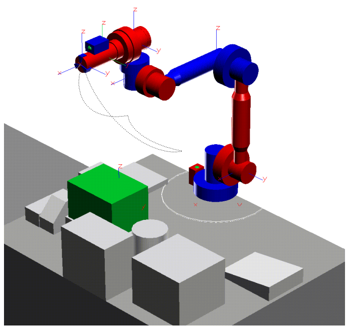

Figure 7b Closed-loop manoeuvre

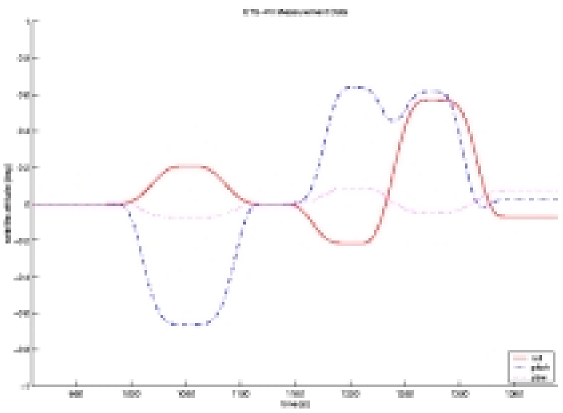

Figure 8a Simulated satellite attitude parameters in function of time

Analysis of the experimental results

Figure 8a shows how, by comparing the initial and final values of the attitude parameters, the closed-loop manoeuvre gives rise to a small variation of the satellite attitude.

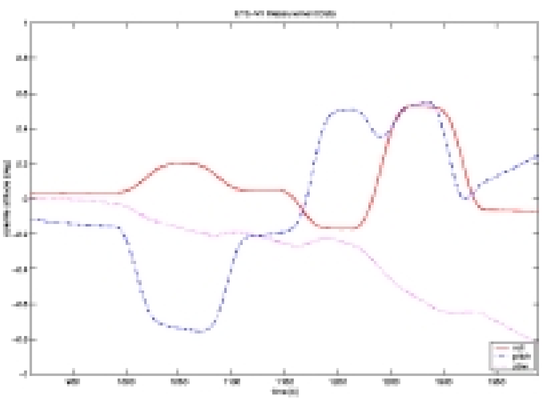

Figure 8b Measured satellite attitude parameters in function of time

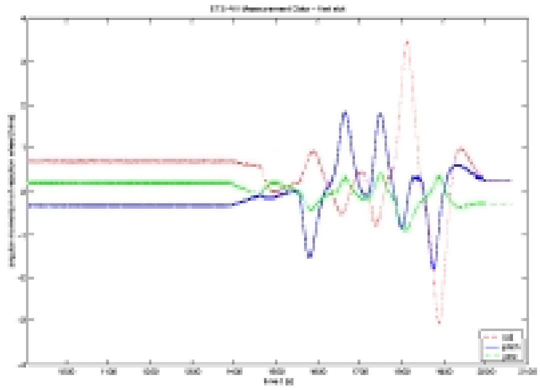

Figure 9 Angular momentum of reaction wheels in function of time

Figure 8b however, shows a substantial drift of the satellite superimposed on the motion induced by the manipulator motion, shown in figure 8a. This drift has been found to depend mainly on the following factors:

- the gravity gradient acting on the satellite
- the coupling between the residual angular momentum of the momentum wheels and the orbital angular velocity of the satellite
- the residual angular velocity of the satellite with respect to the orbital frame of reference at the beginning of the experiment.

Other factors, such as the interaction of the satellite magnetic dipole with the Earth magnetic field, solar pressure and aerodynamic drag were taken to be second order effects. The aerodynamic drag was in fact measured by NASDA and was found to be small in size. Finally, moving parts on the satellite, such as the solar panels and the communications antenna, were found to give a small disturbance to the motion of the satellite about the pitch axis, after simulation.

The simulated data of the updated multibody model, which accounts for the above points, is shown in figure 10 (dotted lines), in comparison to the measured data (continuous lines). It is clear from this figure that there is still a discrepancy between the two sets of data. This is thought to be due to an approximate value of the mass and inertia of the simulated model with respect to reality, as the results were found to be very sensitive to variations of the simulated values. In fact, although the properties of the manipulator arm are known from measurement prior to the launch, those of the satellite are only known approximately due to the fuel consumption during the lifetime of the satellite. An estimate of the initial satellite inertia was also necessary due to the fact that the mass and inertia data was only known at launch for the complete system with the manipulator in the stowed configuration.

A parameter identification problem can be defined and solved such that these quantities can be determined. Note that the unknown quantities are the mass and inertia of the satellite and the position of the center of mass of the multibody system. This problem, if solved, will give rise to the possible development of a new method for measuring mass and inertia properties of a space robot in orbit.

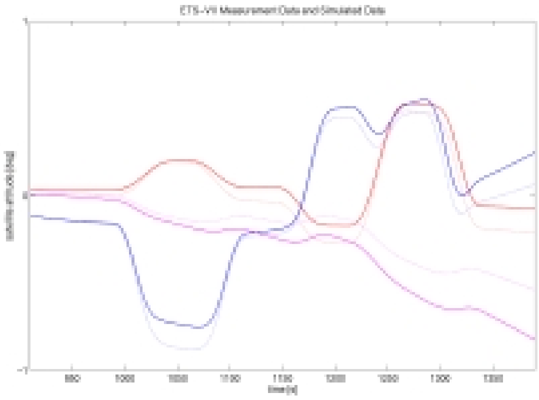

Figure 10 Measured (continuous line) and simulated (dotted line) satellite attitude

The experimental results have also shown that the modeling of the external torque acting on the satellite (standard disturbances which act on orbiting space systems) have to be included in the overall model of the system, if manœuvres of the manipulator need to be referenced to inertial space, or to another spacecraft. In developing the model used for this experiment, in fact, it was assumed that such disturbances were negligible for the purpose of the experiment. This is because the duration of the manœuvres was thought to be short enough to neglect any external action on the satellite.
The unexpected drift of the satellite in time resulted in a partial failure of the second manœuvres listed above, since it was not possible to determine the rotation of the satellite with respect to inertial space during the experiment. However, despite this unexpected behavior of the system, all manœuvres were performed while satisfying the limitations on satellite attitude variations of 1 degree about each axis to an acceptable degree.
As a conclusion, the GETEX dynamic motion experiment has been useful in

- validating the model of the ETS-VII satellite-manipulator system for manœuvres referenced in the satellite's frame,
- realizing that it is necessary to account for the external disturbances acting on a spacecraft in low Earth orbit for a correct modeling of the manœuvres referenced in the fixed inertial frame, and
- developing a model for the external disturbances to be validated with the experimental data.

Conclusion

We have shown the universal capabilities of DLR's control system for controlling any kind of robotics applications, especially for space. Recently (April '99) we have performed the GETEX mission at ETS-VII with very successful results, i.e. in applying the vision&force control scheme to the peg-in-hole environment of the ETS-VII TaskBoard as well as in verifying our dynamic models of free-floating space robots. Now we believe that the extensive use of robotics, e.g. at the International Space Station or as a free-flying servicing satellite[12] including intelligent robot arms and grippers, must be pushed by all industrial and political partners.

Acknowledgements

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