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Design of a Cost-Effecive Robotic Manipulator for an Educational Mars-Analogue Rover

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***Abstract*—The BEAR manipulator is a small, multi-functional robotic arm for the Berlin Educational Assistant Rover (BEAR), developed at the Department of Space Technology of the Technical University of Berlin. Besides providing an alternative application for the Department's research activities in space hardware miniaturization and autonomy, BEAR and several other Space Rover Projects serve as a platform for educating future systems engineers.**

Deriving requirements from student challenges such as the DLR SpaceBot Cup and the European Rover Challenge, the BEAR manipulator is primarily intended for object manipulation and visual inspection tasks. The arm's five degrees of freedom are instrumented for closed-loop control and allow versatile, be it slow, interaction with the field robotics environment. Moreover, the manipulator's simple mechatronic design and control architecture streamlines integration onto BEAR while enabling the system's reconfiguration for other tasks. The manipulator is currently configured for teleoperation, but it is fully instrumented for future autonomous activities.

This paper traces the BEAR manipulator's development from a conceptual link model to ongoing AI&T activities. We describe its structural and mechatronic design, as well as its control architecture. The impact of challenging programmatic constraints typical of student projects is examined throughout the development process, with a particular emphasis on cost-effective design using limited manufacturing capabilities, and high personnel turnover.

Keywords—manipulator, planetary rover, robot, education, student research

I. BACKGROUND – ROVER PROJECTS AT THE TU BERLIN

The Chair of Space Technology of TU Berlin has engaged in planetary robotics projects for several years for educational and research purposes. Major activities began in April 2013 in preparation of the DLR SpaceBot Cup, for which the Small Exploration Assistant Rover (SEAR) was developed. The system was to autonomously explore an unknown planetary surface on a competition field, find different objects and conduct an assembly process. The SEAR team of TU Berlin successfully participated in the competition in 2013 and its iteration in 2015, as one of the only three teams to pass the official qualification process during the latter [1].

The BEAR (Berlin Exploration Assistant Rover) project was initiated in 2016 in preparation for the European Rover Challenge [2]. A competing student-developed rover system has to accomplish several tasks during the competition, ranging from navigational challenges to various manipulation tasks. The diversity of the given tasks require the rover to interact with various objects, such as switches, handles, knobs and power sockets. Different samples ranging from loose soil to small rocks have to be collected [3]. Furthermore, a robotic arm for these tasks still had to fit the overall system architecture, respecting given budgetary, power, space and weight constraints. Thus a versatile device had to be designed which can be utilized in different mission scenarios and allows the robot a range of interactions with its environment, while making use of complementary system parameters in order to minimize the manipulator’s complexity and cost.

II. DESIGN CONSIDERATIONS

The BEAR manipulator is a lightweight, 5 degree-of-freedom tele-robotic manipulator arm designed for the BEAR rover. It is primarily intended for object manipulation and visual inspection tasks in planetary-analogue competitions. The manipulator was developed by graduate students over the course of several semesters as part of a lecture series about planetary exploration and space robotics.

A. Tasks and End-Effectors

The primary tasks of the BEAR manipulator consist of inspecting and manipulating objects in the field. The initial design called only for tele-robotic operation, with the development of autonomy foreseen for a later point in time. One archetypical task driving the design consists of grasping a small rock sample – up to 30 mm diameter, 300 g and an irregular shape – and placing it in a receptacle on board the rover. Another involves grasping and rotating an electrical switch on a piece of heavy equipment.

To that end, a preliminary end-effector selection was made with plans for later refinement. The mechatronic gripper of the SEAR manipulator was selected for its demonstrated performance of this class of tasks and relatively straight-forward procurement. Since all tasks would need to be completed using only the on-board sensors for feedback, a webcam interfacing with the rover's On-Board Computer (OBC) would be integrated into the end-effector, complimenting instrumentation of individual joints.

For the archetypical tasks described above, the manipulator needed to exhibit 3-dimensional repeatability on the order of 10 mm, assuming human-in-the-loop control using only on-board instrumentation. The dynamic performance of the manipulator, however, is of little importance for its intended purpose. There is no particular emphasis on the speed with which the tasks are to be completed, and there are therefore significant advantages to operating the manipulator slowly. The resulting dynamics avoid overshoot in end-effector position, and vastly simplify the structural load models and load paths to the rover body.

B. Rover Interfaces

The multitude of interfaces between the rover and the manipulator were considered from the beginning of the design process. First, the mechanical interface to the rover body had to maximize stiffness and reliability while enabling practical assembly and maintenance. The rover OBC would interface with the manipulator over a Control Area Network (CAN) bus and provide control inputs in the form of joint positions and angular velocities, foregoing the need for path planning onboard embedded systems. Managing the harness of the various joints and sensors for the manipulator's full range of motion, however, would prove challenging.

The effect of manipulator movements on the rover also had to be considered. In order to avoid any chance of compromising the rover's stability, the manipulator may not significantly alter the Center of Gravity (CoG) of the rover at any position in its range. While the slow movement of the arm ruled out major problems caused by arm dynamics, the effect of static loads on the CoG had to be considered.

In addition, hardware interlocks were foreseen as a way to prevent the arm from interfering with its own structure. Placing interlock switches that brake the joint, cycle its power supply or otherwise eliminate torque when the arm is in danger of doubling back on itself is a robust way to mitigate operator error and increase system safety.

Finally, a power loss to the manipulator could present a risky scenario because the arm could fall from a highly extended position - damaging itself, the rover, or its surroundings. This risk had to be taken into account since the robot is to operate close to humans and an emergency stop is required to completely isolate the rover's batteries, rendering all power output to zero. One way to mitigate this risk would be the introduction of brakes on the lower joints.

C. Mass and Volume

Mass plays two key roles in manipulator design. First, weight constrains the steady-state loads on the manipulator, driving both the structural design and the minimum torque of the actuators. Second, inertial mass affects the manipulator dynamics which, given the small operational velocity of the arm, is of lesser importance.

While structural failure clearly presents a critical loading scenario, the more challenging failure mode to predict is deflection. The arm must be sufficiently stiff and lacking in backlash to ensure a steady-state end effector deflection complying with the position accuracy requirement. This steady-state arm deflection may be calculated from the aggregate deflection in the structures and backlash in the actuators, which may be mitigated to some extent with brakes.

Volumetric requirements for the manipulator are few. Confined spaces are not foreseen in the field, and as long as the manipulator does not interfere with the ground or the rover itself, there is significant flexibility in the configuration of the actuators. This allows for simple joint design and maximizes the utility of Commercial-Off-the-Shelf (COTS) components.

D. Design for Manufacture; Assembly

The ILR's (Institute of Aeronautics and Astronautics) in-house manufacturing capabilities had to be considered from the outset of the design phase. The project's limited budget was a major incentive for maximizing in-house production and where practical, a preference was to be given to manufacturing mechanical parts over buying them. The following manufacturing capabilities were assumed:

- Machining: 3-axis milling - .01 mm horizontal accuracy, up to 300 mm pocket depth; 2-axis turning
- Fabrication: rough sheet metal folding ; Basic tack welding of steel parts
- Additive: PLA and ABS 3D printing with 0.1 mm accuracy

Modular assembly features were considered throughout the design phase to facilitate assembly for users, optimize analysis resources by reusing robust features, and enable several manipulator configurations. Carefully designed bolted connections between manipulator structures and mechanisms would allow fast assembly and disassembly, simplify interfaces with Ground Support Equipment (GSE), and enable alterations to the manipulator's joint configuration to optimize it for specific scenarios.

III. MECHANICAL DESIGN

A. *Overview*

The manipulator's required range of motion was determined from the archetypical tasks defined above and the system's planned position on the rover. The joints and structures were then configured as shown in Figure 1.

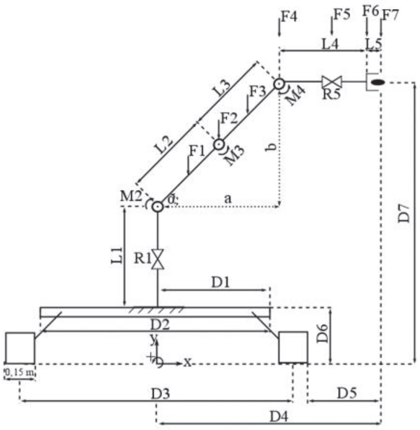

Figure 1 – Joint configuration of the BEAR manipulator

This joint configuration in turn drove the structural and mechatronic dimensioning of the manipulator. Supporting analysis included a MATLAB point mass model to verify steady-state arm deflection the dynamic performance of joint M2 and hand calculations of the stress and deflection in joint R1's shaft – a critical node in the load path. These were supported by component-level finite element analysis. Subsequent design for manufacturing and assembly yielded the design depicted in Figure 2, which is discussed in detail below.

Figure 2 – Render of the BEAR manipulator

B. *Actuators and Sensors*

Actuators were selected to enable the joint configuration depicted in Figure 1. With the exception of the rotary base joint, R1, all actuators had to be dimensioned for the worst-case load condition: arm horizontal and gripping the maximum payload in the end effector. To provide adequate torque for the long moment towards the arm base, joints M2 and M3 relied on stepper motors with planetary gear boxes that step the torque up by a factor of 40. R1, with no significant static torque requirement, excluded a gearbox. The two joints at the manipulator tip required less torque and greater precision for fine control of the end effector, so servomotors were selected for M4 and R5.

Besides high-level inspection instruments like the end effector webcam, the arm joints require instrumentation for their effective control. The servo motors' internal closed-loop position control meant they could be assumed to reach their demand position in negligible time, but the stepper motor joints required active position feedback. Optical encoders were added to the actuators for this purpose. The three stepper joints were also fitted with brakes to mitigate backlash and the risk posed by power cuts, as well as allowing selective denial of degrees of freedom to simplify manipulator control.

While software interlocks were envisioned to prevent the arm from interfering with the rover, hardware interlocks were added as an additional safety measure. A pair of lever switches mounted on joints M2 and M3 are triggered by a 3D-printed protrusion bolted to the top of each arm support and dimensioned to interrupt the microcontroller if the manipulator exits its design range. These switches also serve as an absolute position reference for homing the manipulator after power cycling.

The M3 gearbox-motor-brake-encoder combination, as well as its interlock switches and mounting holes for the IMU assembly are visible in Figure 3.

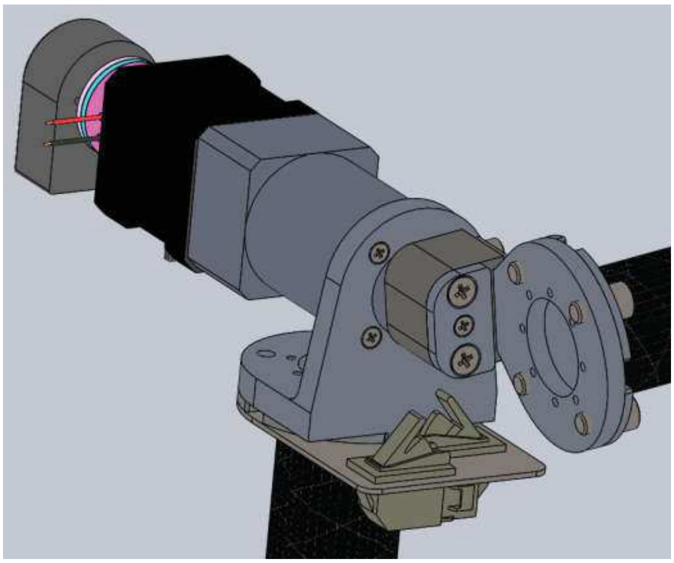

Figure 3 – CAD model of joint M3. 3D-printed protrusion that triggers interlock switches not shown.

C. *Structures*

Carbon Fiber-Reinforced Polymer (CFRP) was identified as an appropriate material for this application due to its high stiffness to density ratio under the arm's relatively predictable loading. COTS tubes of 1 and 1.5 mm wall thickness were selected for the arm structure, and their performance verified using the MATLAB model mentioned above. Subsequent FEA then demonstrated that the CFRP tubes would have sufficient stiffness to meet the arm deflection requirement.

The main drawback of CFRP is the difficulty in joining it to the mechanical assemblies. This was overcome by designing turned aluminum flanges that would be permanently bonded into the CFRP tubes along their inner diameter. These permanent fabrications would simplify arm assembly, as shown in Figure 3, and facilitate cabling by routing the harness through the hollow tubes.

D. *Mechanical Interfaces*

Custom mechanical assemblies were designed to manage the interfaces between the actuators, structures, sensors and arm services. Machined aluminum brackets like the one shown in Figure 3 interfaced with primary structure on the stepper motor gearboxes, whose keyway shafts protrude form the assembly and transmit torque to the arm structures. The gearbox bearings are able to handle the resulting radial loads on these cantilevered shafts, eliminating the need for external bearings to facilitate assembly and dimensional tolerancing.

Milled alignment features on the arm structure flanges mate with high-tolerance protrusions on the arm supports that interface with the actuators. This ensures angular alignment of the actuator assemblies without the need for dowel pins. In addition, these alignment features enable a modular assembly by reconfiguring the joint dimensions at 90-degree intervals. One such configuration is shown in Figure 4.

Figure 4 – Alternative manipulator configuration

IV. CONTROL AND ELECTRONICS DEVELOPMENT

A. *Control Architecture*

The overall control architecture called for a digital communication bus between the manipulator OBC and a microcontroller handling each of the stepper nodes. A separate bus would communicate with the series of servo motors.

The manipulator OBC, receiving commands from the rover's central embedded OBC over a CAN bus, would distribute these in the form of position or velocity demand signals to the various control nodes. These control nodes, as shown in Figure 5, implement closed-loop position or velocity feedback control with dedicated hardware to drive the steppers, condition encoder signals, and handle the brake and hardware interlocks.

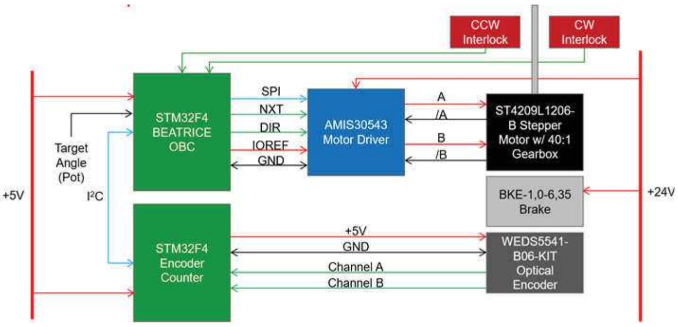

Figure 5: Schematic of control electronics for a stepper motor joint

B. *Hardware Selection*

The manipulator OBC had been predetermined as an STM32F407VGT6 chip [4]. Embedded OBCs designed by the project team use a similar microchip of the F427 family and utilization of commercially available discovery boards for the given F407 chip promised rapid prototyping. Software developed for the STM32F407 is usually easily migrated to STMF427 boards. The encoder counter board presented more difficulties. Originally, it was intended to use a basic 8-bit ATMega board with two external interrupts and I2C capability, however operating this board as an I2C slave proved to be a difficult task. Delays due in troubleshooting the ATMega chip threatened the work package's success, and so instead a second STM32F407VGT6 chip on an STM32F407 Discovery Board was used despite being overpowered for the application. This has advantages, however, in terms of reducing the required number of unique parts, workflows, and system-specific knowledge for future work on the manipulator. Furthermore, these processor might take over additional tasks in the future and complement rover's redundant design.

C. *Bread Board Verification*

A bread board verification for the first joint was set up early during the manufacturing and assembly process. Since the underlying concept for motor control is similar for all stepper motors, the set-up was representative for most joints of the robotic arm.

Given the required speed of the manipulator's movements, only a PD controller would be required, and adjusted so that the maximum joint velocity would be used up until close to the target angle. In order to achieve higher accuracy, the control loop operates in steps rather than degrees. This means that the encoder counter boards simply pass the current counter value when requested via I2C. The I2C communications are able to operate robustly even while the motor is moving and the encoder interrupts are occurring. The magnitude of the error is used to adjust the timer period determining the frequency of step pulses sent to the stepper motor. This is an inverse relationship between step count error (position) and timer period (velocity):

$$T = \frac{10000}{k_p \cdot \mid e_{(t)} \mid + k_d \cdot (\mid e_{(t)} \mid - \mid e_{(t-dt)} \mid)} \qquad (1)$$

The gains and constant in the numerator were determined empirically by a test campaign after assembly of the first joint.

As the test system was only being breadboarded, some method of user input was required. The method of input, a potentiometer, was selected to replicate a future input from the R1 joint custom rotary encoder, which required use of the Analog-to-Digital Converter (ADC) onboard of the manipulator OBC. Once incorporated into the control loop, the joint was now capable of performing a start-up routine to find the limit switches and determine its absolute position, accepting a target angle, and achieving that angle with an accuracy of ±0.05°, and repeatability of $> 99\%$.

V. CURRENT STATUS

Mechanical assembly of the of the manipulator's high-torque joints is complete and ready for cabling and integration of the end effector, as shown in Figure 6. Software is now being developed, with a focus on enabling autonomous control with the Robot Operating Software package MoveIt! [1]. The software allows to autonomously create motion trajectories for the manipulator. These trajectories shall then be interpreted and executed by an embedded OBC which has real-time control over sensors and actuators. Furthermore, a custom gripper design for the manipulator is being developed.

Figure 6: Assembled BEAR Manipulator

An upcoming challenge will be the implementation of the arm's harness. Cables have to be routed in such a way that reliable data and power transmission is possible over long periods of time while not hindering the movement of the system in any way. With cabling complete, functional testing will proceed to verify the arms dynamic performance using dummy payloads, before assembling the end effector and integrating the system onto the BEAR rover.

VI. LESSONS LEARNED – STUDENT PROJECTS

The BEAR manipulator exemplifies some of the unique opportunities provided by collaborative student projects. They provide hands-on systems engineering training that replicates the communication and programmatic challenges of industrial R&D, while promoting collaboration between students of different backgrounds. But they also come with unique challenges. Besides restrictive budgets and manufacturing capabilities, student work must take place during the short semesters of study programmes, with a high rate of personnel turnover. Fostering the continuity needed to build effectively on previous work therefore requires careful management. To that end, we identify two major strategies.

First, software tools for collaboration and version control, supported by dedicated infrastructure, go a long way in decreasing communication overhead, promoting disciplined documentation, and preventing version conflicts. The required training and uptake time for tools like Git is generally justified in projects spanning multiple semesters.

Second, carefully calibrating students' academic and personal incentives for contributing to the project is critical for ensuring long-term success. Project objectives and academic requirements should be harmonized wherever possible, with a particular emphasis on allocating critical work packages to individual academic deliverables, like the master's thesis. As for personal incentives, university competitions are perhaps the most effective tool. Their strict schedules help drive the project forward, while the competitive element galvanizes the student team for a common goal.

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