MORE, a novel approach for mini manipulators for space

Wolf-Peter Foth, Dr. Bernd Mädiger, Cornelia Mädiger, Hansjürgen Günther
EADS Space Transportation GmbH
Postbox 286156
28361 Bremen
Phone: +49 (0)421 - 539 - 4880
Fax: +49 (0)421 - 539 - 28 - 4880

1. Abstract

Future in-orbit space infrastructure and constellations will require a large amount of automatic functions for general inspection, servicing and maintenance including refuelling and repair. Future robotic systems need next to this to be more flexible than current designs, they have to serve for various, currently even unknown missions and scenarios. Many of these functions need to be verified by demonstration missions using small spacecrafts in low earth orbit.

EADS-Space Transportation has performed in the past several feasibility and definition studies for modular robotic concepts to allow an adaption to changing mission and operations conditions. These concepts allowed with minor changes up to now an utilisation of identical basic elements in various scenarios, from simple pick-and-place operations over autonomous inspection of the outer shell of ISS up to complex in-orbit servicing tasks with free-flying robotic spacecraft. The current work concluded in the definition of a robotic technology demonstration with a small modular 6-DoF manipulator including all steps to demonstrate online or remote commanded robotic and tool supported in-orbit operations.

This paper gives an overview about the conceptual approach for such a novel design and will give a short outlook to the future activities for this demonstrator.

2. Introduction

The role of manipulators in future in-orbit space infrastructure will change dramatically and will require a large amount of additional automatic functions for general inspection, servicing and maintenance including refuelling and repair.

Future robotic systems need to be more flexible than current designs, they have to serve for various, currently even unknown missions and scenarios. Space relevant robotic systems in our days are based for the manipulator part on a unique configuration and design, which is especially established for one specific mission or operations type. The robots have a known, but fixed configuration with a known, but fixed control system for it. The required flexibility is mandatory for all robotic devices, from hardware modules (joints, limbs, end effectors, sensors, etc.) up to software modules (different control principles, planners, execution control, etc.) and even for operations control.

Therefore an integrated mechanism and device infrastructure shall be developed and lateron established on breadboard and prototype level. The technology development shall result in a set of modules to enable an easy and quick (even an online) configuration and reconfiguration of multi-functional robots and mechanisms. The modular set shall include the relevant hardware items for various missions and conditions, but also all the interfacing data and elements to ensure compatibility throughout the entire system.

Many of these functions are independent of the precise scenario description and will be verified by dedicated demonstration missions.

3. Scenarios

The destinations and scenarios for the next steps for exploration are clearly visible as to prepare an infrastructure for man in space, on Moon, on Mars and on other destinations of our solar system. The preparation of the infrastructure includes explicitly also robotic infrastructures as preparatory and accompanying program to a later human exploration.

Thus robotics will be a servant for the exploration, servant for ground control in the initial exploration of new and unknown destinations, servant for ground control in establishing and build-up of the infrastructure at the new destinations, but also servant for the crew on-site either in daily maintenance and repair or in high sophisticated scientific exploration missions.
Utilisation of such robotic servants will be at any place of exploration, inside as well as outside of the man-tended stations.

Up to now robots are usually designed and optimized for a special mission type or scenario, but not for several. In the future exploration scenarios, the role and function of the robots will vary over the programs lifetime. In the initial “automated” phase the robots will mainly have to work for the creation and assembly of the local infrastructure, in the man-tended phase the services of robots will vary from assembly tasks up to support for the crew, while during the manned phase the robots will also take over the regular autonomous inspection service. As in this short list the tasks and by that the required skills of robots in future space exploration scenarios will comprise a large variety of different operations, which in some instance are not defined in detail today.

Basic Requirements
The basic requirements for robotic support for the different scenarios can briefly be summarized to:
- Scenario conditions not fixed or unknown
- Operations a-priori unknown/undefined
- No specialisation possible; all different scenarios are equal in ranking
- Extendibility for the future operations and missions required
- Specific MORE characteristics for the local operating crew
  - H/W reconfiguration without tools,
  - Reconfiguration without complex procedures and operations,
  - S/W reconfiguration as automatic as possible
- Strength Depending from scenario and loads to be handled
- Dexterity as high as possible
- Velocities similar to human behaviour

The development aims in a system where an user will collect the different modules out of a "shop-floor"-like set and will combine them to the desired local configuration.

4. Basic Concept
State of the art for space robotic development is currently to design and optimize a single robot in a quasi-fixed configuration. Once the robot is qualified and sent out to mission, a change in the basic configuration of the manipulator is almost impossible. Reconfiguration today is limited to an exchange of tools and some adoption of control algorithms.

To avoid a redevelopment and new designs for the robots to be optimized for each different scenario in this project an alternative approach is proposed. It is proposed to develop a set of standardized robotic modules which will be used in every scenario and which will be assembled on-site to an (for the mission and operations) optimal manipulator. The assembly of the manipulator might either be performed prior to launch, to have an already working manipulator when reaching the desired destinations or it might be done at the location, when the astronauts have different operations and missions to perform.

The technology development shall result in a set of modules to enable an easy and quick (even an online) configuration and reconfiguration of multi-functional robots and mechanisms. This modular set includes the relevant hardware items for various missions and conditions, but also all the interfacing data and elements to ensure compatibility throughout the entire system.

The set of smart robotic modules shall allow a combination to any required configuration (kinematic chain, robot control, end effectors, sensor elements) allowing to create a very flexible robotic infrastructure (e.g. single standalone robot, robot arm(s) ontop of a rover, cooperating robot arm(s) in stationary or mobile planetary exploration elements as shown in Fig. 4-1 and Fig. 4-2.

Fig. 4-1: MPL Concept for Marsian Exploration

Fig. 4-2: UT for Martian Infrastructure
Such a modular concept has been preliminary defined in the EADS-ST robotic laboratories. The concept is based on several standardized exchangeable mechanical modules and their appropriate control segments. This concept shall be developed furtheron with the emphasis to:

- Enhancing the set of smart (intelligent) joint modules with different characteristics (rotatoric, linear, torque, velocity, dimension)
- Establishing of a set of intermediate modules (limbs, bases, booms, etc.)
- Establishing of smart end effector modules for various mission requests
- Establishing of a set of smart sensor modules for various functional tasks
- Establishing of a set of equipment control modules for the various mechanical elements
- Establishing of an open interface concept (mechanical, electrical, data) to enable the easy integration of modules of external partners and suppliers
- Establishing of an infrastructure of adaptable communication interface modules (for data and power)

Special attention will be placed to the harmonized interface structure, in which the stiff mechanical connection will be combined with a robust and reliable internal communication and power interface. When the mechanical reconfiguration is completed, the control of the system shall be adjusted automatically i.e. the IKT shall be updated to represent the current configuration, the preplanned position values in the worldmodel will automatically been checked for workspace violation and corrective measures been started (e.g. change of activity sequence, adoption of positions, etc.).

5. Development and Breadboarding

The concept is strictly modular, i.e. any robot based on this concept is assembled of mostly identical building blocks for the joints and the intermediate structures. In order to limit the number of module classes a basic set has been defined consisting of

1. Joint modules (rotatoric, linear),
2. Intermediate elements
3. Operation specific end effectors
4. Unified central control

All modules will be equipped with identical interfaces to enable to arrange any kind of configuration fitting best for the different mission profiles. Even for the same mission profile different basic configurations can be chosen as shown in Fig. 5-1.

Fig. 5-1 Different combinations of modules set

Joint Modules

Basic elements for the new modular concept are the smart joint modules. These modules contain next to housing, motor and gearbox also all joint relevant sensing, control, power supply and communication. For the concept different module sets are defined, especially rotatoric and linear modules. For rotatoric joints at least 2 different versions, a single-joint module and a double-joint module will be established.

These control adjustments shall be performed mostly without a direct user impact. The user in this sense may be the system engineer responsible for a new mission, but also the astronaut, who disassembles a given robot and assembles a new robot with different configuration and different characteristic on the spot.
Limb Modules
The intermediate structures will be mainly simple tubes with special interfaces at the endplates to be easily assembled to the joint modules. The arm is designed such that the different joint modules are interconnected with these standardized limbs.

All limb modules are equipped with internal cabling and standardized connectors at each end.

End Effectors
In this concept the interface of the generalized modular system to the scenarios are introduced with the end effectors. These modules are designed specific for their special applications and mission types. The end effector modules will be structured to certain classes of grasping, inspection/analysis, scientific, all-purpose modules. Common to all are the interface to the other MORE modules mechanical as well as electrical and for commanding, control and data exchange.

6. Control
Based on the operations concept of hierarchical distribution of functions and commands a functional architecture, following in principle the Functional Reference Model (FRM) of ESTEC, will be used, which includes all functional modules for MISSION, TASK and ACTION oriented planning, scheduling and parameter instantiation as well as the overall control modules for nominal and non-nominal feedback.

The scheduling and parameter planning for operations is always performed respecting the environment and the capabilities of the actual system configuration (especially when several different robotic subsystems as multiple arms, platforms, special sensors, etc.), but is independent of real values of parameters as positions, accuracies, forces etc. Thus a sequence of implicit ACTIONS including consistent symbolic attribute lists is generated. All attributes are numerically instantiated immediately prior to the execution using actual data of the environment model.

In case of nominal execution of ACTIONS the databases for world modelling are updated after each ACTION completion followed by the instantiation and execution of the next ACTION. This sequence is repeated until the last ACTION of the overall operation sequence is completed. In case of non-nominal execution the response will be the exception recognition, thus the realisation, that a non-desired status occurs followed be an identification of the cause of the anomaly and the planning, verification and execution of appropriate recovery activities. In this sense exceptions shall be handled by the lowest possible instance with only the information of the upper layers.
Main Controller
The robot control is based upon a separation between arm-relevant control levels, implemented on a main controller and joint-relevant control components, performed in the module controllers. Fig. 6-2 shows the overall architecture of the control system of MORE. It represents here the Double-Joint design with separate joint controllers, which are connected to the main controller via a regular communication bus (e.g. RS485, CAN, SERCOS).

Fig. 6-2: Overall functional control architecture
The robot controller is based on a conventional robot control structure containing path generation (interpolation), inverse kinematics computation for controlling the joint controllers. Further modules within the main controller are separate modules performing special operations such as grasping including image processing or functional modules required to compensate motion-disturbances. Functional principle of the control system is a hierarchical control concept, extended by sensor control loops and sensor-based skill modules for grasping operations and coordination activities with additional elements such as platforms, multiple arms, etc..

**Joint Controller**

All movements of MORE will be controlled using only three different motion controls.

- **For coordinated motion in general Point-to-Point motion control (PtP) will be used.** In this mode only the goal state will be given in carthesian coordinates.

  For the preplanned carthesian coordinates the joint angles for the goal point will be calculated via the actual IKT for the actual manipulator configuration. In this control mode the precise path of the end effector will not be predicted; it is not of importance.

- **For approaching and targeting an object a quasi continuous path control (CP) using position-based visual servoing is incorporated.** In this mode the goal state for the motion is analyzed and calculated on the basis if images and image recognition and a short path PtP motion.

  An image is analyzed for the actual target location in camera coordinates and the coordinates be transferred into a set of new relative cartesian goal coordinates, which will then be sent to the central control for execution. At the goal point the next image will be taken and processed and the loop is repeated again until the activity is completed.

  In this concept the image processing capabilities and periods are determining the precision of the path of the end effector. On the other side with this approach the requirements for the computing power for the central manipulator control are predicted by the performances of the image processing tasks and can be scaled and optimized for the entire MORE control.

  A special mode only for safety reasons will be the control of each joint separately in joint coordinates. This mode will be restricted to emergency situations and the activation only by special educated personal.

![Functional Control of one single joint](image-url)
Fig. 6-3 gives an overview over the functional control loop required for controlling of one single joint is given. The control principle is a classical hierarchical cascade control loop, consisting of the three levels of position, velocity and current control.

7. Breadboards and Testing

Since several years EADS-ST has developed the modular concept and has proven the validity of the concept with different breadboards. From model to model the modularity of the systems has been enhanced. Starting with a single commercial mono-Arm the system was enhanced to a multiple-arm system on a laboratory platform. With this breadboard the cooperation and coordination of the several different elements were investigated and developed.

The modules are identical in their interfaces and control; they differ only in different ratios of their gearboxes. These modules were used to establish manipulators with different kinematic configurations (6-joint -- 7-joint configuration).
The current final step is the optimization of the modularity for small manipulators based on double-joint modules. That system will be extended by an upgrade of the EADS-ST linear joint and adequate end effector modules, in this case a small 2-finger gripper with stereo-camera.

Aim of the developments are the extension of the capabilities to allow an assembly and disassembly (and by this an easy reconfiguration) of manipulators without specific tools and an optimization of the design towards the special environmental conditions as assumed for lunar and martian scenarios.

8. Summary

An important impact for systems for exploration lies in a huge flexibility of the infrastructure to cope with different and changing scenarios and requests. Such requests for those future exploration missions can sometimes not explicitly been defined in detail in our days or can even not been adressed. A set of smart modules to be combined easely and reliably to a robust multi-functional robot will enhance the spectrum of missions and tasks for such future robots dramatically. It will enable the future system designers to establish (out of a shop-floor like set) a well fitting robot and to reconfigure such machines easily to new (probably unknown) requests and conditions.

9. References

5. ChiRoSS CRM Analysis, Final Report, 2004