TOOLBOX OF MODULAR COMPONENTS TO DEMONSTRATE APPLICATION-SPECIFIC CONFIGURABLE SPACE ROBOTS

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ABSTRACT

Robotic solutions are preferred in manned and unmanned space missions, especially for planetary exploration, e.g., due to lower risk and thus lower costs. The robotic systems that have been designed and used so far are specially adapted to the relevant mission and it is not considered to be used elsewhere after the mission is completed. However, the MODKOM project pursues the approach of creating a toolbox that allows a robot to be configured and recombined for specific tasks from specialized and standardized building blocks, even after a mission has been completed. Ensuring mission assurance in mission-critical situations such as maintenance requirements as well as sustainment and reuse of resources. In addition to providing a set of these standardized modules, a software toolbox is developed alongside, which simplifies modular system design and creation also for non-experts. This includes adding new hardware parts via creating their simulation/control models as module representations to the corresponding component database. The toolbox consists of many modular components, like at least three payload modules, three basic modules, one manipulator, and multifunctional interconnects. The advantage of these components is that they are scalable. Using an example of a manipulator arm, it can be shown that two different drives with different torques can be connected in various combinations. There are extra adaptations and connecting elements enabling this feature. Other components include so-called base modules, which are functional on their own, as well as in combined form when assembled. In this way, for example, a rover body can be assembled with the necessary electronics, computer units, etc., while maintaining the possibility of future reconfigurations/upgrades. Further components are, for example payload modules, which can extend the functions and tasks of a system or the DFKI X2D Joint, a direct-drive actuator made for future walking robots in space and as platform for high speed applications. The main piece that supports combination and extension is a multifunctional interconnect (EMI-MOD). Once a robotic system or subsystem is equipped with the EMI-MOD, it can be connected to other (sub)systems. With the help of the software toolbox all modular components can be represented, stored and made available to the user. A user interface is provided to guide the user in handling the parts to eventually assemble them into a new system. This paper presents the current status of the modular components, the resulting combination possibilities and the planned performance demonstration scenario, as well as results of the initial functional tests.

Key words: modular robotics, space robotics, standard interconnect, space joint, computer-aided system design.

1. INTRODUCTION

One of the dilemmas of manned and unmanned space missions is the logistical challenge of payload transport. In addition, in situations or extra terrestrial environments where human life is at risk or where human capabilities are not sufficient, robotic solutions are preferred. For long-term exploration missions beyond the Earth, robotic systems are already used. So far, mainly large, complex rover systems such as the Perseverance Rover on Mars have been used [1]. Such robotic systems have been specially adapted to the relevant task and are not planned to be used elsewhere after the task is completed. By establishing modularity in a robot, the system can not only be adapted to the various tasks through out the mission, but reusability for further missions is gained. The Modular components as Building Blocks for application-specific configurable space robots (MODKOM) project considers robot components as standardized building blocks and builds the robot composition from these building blocks. This approach of building a toolbox allows for systems to be configured and reassembled

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according to the missions. MODKOM aims assurance of success in mission-critical situations such as interchanges, upgrades or maintenance requirements, as well as to save and reuse resources. So, one of the main goals of the MODKOM project is to build a scalable toolbox consisting of modules that can be considered as the main components of the robotic system. While these standard modules are provided individually, a software toolbox is also being developed to simplify the process of designing and assembling modular robotic systems in such way that less expert knowledge is needed, and tedious tasks become less error-prone [2].

This paper provides an introduction to the MODKOM project goal and the robots subsystems developed, focusing especially on how hardware models are designed and handled. It gives an overview of the modular design idea of the robot building task with the hardware and software toolbox developed within this project and the current state of the modular components, the resulting combination possibilities and the planned performance demonstration scenario, as well as the German Center for Artificial Intelligence (DFKI) X joint motor and manipulator arm as a layer of the subsystem and system components.

2. MODULAR COMPONENTS

Manipulator arm

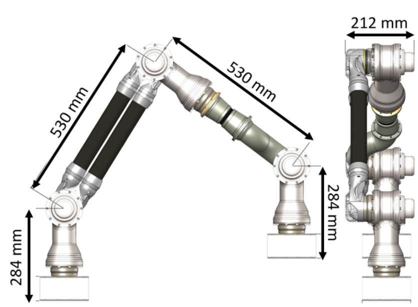


Figure 1: Manipulatorarm with its dimensions

As one of the core elements, a modular manipulator arm is developed. The design here directly follows the toolbox systematics, so that the manipulator is constructed from various functional units. The core modules are modular robot joints, each of which is combined into a 2 DOF pan-tilt unit. These are connected to each other to form a 6 DOF arm. The link lengths can be adjusted according to the application, so that the necessary work space can be configured during the design. Carbon tubes, which are designed in variable length, are used to connect the drives. For the application of use of involved systems a link length of 530 mm was chosen, which connects three pan-tilt units. This results in a total length of 1486 mm between the base and end flanges (see Fig. 1). However, this is variable and can be adapted to the task by the length of the carbon tubes. For both purposes, end effector and manipulator base, the arm is equipped with an active EMI-MOD on both sides. This allows the location of the manipulator to be changed during operation by bridging over from EMI-MOD to EMI-MOD and even changing the deployment system. In order not to limit the payload capacity after a change of position, the base and wrist joints are designed identically. This also avoids preferential orientation of the manipulator and provides maximum deployment flexibility. In addition, equipping the arm with two EMI-MODs allows the system to be fully integrated into the modular tool kit, creating a stand-alone system module for reconfiguration.

DFKI-X Direct Drive (X2D) Joint

As stated in [2] a part of the modules will be a continued development of the DFKI-X joints [3]. For several applications, like walking robots, gimbals or for fast sensor stabilization, a direct or quasi-direct drive electric motor unit is beneficial because of its high dynamic motion capabilities. However, the focus on the developments presented in this paper is on the use in a locomotion system for legged robots. This kind of locomotion is new in the field of space exploration systems, and could be the decisive step ahead for reaching points of interest in the roughest environments [4].

More than in the conventional direct drives designs, the efficiency under electrical and thermal aspects poses a challenge for the design of dynamically walking robots for space [5]. That means there is a need to find a good trade-off between high mass-specific torque, the impact mitigation capability and motor efficiency. However, optimization for high, mass-specific torque and impact mitigation capability inevitably leads to a design of actuators that operate at the physical limit and have high dissipation. Addressing this challenge, there are two ways to achieve a more efficient operation; (i) The reduction of linear power losses by choosing a larger motor with a higher motor constant as described in [5], (ii) to increase the gear ratio what means to get negative effects on the impact mitigation capability of the direct drive.

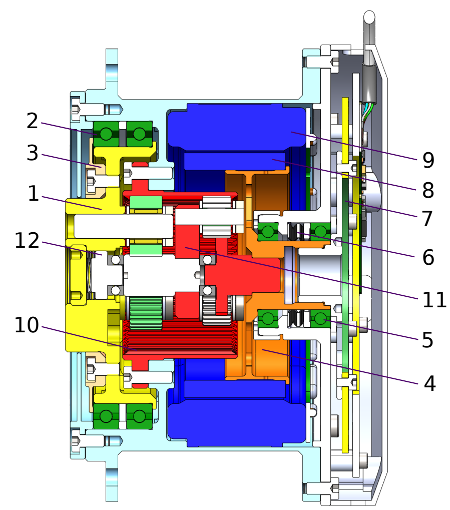
Fig. 2a and Fig. 2b show the current design of both variants of the DFKI-X2D joints, which are both designed as quasi-direct drives. To minimize bearing friction, both joints outputs are equipped with angular SBB ceramic slim section bearings. The pre-load on the output will be applied by a diaphragm spring. Since an absolute output shaft encoder is not necessary for an application in a legged robot, we reduced the design to one encoder for commutation. For this purpose, the VLP series from Netzer-Precision was included in the design. However, the VLP-100 will be replaced by the smaller VLP-60 in following iterations after radiation testing by the manufacturer is completed. As the first iteration is for testing the motors and gearbox combinations, housing and structure have still potential for further mass reduction. Both designs are made for short live time ($T_{live} < 10h$), what effects especially the gearbox selection cause both operating on to the maximum limit.

The in-runner Fig. 2a consists of a ILM 85x23 RoboDrive motor with a HPGP-14A-11 double staged planetary gear (ratio 1:11). Realizing a fixed mounting of the inner stage holder of the gear box led into adding two axial bearings pre-stressed by wave springs from Febrotec. Nevertheless, it must be shown in vibration tests whether this solution can prevent the middle stage holder from acting as hammer on the rotor bearings. As rotor bearings standard SBN steel bearings were used due to delivery time issues with GRW ceramic spindle bearings, which are worth mentioning for a more performed version. The pre-stressing of rotor bearings are realized by Febrotec wave springs. The design can be modified by replacing the gearbox with a HPGP-14A-15 double staged planetary gear (ratio 1:15), to test the function with an even higher reduction. This results in lower power losses and a maximum current at 50Nm that is closer to that of the out-runner. At the same time, it has negative effects on the impact mitigation and dynamics of the joint. Both variants must be compared experimentally.

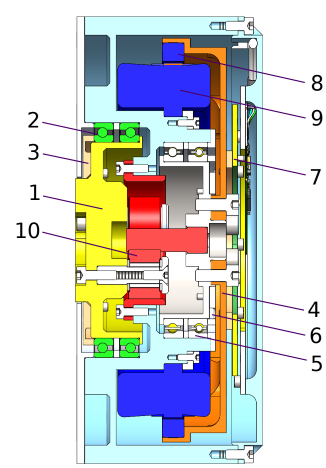
For the out-runner Fig. 2b the TA095-058 from Fischer Elektromotoren (similar to Halodi REVO1), which was optimized to obtain a higher torque-to-mass ratio , was replaced by an slightly adopted design by the manufacture. At the cost of increased mass and in favour of efficiency we choose to use a higher motor diameter resulting into around 100g of extra mass to reduce linear power losses which could be realized by a motor of type TA115-080-006. The gearbox will be an customized HPN-14A angular toothed planetary gear with a ratio of 1:7. Due to the high lateral forces applied to the sun gear, the rotor bearings had to be designed much larger as in the the case for a straight toothed gear. Here also SBB ceramic slim section bearings were used. Thus, for the next iteration, it is an open point to investigate effects of the angular tooth on the inner friction depending on load and then adapt the gearbox design.

As described in [2], we have designed both variants and will test them to practically investigate the benefits of each. Fig. 3 shows, based on theoretical values, the assumed linear power losses of both variants. Friction and gap losses were initially disregarded as they only play a minor role ($< 10\%$). The reflected inertia, critical for the impact mitigation of both variants are compared in Table 1. Despite of the differences in the gear ratio, the reflected inertia after the gearboxes could be held on a similar level due to design effects between in and outrunner. However, we see that due to friction and cogging the controls will be more challenging then that of the classical out-runner.

Both designs are being integrated and prepared for testing within to the end of 2023. Table 1 sums up the basic performance values of the DFKI-X2D joint approaches.



(a) DFKI-X2D in-runner concept



(b) DFKI-X2D out-runner concept

Figure 2: Both concepts to be evaluated for the DFKI-X2D joint. *1:* output shaft, *2:* Output bearings, *3:* diaphragm spring, *4:* rotor holder, *5:* rotor bearings, *6:* rotor pre-stress spring, *7:* encoder, *8:* rotor, *9:* stator, *10:* gearbox, *11:* middle stage holder, *12:* middle stage pre stressing

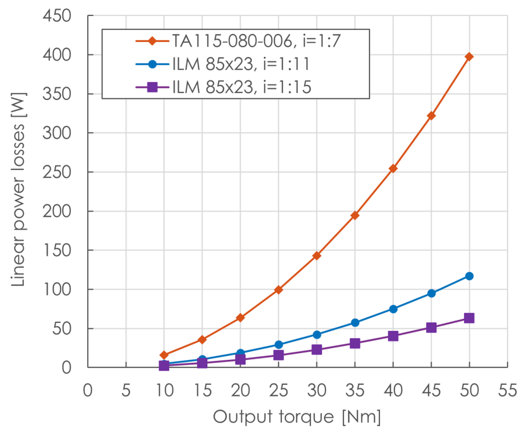


Figure 3: Calculated linear power losses from 10 to 50Nm at 20C°. It can be seen that in both versions the in-runner has a significantly better efficiency as the out-runner. Friction losses are not included.

Table 1: Characteristics of the two DFKI-X2D joints approaches. The values are based on first calculations with manufacturer's data.

Motor properties	In-runner	Out-runner
Gear ratio	1:11 / 1:15	1:7
Mass [g]	1340	1530
Reflected inertia [$\frac{kg}{m^2}$]	0,021 / 0,025	0,024
Max. torque [Nm]	50	50
Output speed [rpm]	157 / 115	146
Supply voltage [V]	48	48
Current @50Nm [A]	19,8 / 14,5	16,5
Encoder type	VLP-100	VLP-100
Communication type	CAN	CAN

EMI-MOD

For reconfiguration on system module level, the application of one or more multifunctional interconnects also called as electro-mechanical interconnect MODKOM (EMI-MOD) [6] is the baseline for the toolbox systematic. The EMI-MOD, as shown in Fig.4 consists of an active and a passive part. While the active (and female) part contains the locking mechanism along with interface/module management electronics, the passive side provides pins for mechanical guidance and marker for visual servoing purposes. Once connected, the interface enables the transfer of physical forces as well as energy and electronic information between the two subsystems or from the subsystem to the user modules or tools. The predecessor EMI[7] is developed for planetary exploration purposes, enabling its use in environments with a high dust load. During the course of the MODKOM activity the locking mechanism and mechanical guidance are improved, based on lessons learned during extensive use within a Mars analogue environment in the desert of Utah[8]. Furthermore, a commercial multifunctional interface will be implemented into the toolbox, as a proof-of-concept. Here, the iSSI© by iBOSS GmbH[9] will be integrated. For the toolbox demonstration, it is envisioned to implement an adapter between EMI-MOD and iSSI© to demonstrate the full integration and extension of the toolbox with already existing modular components.

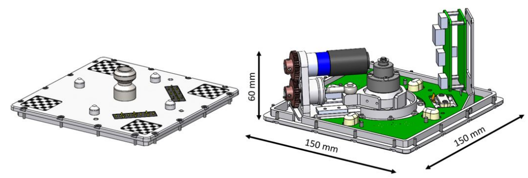


Figure 4: Passive EMI-MOD (left) and active EMI-MOD (right)

All involved systems will be equipped with at least one EMI-MOD to enable (re)configurations between them.

Base modules

The base module is an object Electro-Mechanical Interconnect MODKOM (EMI-MOD). It therefore serves as a demonstrator for the capabilities of the toolbox concept with regard to (offline) configuration and (online) reconfiguration, using electronic modules and a structural frame design based on a parameterised model. It also fulfills the function of an object that the mobile platform can interact and exchange payload items with, using the manipulator.

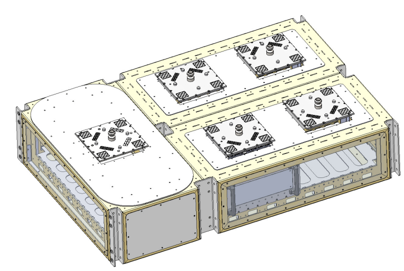


Figure 5: Three combined base modules

Figure 5 shows three combined base modules. One base module is a basic structural unit from which larger structures and systems can be built by combining several modules. Here, individual basic modules can be combined horizontally and vertically with each other via connection profiles and theoretically extended indefinitely. At the same time, the basic module is the carrier platform for the electronic modules and other mechanical modules, such as motors, sensors or EMI-MOD. By adding EMI-MOD additional payload modules can be accommodated and data transfer to them can be established. The width (300 mm) of the base modules is exactly half their length (600 mm). The height is 180 mm. This

60 mm basic grid is also used by the plug-in modules.

Payload modules

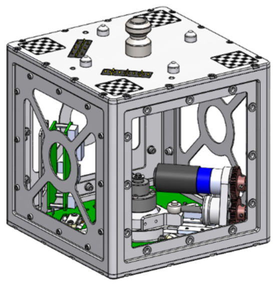


Figure 6: Basic structure of the payload module

The modular payload modules are based on previous developments, as described in [10]. They combine two EMI-MOD (active and passive) with a standardized payload container. This allows to easily add new function blocks for system extension and reconfiguration into the toolbox (see Fig. 6. For the proof-of-concept demonstration it is envisioned to implement three distinct payload items, each representing an individual application on the reconfiguration layer.

As for now three different payload modules are foreseen. A Processing and Communication Module, which will be equipped with an on-board computer and mesh capable communication module. The module can therefore be used to gain additional processing power on a given system, e.g., for preprocessing of high demanding sensor data streams. The additional mesh capable communication module enables to integrate the payload item into a given communication network and even extend it, as soon as a new system entity is formed. A stereo camera module with integrated gimbal for image stabilization is planned for system reconfiguration purposes, by combining the module with the modular manipulator to create a camera mast and mobile platform, to extend the functionality of the system. And a Environmental Sensor and Power Module. This module consists of various environmental sensors for different gases, temperature and humidity and holds its own battery pack to act as a range extender or to provide power for a new system entity.

Third-party components

An important aspect is to keep the modular system open for already existing third-party robotic components. To cover this aspect for the performance demonstration, a commercial mobile robot platform is introduced as a system module. This is integrated into the module systematics on the hardware side by means of EMI-MODs and must also be integrated into the module framework on the software side accordingly in order to serve the operational and reconfiguration tasks. For this purpose the rover HUNTER SE from generation robot is chosen (Figure 7).

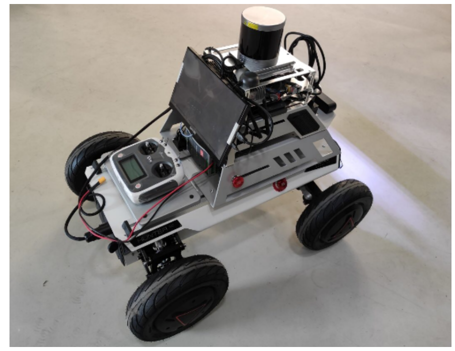


Figure 7: Hunter SE from generation robot

3. SOFTWARE REPRESENTATION

To deal with the described hardware modules on the software side. Two representation layers have been established. On the general layer only the very basic hardware module is represented as an entity with a number of defined interface types. For this, the so called XTypes defined in MODKOM are used. XTypes split up in *ComponentModels*, a general type definition for a sort of entities, that can also consist out of mulitple *Components*. The connections between these *Components* are drawn between there *Interfaces*. Each *Interface*'s type is defined by it's *InterfaceModel*. E.g., the modular manipulator would be a *ComponentModel* which consists out of the atomic *Components* pan-tilt units, a straight link and a curved link. Those parts are interconnected by their *Interfaces*, the flanges. The *InterfaceModel* ”ModularManipulatorFlange” describes the type of this Interface. Once such a *ComponentModel* is defined it can be used to instantiate *Components* from it in bigger ComponentModels e.g., Hunter SE[1], a mobile platform as rover and a modular manipulator which are connected via interfaces of the Electromechanical Interface (EMI)-*InterfaceModel*-type. For each *Component* there exists an *ComponentModel* that defines its type, no matter whether atomic or not. All these representations are stored in a database, to be available for reusage.[11]

However, for the atomic hardware representations, their *ComponentModels* are annotated with an *ExternalReference*. Those references hold information on the details of the hardware. This can have any form, e.g., data sheets, manuals or simula-

[1]https://global.agilex.ai/products/hunter-se

tion/control models. The latter build the layer of more detailed, physical hardware representation.

Through those references, *ComponentModels* can be linked with an ontological description of the model MoreOrg, which is stored in a separate ontology-database within the software-stack. Descriptions for new *Components* and respectively *ComponentModels*, can either be copied, adjusted or added from the database. They get automatically instantiated with the related hardware properties, contained in the data sheet of a new *Component*. After the virtual assembly of a robot is done, an accumulated ontological model of the new system can be created, which is then stored in a reference directory and is also included into a later deployment of a robot. This application specific model can then be used to plan the mission of the systems, including possible reconfigurations of the hardware.

Whenever an user wants to add a new atomic hardware representation. They will use the MODKOM software tools to create and deal with those representations. In this case the user would start with the tool Phobos[12] which is a Add-on to the open-source software Blender. Phobos allows the user to create and annotate a simulation/control model of the hardware including its kinematic structures, visual appearance, collision representations, masses and intertias etc. Also all the data that an CAD export does not allow for can be annotated to the model: Sensors, Interface information, defining parallel kinematics and any other generic information.

Once this model has been created the user may put this model into a Git repository. Then MODKOM software tools come also with command line tools. In the evaluation setup of MODKOM, these tools are used in a CI-pipeline to automatically go through all those model repositories to create and maintain their corresponding *ComponentModels* and *ExternalReferences* in the database.

Then when it comes to designing a modular robotic system the user can rely on the database to select the parts they want to use and create a new *ComponentModel* for their system. To facilitate the composition of the parts the tool Deimos helps the user to specify which part is interconnected by which interfaces to other parts. Deimos is a 3D-Web-GUI that displays the visual representations of the parts and let's the user specify in a WYSIWYG (*„what you see, is what you get“*) workflow how the connected Interfaces are oriented with respect to each other.

This assembly is then stored to the database and can be used in other ComponentModels e.g., it can be reference in software-ComponentModels. This way the described software modules can use the hardware representation to include it in there configuration.

During the deploy step, regarding the hardware integration the deploy tool of the MODKOM toolbox then takes care of two steps: From the fully defined hardware representation, a command line tool of Deimos and Phobos generates a joined simulation/control model representing the complete assembly. Consecutively, the deploy tool then resolves the references in the software configurations to the correctly assembled overall hardware representation.[11]

4. CONCLUSION

The previous sections give insight into the formulation and creation of a modular building block system, that incorporates specially designed modules based on the general modular toolbox systematics as well as industrial third-party components. The overall toolbox systematic is outlined, explaining the underlying top-level requirements, level of module granularity and system decomposition as well as the software architecture, enabling the actual operation of all modules in the end.

The mentioned systems like manipulator, base module, payload module and the third-party rover can be connected together via the EMI-MOD to fulfil the task requirement during a mission scenario.

The development of all systems has been completed. EMI-MOD and DFKI-X2D Joint are in the iterative improvement phase after preliminary tests. They will be further manufactured and integrated in the next project step in MODKOM.

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