Development of an articulating mechanism for sensory and in-situ LIBS applications on rover platforms

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The University of Stuttgart's Institute of Space System's space robotics group is researching the technical implementation of deploying instruments onto planetary surfaces for in-situ measurements and analysing the surface's chemical composition by laser induced breakdown spectroscopy (LIBS). In a joint project with the German Aerospace Center's Institute of Optical Sensor Systems in Berlin an instrument mechanism capable of performing these tasks was initiated. The DLR Institute of Optical Sensor Systems (DLR-OS) develops and provides the ARCHES LIBS instrument for in-situ measurements [1], while the University Stuttgart (US) provides the mobile surface element (rover platform) and develops the actuated Instrument Mechanism (IM). This mechanism handles the deployment of the LIBS instrument and places it on the sample of interest. This project enables close cooperation and connection between the two institutions and pursues the goal of bringing together the research fields of in-situ scientific instrumentation and mobile space robotics. This paper briefly describes the LIBS instrument, the current state of the mechanical, electrical and software development and the implementation of the IM.

The IM is a two degrees of freedom (DoF) mechanism which carries and positions the instrument over a sample. It is mounted to the Modular Rover Chassis Platform also developed at the US [2] (Figure 1). The mechanism consists of a lever, two actuators which raise and lower the lever and rotate the instrument. This setup reflects a simplified robotic manipulator with two DoFs, thus modelling can be performed similarly, however this design allows for simpler kinematic calculations and control. The development is supported by student theses, this allows the students to participate in cooperative, frontline research projects.

1. System Requirements and Constraints

All design work aims to adhere to the requirements and constraints defined at the start of the project. These include size, mass, electrical power and harness constraints, interface and environmental requirements, but also load requirements for carrying and operating the instrument.

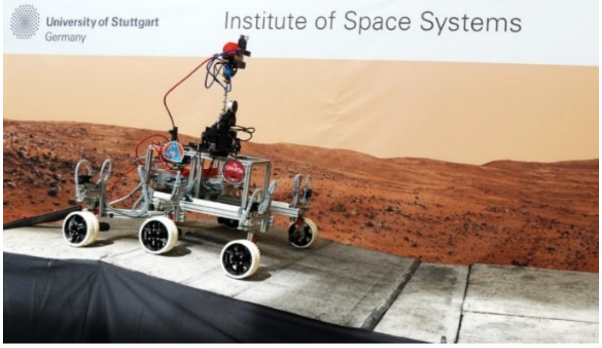


Figure 1: IRS Modular Rover Chassis Platform during testing of student designed on-board sensory packages.

The mechanism is to be mounted on the MRCP, a 6x6x4 rover platform, meaning it has six-wheels, all six wheels are powered but only the four outer wheels are used for steering. This allows for differential and Ackermann steering and point turns. The rover platform also features a reconfigurable locomotion suspension system, resembling a passive rocker bogie concept, This reconfiguration feature allows manipulating the major locomotion parameters to fit the current mission profile and changing payloads. The MRCP weighs in at 18.5 kg. [2] To not infringe on the rover's performance and structural loads, the IM's mass is limited to 4 kg. The rover provides a 200x200x263 mm³ volume inside the chassis' front for mounting payloads. Additional mounting areas are available on the rear side and can be used to calibrate the overall centre of gravity. Power is provided by the rover in the form of two power busses, an unregulated 12-15V bus and a regulated 24V bus, with the total power output limited to 15 Watts. As this project intends to bring forth a technology demonstrator on Earth, the environmental conditions to endure were initially defined to be compatible to COTS components (-10°C to 40°C temperature range, sealed against dust particles and humidity). This would allow the mechanism to be tested not only in a laboratory environment but also space analogons on Earth, which is intended in the future. As the LIBS instrument includes a class 4 laser device, specific safety measures were to be implemented to shield bystanders from laser radiation during measurements. This could be achieved in multiple ways (structural changes: baffle; operational constraints: multiple safety layers to activate laser, constraints on the instrument orientation). The instrument consists of distributed components (instrument head, laser pump, spectrometer) which are connected by optical cables. This introduces the constraint of keeping the cable's bending radius above 50 mm.

The choice of hardware components, e.g. motors and controllers, also introduced component specific software and interface requirements, such as the need for CAN-bus and CANopen compatibility. Specific software features required include inverse kinematic calculations and ample safety features based on the system's live feedback. During the development, further software requirements appeared, such as the need for simulating hardware components and system responses which would allow Hardware-in-the-Loop (HIL) testing, without risking damage to the real hardware. Optional features include a presentable user interface and visual output of the mechanism's joint configuration.

All consecutive design iterations of the system considered the reuse of already implemented mechanical, electrical and software interfaces to simplify the design. Implementing safety features was viewed as particularly important to ensure safe laser operation with respect to the rover platform and bystanders during attended ground testing.

2. DLR LIBS Instrument

Laser induced breakdown spectroscopy (LIBS) allows elemental analysis of ground samples by ablating a small amount of surface material by pulsed laser radiation, creating a high-temperature plasma and analysing the emitted light. As every element on the periodic table emits specific spectral peaks, the ablated elements can be deduced from the measured spectrum. The German Aerospace Center's (DLR) Institute of Optical Sensor Systems developed the ARCHES LIBS instrument for in-situ measurements from on-board the DLR's LRU2 rover platform. This small sized instrument is built from COTS components, weighs approximately 1 kg and is positioned close to the sample for measurement. It can detect typical elements in rock-forming (silicon, calcium, sodium, potassium), minerals as well as trace elements (hydrogen, lithium). [1]

3. Project Goals Analysis

The overarching goal is to implement a technology demonstrator, compatible with the US's MRCP and capable of storing and deploying a scientific instrument from on-board the MRCP, however with no intention of qualifying the demonstrator for space applications at this stage. Thus, the project is conducted on a prototyping level, using rapid manufacturing techniques (FDM), commercial-off-the-shelf (COTS) components and easy to implement robotic software frameworks. In later stages, a switch to machined parts and space qualified hardware could still be considered. The MRCP system is optimal for this type of research as it features a highly modular chassis capable of interchanging components such as payload mechanisms and instruments. In addition to the research described in [2], this project allows further testing and modelling of the rover's performance parameters while a subsystem of significant mass is mounted to the chassis. The main focus of the inter-institute cooperation is to provide another platform and use case for implementing the ARCHES LIBS instrument (besides LRU2 [1]), as well as the in-house development of an instrument mechanism, its integration, operation and testing. This provides the additional mission profile of a deployable scientific instrument to US's MRCP. The DLR's ARCHES LIBS instrument is being developed in parallel to the mechanism described in this paper. This project shall further provide a research and development platform at the US, giving insight into the development procedures of manipulator systems.

The design problems to overcome and questions to be answered were separated into the categories of structural, electrical and software design, as well as the topic of control and feedback which encompasses both the electrical and software design. Choosing a simple but sturdy mechanism with optimal kinematic characteristics for dexterity was the main driver for the structural design. This included coming up with the most suitable mechanism capable of manipulating a 1 kg payload. However, the mechanism must be manufacturable in-house using COTS components. Implementing a functional PCB mainboard containing all required electrical hardware and sensitive components and enclosing it inside an electronics box (E-box) was the main driver for the electrical design. This E-box should be self-contained by regulating incoming bus voltages, and provide all necessary interfaces to connect to components on the outside (e.g. motors, sensors). Due to the research, development and demonstrator nature of this project, openly available software frameworks were viewed as most suitable to develop a preliminary control software. Thus the focus was placed on the easy to use ROS2 framework to be able to introduce students to the field of space robotics software. The topic of control and feedback was to include a kinematic model able to calculate joint configurations from a target position and orientation (inverse kinematic model), hardware interfaces to control joints and read sensors, as well as supervision of the diverse feedback data. The kinematic model should output valid trajectories to not violate the mechanism's configuration space (C-Space). For the feedback system a diverse set of sensor elements should be conceived and implemented to be able to detect and supervise the joint motions. This allows precisely positioning the payload, as well as implementing procedures for safe operation. The feedback data should also be visualized for the user.

4. System Concept and Overview

First, several kinematic concepts were analysed, the final design resulted in a 2-DoF lever mechanism. Such an articulating mechanism capable of manipulating a 1 kg instrument requires a particularly sturdy structure and gearing, especially when transitioning from rest in a high load configuration to movement against gravity. For this, the joints consist of a DC motor with a two staged gearing each, with the gear ratio adapted for each joint.

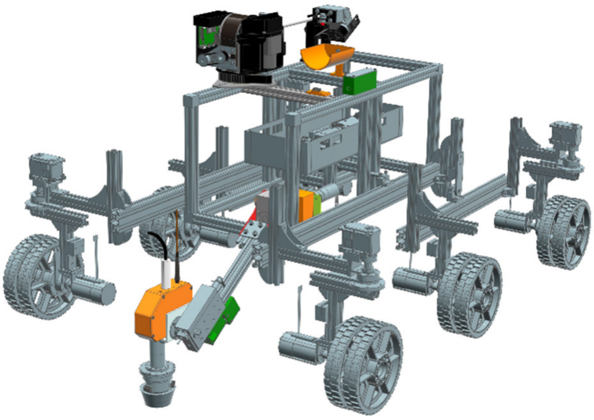


Figure 2: CAD analysis for determining performance parameters, harness specifications, as well as kinematic constraints. The lever mechanism is mounted to the front of the MRCP. [3]

For monitoring and feedback of the mechanism, several use cases for sensor elements were conceived and implemented. This includes motor encoders, tactile sensors, end-switches, time-of-flight (ToF) sensors and inertial measurements units (IMU). Operated and analysed in unison, these elements allow perception of the mechanism in relation to its surroundings. This allows correct positioning of the instrument and protection against unfavourable or prohibited joint configurations.

Particular constraints were introduced by the optical cables which are available only in specific lengths and with large bending radii. As these constraints are in opposition (large bending radii require longer cable routings), the design must to be compact, yet allow sufficient movement of the optical cables.

5. Mechanical Design and Implementation

The mechanical design process started by analysing different kinematic concepts for moving and placing the LIBS instrument by varying the articulation mechanisms and degrees of freedom. This ranged from simply lowering the instrument onto the sample after positioning the rover above it, front and sideways actuation and lowering as well as robotic manipulators with varying DoFs. The trade study also took design aspects for space applications into account by highly grading simplistic but versatile solutions, this resulted in a 2-DoFs lever configuration as the optimal design choice. The lever is actuated by two DC motors, both geared down using planetary gearboxes and worm gear drives. This configuration was chosen to prevent back-driving of the mechanism and damaging the planetary gearboxes and motors. Feedback is provided by incremental encoders on the motor shaft. This required the gearing to be very precise in order to minimize play. Figure 2 shows the CAD design of the IM mounted to the MRCP. This was used to analyse the performance parameters, such as the IM's reach below the wheels, the harness length and bending radius, as well as to extract kinematic constraints, such as limit angles.

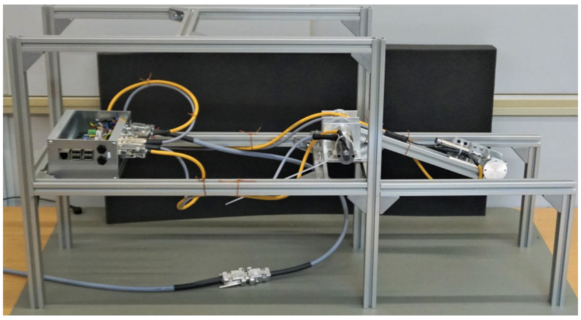


Figure 3: Test bench assembly with lever mechanism and actuators (right), electrical box (left) and harness.

Figure 3 shows the breadboard model within a test bench assembly. This includes the lever mechanism with the motor and gearing assemblies (right), the electronics box housing the OBC and motor controllers (left) and the preliminarily routed electrical harness.

Subsequent work covered multiple safety features which required the design of additional structural elements and the implementation of specific sensory elements. End-switches are mounted to the rover chassis to register collisions and initiate stopping of the mechanism. One additional structural element that provides both safety and operational features is a baffle mounted to the LIBS instrument. Besides shielding the laboratory environment from intense laser radiation the baffle also provides tactile feedback when in contact with the ground sample. This positions the laser instrument at the correct focal length when the tactile sensors are triggered. The baffle's contact element is spring loaded and triggers multiple tactile sensors positioned around the baffle, which introduces redundancy to this vital sensory component. During the baffle's design, different tactile trigger concepts were analysed of which two designs were implemented as prototypes and tested. Both consist of spring loaded trigger mechanisms for resetting the tactile switches, while keeping the trigger force low and the trigger point stable. One design implements four locating bolts, springs, linear bearings and tactile switches (Figure 4, left), the second design consists of a central hollow shaft with a linear bearing, a single spring and three tactile switches (Figure 4, right). The spring mechanism is designed to also prevent triggering of the tactile switches due to gravity in some joint configurations, once the contact element is machined from aluminium. Testing of these prototypes revealed the single hollow shaft to perform more reliably. The low manufacturing precising of FDM parts did not allow for smooth motion of the four locating bolts and resulted in locking. Thus, the first concept should be tested on a more precisely manufactured baffle model. Until then, the hollow shaft concept will be used for further development of the IM.

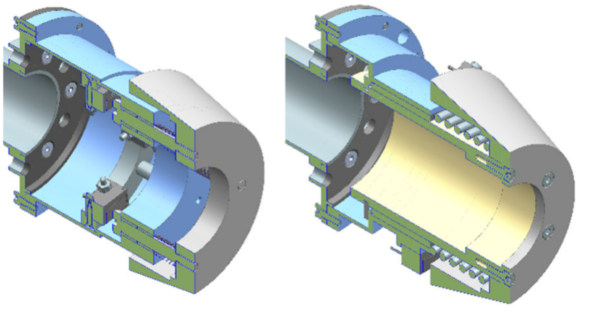


Figure 4: Cross section view of the two tactile feedback concepts (left: tactile head mounted to locating bolts and springs; right: single hollow shaft and spring).

Further sensory elements such as an inertial measurement unit (IMU) and a time-of-flight (ToF) sensor were also implemented. The IMU allows calibrating the incremental encoder of the second joint motor at start-up by moving to a predefined angle and resetting the encoder count. Once calibrated, the encoder and IMU work in parallel in determining the orientation of the instrument head. This allows for compensation of gearbox play by means of sensory feedback. In addition to the baffle's tactile feedback, a ToF sensor is implemented on the instrument head to determine the distance to the ground. This allows the kinematic model to adapt the joint velocities depending on the remaining distance to the planetary surface. The added components increase the safety of the system by providing sensory feedback to detect contact with the environment and rover, determine the orientation of the instrument using the IMU and measure the instrument's distance to the ground by ToF sensor. Figure 5 shows the assembled dummy instrument, baffle and sensor unit.

The current mechanical design results in a mass of 5 kg, already including switching to machined parts from aluminium. This exceeds the previously stated mass requirement, however so far only performance optimizations but no mass optimizations of the mechanism have been conducted.

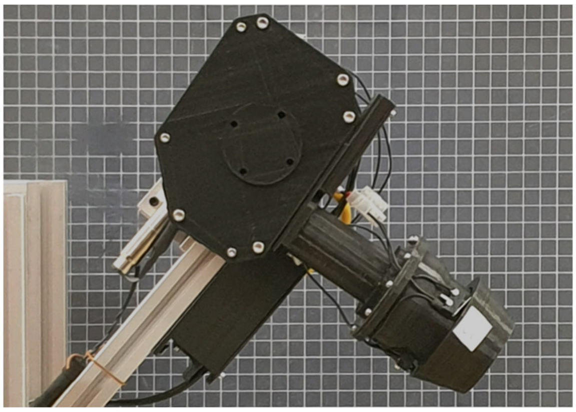


Figure 5: Instrument dummy mounted to the second joint (centre); Functional baffle prototype and contact element (bottom right).

6. Electrical Design and Implementation

The electrical system consists of a printed circuit board (PCB) on which all electrical components are mounted (voltage regulators, OBC, motor controllers). This allows for a small-sized electronics box (E-Box) shown in Figure 7, while increasing the reliability of electrical connections compared to typical prototyped electronics. Besides the major electrical components, the E-Box also houses the CAN-bus interface board to communicate with the two motor controllers, as well as a RS232 interface for backup and redundancy. The E-Box receives electrical power from the MRCP and provides all necessary interfaces to the external hardware (USB, SSI and power to actuators). Internally, the CANopen protocol is used to communicate with the motor controllers over CAN-bus. As described above, additional sensory elements were added (IMU, ToF, tactile sensors) for calibration purposes and to increase safety and autonomy. These sensor elements also interface with the OBC through a microcontroller connected over USB. Figure 6 gives a brief overview of the electrical component groups and their interfaces.

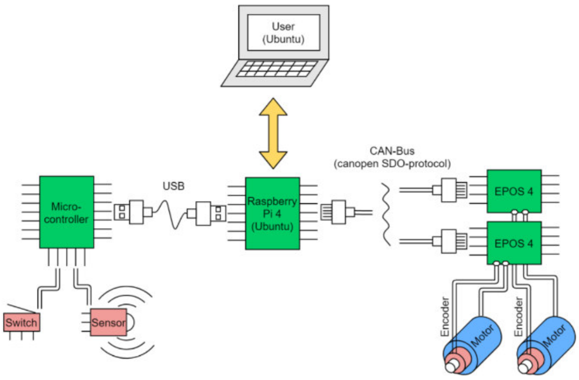


Figure 6: Topological diagram including the User PC, OBC, motor controllers (right) and sensors (left).

The COTS components used for fast prototyping include a Raspberry Pi 4B with a CAN-bus shield for the OBC and Maxon EPOS4 for the motor controllers.

Figure 7: Electronics Box Assembly housing the OBC and motor controllers.

The electrical design resulted in an operational electronics box, the CAN-bus interface and CANopen protocol is functional and can be used to control the actuators. The additional sensor elements were also implemented successfully on a breadboard level.

7. Software Development

To control the mechanism's movement for deployment, orientation and subsequent storage of the instrument, a control software was developed. For this the robotics framework ROS2 was used which allows easy software development of robotic control and perception features. The resulting software architecture is shown in Figure 10. It receives user input, performs the control algorithms and handles the communication with the two CANopen motor controllers. Instead of interfacing with the real hardware, the software is also capable of simulating the two actuators and tactile sensor elements. This simulation was kept on a simple logic level as its purpose is to test different control algorithms without the risk of damaging the hardware. The simulation consists of multiple ROS scripts, each simulating one device (Figure 10, cyan backed elements). This concept is very modular and can be adapted to using more sophisticated models for a more realistic system response.

Inside the architecture the data exchange between nodes is standardized using ROS topics and services. This allows for modularly interchanging nodes, e.g. switching from simulation to real hardware. The current control algorithm is made up of predefined sequential states of joint configurations specific for every command input. This results from the kinematic concept of moving within the convex set of joint configurations. This allows for simple transitions between configurations as linear transitions inside convex sets ensure no exiting of the C-Space. This simplifies the motor commands as they can turn with constant velocities between configurations. As the mechanism prescribes specific kinematic constraints, the storage and deployed configurations do not lie within a single convex set. Due to this, an "All Access" point was defined which lies inside both convex sets, thus this point allows transitioning between these sets of configurations. This "All Access" configuration is always transitioned to once for every command input. The kinematic calculations are also kept modular by storing the mechanical dimensions in a configuration file, this allows easy adaption of the software if hardware changes occur.

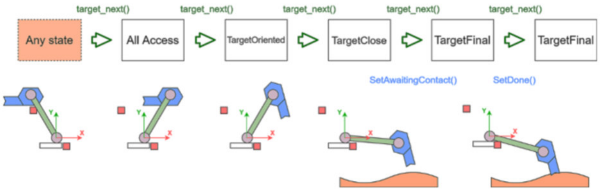
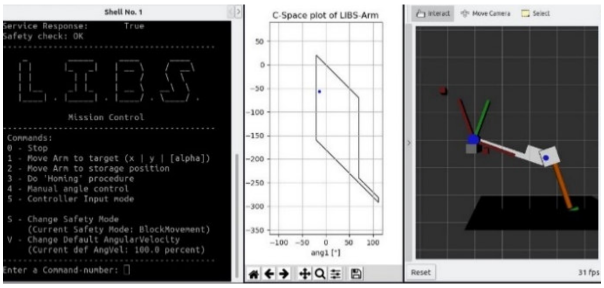


Figure 8: Example of predefined states for the targeting sequence.

Figure 8 shows the target sequence and its individual operational states dependent on the IM's configuration at which the behaviour of the system changes. The software architecture implements the concept of device handlers representing the interface between the abstract software architecture and the hardware by managing the communication with the specific hardware components. These handlers receive generic data from inside the architecture and access the OBC's I/O ports to communicate with the hardware. Thus the device handler must translate from generic data to a hardware specific data stream. This design also allows for a simple exchange of nodes in case the hardware configuration changes, or porting the software to systems with different hardware components. This includes the multiple device handlers and device simulators, but also nodes such as user I/O and kinematic simulators and solvers. Results from the software development include a simple user interface allowing the input of commands, real-time visual output of the lever configuration, error detection, rejection of erroneous inputs or in case of collision or constraint violations, simulation of the lever mechanism and all involved devices as well as reliable communication using device handlers and the CANopen protocol. Figure 9 shows the software user interface allowing user input and hardware response output in the form of a C-Space graph and 3D model animation of the mechanism. [4]



```
Service Response:        True
Safety check: OK
-------------------------------------------

           Mission Control
-------------------------------------------
 Commands:
 0 - Stop
 1 - Move Arm to target (x | y | [alpha])
 2 - Move Arm to storage position
 3 - Do 'Homing' procedure
 4 - Manual angle control
 5 - Controller Input mode

 S - Change Safety Mode
     (Current Safety Mode: BlockMovement)
 V - Change Default AngularVelocity
     (Current def AngVel: 100.0 percent)
-------------------------------------------
Enter a Command-number: 
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Figure 9: User interfaces for command input and kinematics visualization (C-Space and 3D model). [4]

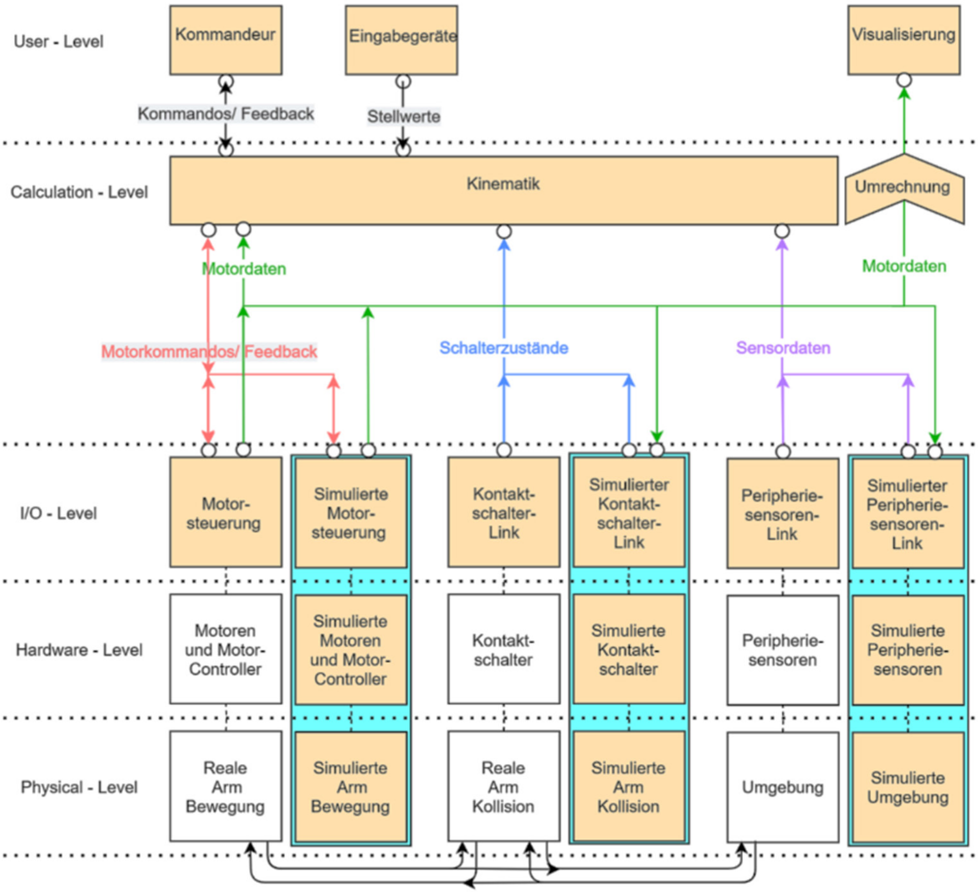

Figure 10: Software architecture for control and perception, also including simulation nodes (cyan). From the bottom to the top the software system becomes more abstract using standardized ROS messages and services. [4]

8. HIL and Bench Assembly Testing

As described in a previous chapter, software simulations of the actuators and sensor elements were implemented, this allowed for hardware-in-the-loop (HIL) testing of the control algorithms. However, as the purpose of the simulation was solely testing the controller logic and the underlying algorithms, the simulation models are also only logical (forward kinematics) without dynamic physics simulations. For example, the actuator simulation only describes linear movement and does not include response delays or s-curve transitions of motor rpms. The subsystems implemented in HIL are the joint actuators, tactile sensors, end-switches and IMU. Despite this rather low depth of details, the HIL simulation allowed the detection of software bugs, and testing and optimization of the control logic. Additionally, the HIL simulation allows running the software on a PC for demonstrational and educational purposes by visualizing the IM based on the simulated feedback data. Finally, the control software was run on the test bench assembly's OBC which then interacted with real hardware as presented in Figure 3. These tests resulted in the application of control algorithms on the real hardware. The algorithms were previously only tuned for HIL simulations. This included commanding the real actuators, as well as reading sensor data. For testing purposes, a mass dummy of the DLR ARCHES LIBS instrument is being used. Like with HIL simulation, during real hardware tests, the incoming feedback data was analysed, visualized and used to precisely move and stop the joint actuators.

9. Results and Conclusion

This paper summarizes the development activities in-between the University Stuttgart and the DLR Institute of Optical Sensor Systems up to this point, presenting the current implementation of the instrument mechanism. This document presents a functional articulation mechanism for the specific task of deploying and positioning the ARCHES LIBS instrument as a payload on the rover platform MRCP.

To this point the prototype lever mechanism has been fully integrated and includes the changes introduced by iterations for optimizing the mechanical design. The electrical system and control software have been realized successfully. The motors have been actuated using the control software and first kinematic tests on the real hardware are currently being conducted. Further software development will include updating the kinematic model to introduced structural changes, as well as calibrating the kinematic model. Furthermore, the transition from the mass dummy to the real instrument will take place, as well as integrating the laser pump and spectrometer to the rover chassis. The on-going software development aims to implement interfaces to the camera mast subsystem to also receive a 3D depth map and integrate this information into the kinematic model.

10. References

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