Evolutionary Development of an Optimized Manipulator Arm Morphology for Manipulation and Rover Locomotion

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***Abstract*— The planetary exploration rover Sherpa is equipped with a manipulator arm used for handling payload items as well as for improving its locomotive abilities. Due to the high weight of Sherpa of approx. 200 kg and the maximum weight of a payload item of 5 kg, both applications need high torques. In addition, a dextrous operating space is needed which has to allow ground contact and the placement of payload items on pre-defined positions on the rover itself.**

In this paper we describe an optimization method which evolves a manipulator arm morphology that requires minimal torques to accomplish these to some extent conflictive applications. Covariance Matrix Adaptation Evolution Strategy in parallel processing is used to optimize the link lengths of the manipulator arm. A real-time simulation is used to model the rover, all constraints, and to evaluate each morphology by analyzing the required torques for accomplishing pre-defined tasks. The paper presents the simulation results and the final manipulator arm morphology.

I. INTRODUCTION

Robots that are supposed to interact with their environment need a manipulator arm in order to handle objects or, in case of exploration rovers, to place scientific instruments appropriately. Many exploration rovers like the Mars Exploration Rovers (MER) *Spirit* and *Opportunity* [8] or their successor, the Mars Science Laboratory (or *Curiosity*) [7], make use of a manipulator arm to increase the scientific value of a mission. The diverse applications are unique considering the constraints (torque, angular velocity, weight, size, precision, and morphology), which make a use of a standardized manipulator arm impossible.

Schenker *et al.* [15], [16] propose to use the arm of a rover not only for placement of scientific instruments, but also for locomotion support. The arm of the rover can be used to shift the center of gravity in order to increase the tip-over stability. Furthermore, they propose to allow ground contact of the arm in order to support the rover in steep slopes where it is close to a tip-over situation. The Hybrid Mobile Robot [1] integrates a locomotion platform and a manipulator arm with three degrees of freedom (DOF) as one entity rather than two separated attached modules. Thus, the manipulator arm can be used as part of the locomotion platform and vice versa.

Because standardized manipulators are not applicable in special contexts, research exists on optimizing a manipulator arm for a given application. A lot of studies can be found on optimizing the drive train, e.g. [12], [19], other work addresses the manipulator arm dimensions, e.g. [17], [9], [10], and Zhou *et al.* [20] optimize drive train and dimensions

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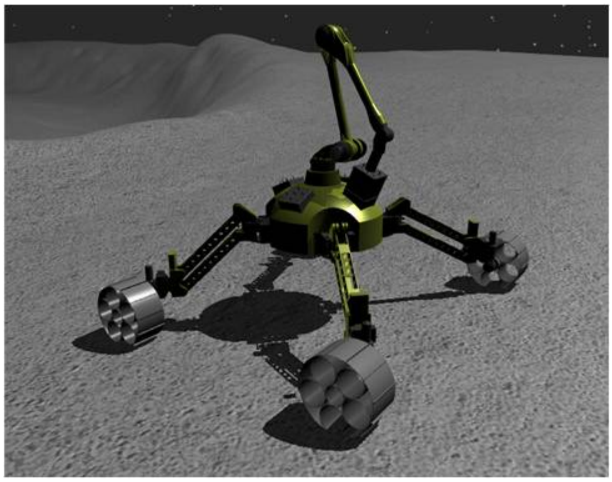


Fig. 1. The planetary exploration rover Sherpa in simulation environment

at the same time. Nevertheless, simple manipulator arm morphologies are often used where just few link lengths are optimized.

The work presented in this paper is part of the reconfigurable multi-module system RIMRES[1] [2]. It consists of immobile modules called payload items and two mobile modules, the walking robot CREX[2] and the exploration rover Sherpa[3]. The system combines the key advantages of the two mobile units: high mobility of a legged system in rough terrain and energy efficiency of wheeled locomotion. To this end, the legged scout robot CREX can be attached via an electromechanical interface (EMI [4]) to the wheeled rover Sherpa. Thus, Sherpa is used for the transportation of Crex over moderate terrain in order to deploy the scout, for example, at a crater rim for exploring the interior of the crater. Sherpa (Fig. 1) consists of three main parts:

1) An active suspension system
2) A central body
3) A manipulator arm on top

The active suspension system consists of four legs called swing units each having four DOF. A wheel with two additional DOF for steering and driving is mounted at the end of each swing unit. The wheels are able to use adaptronics for actively changing the compliance in order to adapt to the soil the robot traverses and to changes of the rover's mass, caused by (dis)connecting CREX or payload items.

[1]Reconfigurable Integrated Multi-Robot Exploration System
[2]Crater Explorer
[3]Sherpa: Expandable Rover for Planetary Applications

The central body of Sherpa comprises the main control and power electronics as well as the main sensors (laser scanner and stereo camera). One docking port for CREX is located underneath the body. Four docking ports for payload items are placed around the central tower. An EMI is installed in each docking port to provide a secure mechanical connection, a power bus for sharing energy between each module, and data lines for communication. Hence, connected subsystems (mobile robots as well as immobile payload items) can be regarded as one single system.

The focus of the developments presented in this paper is on the manipulator arm of Sherpa which is used for manipulation of payload items and locomotion support. In the following second section, the requirements for the arm design and the resulting challenges are presented. Section III explains in detail the method to develop an optimal manipulator arm morphology (kinematic configuration) which fits best the RIMRES application. The results of the optimization process are examined in section IV. Section V summarizes the paper and provides an outlook on the next steps.

II. Problem Definition

The manipulator arm of Sherpa shall be used to handle immobile payload items as well as to enhance the locomotive ability of Sherpa. Both applications have conflictive requirements which basically need different arm morphologies. In our approach, we define a basic morphology for the arm which is capable of achieving all goals. This raw idea of a manipulator arm can then be optimized accordingly to our needs taking into account the constraints established by project, application, constructional feasibility, and decisions made beforehand (Fig. 2).

A. Manipulator Arm Requirements

The manipulator arm is primarily used to handle the different payload items. For that reason, an EMI is integrated in its end effector which enables the manipulator arm to grasp, power, and handle each payload item. The manipulator arm kinematics have to guarantee the placement of at least two payload items on the docking ports of the rover as well as on the surface. Therefore, the dextrous space of the manipulator needs to be large. This is advantageous as well in the case of using the manipulator arm as a supervision tower. Due to an integrated camera in the EMI, the manipulator arm can be used to observe the landscape from a different point

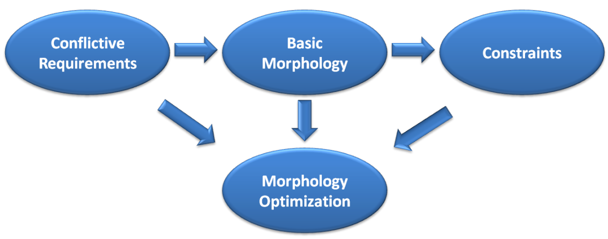


Fig. 2. The application requirements demand a basic morphology. This basic configuration needs to be optimized regarding the application and the arising constraints

of view and to supervise the rover itself. If the dextrous space is large enough to inspect the outer shell of the rover, malfunctions and unknown situations can be monitored from the outside. Thus, long link lengths are needed.

In addition, the manipulator arm shall support the rover locomotion in several ways. First, the manipulator arm can be moved towards the incline if Sherpa climbs up steep slopes. In this way, the rover's center of gravity can be shifted to improve the tip-over stability. Second, the manipulator arm can statically be placed on the ground as an extra limb. With adequate joint torques the manipulator arm is able to partly lift up the rover, which improves the locomotive abilities. One or two rover legs could be lifted up to overcome tall obstacles in flat terrain or to resolve a dangerous situation, e.g. when the rover gets stucked. Conclusively, the reachable space of the manipulator arm should allow touching the ground. When using the manipulator arm as an additional leg, the supporting point has to replace a potentially missing leg. So we define that the reachable space on the ground should be in the range of a swing unit (i.e., 0.9 m radius around the rover center in highest rover posture). For convenience, this should be possible by reaching over a payload item which is docked on one of Sherpa's docking ports. Third, the manipulator arm can be dynamically integrated into the rover's locomotion patterns. Their efficiency can be increased, for example, by minimizing slippage which is likely to occur during swing phases, e.g. if the rover moves in a walking behavior.

Regarding the maximum mass of a payload item of about 5 kg and the mass of Sherpa of approx. 200 kg, high torques are required for manipulation and locomotion support. In these cases, the desired large link lengths are counterproductive, because they would even scale up the torques. This results in stronger actuators which have larger dimensions, more weight, and higher power requirements. Thus, an optimum has to be found allowing the fulfillment of our desired applications with the shortest link lengths. While keeping the mass of the manipulator arm to a minimum, the rigidity should remain high to allow precise positioning. The demands on the angular velocities are not high but should at least match the rover speed of max. 32.6 $\frac{cm}{s}$ and the angular velocities of the DOF of the swing units of ca. 12 °.

B. Basic Morphology

The requirements show that a spherical working space is needed in which all kinds of orientations are desirable. Hence, an arm morphology with at least six DOF is needed. Due to the fact that the developed space exploration system addresses a rather static environment, there is no need for redundant manipulation capabilities. For that reason, one can discard a seventh DOF and consequently save the extra mass and effort.

Due to the huge complexity and the problem that the inverse kinematics cannot be calculated in closed form for every joint alignment, we define a basic morphology which is in general applicable for the project use. Our proposed manipulator arm kinematics (Fig. 3) [11] is very similar to industrial robotic arms. The first joint rotates around the vertical axis of the rover's geometrical center and thus defines the basic direction of the manipulator arm. The axes of the second and third joint are both horizontal and allow tilt movements. The last three joints build a 3-axis in-line wrist which basically determines the end effector orientation.

The forward kinematics can be calculated by using the Denavit-Hartenberg [3] approach. Therefore, a coordinate system for each joint is defined. The transformation from one joint to the next is then given by the rotation angle around the z-axis ϑ, the translation displacement along the z-axis d, the translation displacement along the new x-axis a, and the rotation around the new x-axis α (Table I).

The inverse kinematics can be solved geometrically due to the 3-axis in-line wrist. The point where these consecutive axes meet is independent from the current angles of the last three joints. It can be calculated with the given position and orientation of the end effector and the last link length. The knowledge of this intersection point and the chosen link lengths allow a computation of the first three joints. A rotation matrix can be set up which describes the difference between the desired end effector orientation and the orientation caused by the first three joints. This matrix is used to calculate the last three joints. Their alignment defines them as ZYZ-Euler angles. A maximum of eight solutions is possible allowing a variable movement towards desired set positions, if one considers that some poses are reachable by overhead or not, with upper or lower arm, or with normal or inverse wrist.

C. Constraints

In general, an optimization of every aspect of a manipulator arm is desirable including the variation of the DOF number, their alignment, the link lengths, the cross-sectional area parameters, or the drive train. In our case, a drive train optimization is not needed because motors and gearboxes are chosen based on former experiences [6] which have to be adapted to the required torques.

In this paper we focus on the morphology because optimal physical characteristics reduce the required torques, resulting in smaller actuators with less weight and reduced power consumption. While this basic morphology defines the DOF and their alignment, the link lengths have to be chosen accordingly to the project requirements. In contrast to related work, we are not just optimizing the upper and lower arm. We also address the height of the tower, a possible cantilever[4], positive and negative elbow displacements, and the end effector length which are all important factors for an optimal manipulator arm morphology as well. Since the construction of the rover is fixed, the poses of the docking ports are known. The manipulator arm kinematics has to allow placing the payload items on these ports regarding the joint angle limits defined by the joint construction. The angular joint velocities were chosen accordingly to the swing units. They have to be taken into account because they influence the dynamics and thus the required torques.

Material and construction of the links are not analyzed in this work. In a first step, we want to estimate the torques which the optimal morphology needs in order to fulfill the requirements. In a second step, we construct the links using finite-element-method. In addition, we integrate sensors in the structure to measure deflections in order to compensate potential positioning errors while dealing with immense forces.

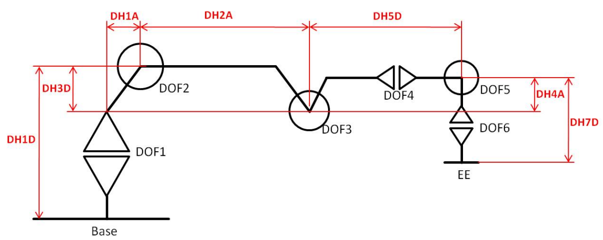


Fig. 3. The DOF of the manipulator arm are fixed as basic morphology but the link lengths are variable. The link lengths are labeled correspondingly to the Denavit-Hartenberg definition.

III. MORPHOLOGY OPTIMIZATION

The goal of the optimization is to efficiently find a solution for the seven variable link lengths which enable the manipulator arm to fulfill the proposed requirements with minimum torques. The following subsections describe how a feasible set of link lengths is generated and how this set of parameters is evaluated.

A. Evolutionary Optimization Approach

Covariance Matrix Adaptation Evolution Strategy (CMA-ES [5]) is used as it can perform efficient optimization even with small population sizes. Evolutionary strategies optimize a vector of decimal parameters by making use of similar concepts like evolution is known in biology, where the parameter vector represents one individual. Several individuals form a generation. Each individual has to be evaluated to get a fitness value. One or more individuals (parents) with the best fitness values of a generation are used to create a

[4]meaning DOF2 is not centered above DOF1 (DH1A > 0)

TABLE I
DENAVIT HARTENBERG PARAMETERS

i	ϑ	d	a	α
1	θ_1	Height of tower (DH1D)	Cantilever of tower (DH1A)	$-\frac{\pi}{2}$
2	θ_2	0	Length of upper arm (DH2A)	$\frac{\pi}{2}$
3	0	Elbow displacement (DH3D)	0	$-\frac{\pi}{2}$
4	$\theta_3 - \frac{\pi}{2}$	0	Elbow displacement (DH4A)	$-\frac{\pi}{2}$
5	θ_4	Length of lower arm (DH5D)	0	$\frac{\pi}{2}$
6	θ_5	0	0	$-\frac{\pi}{2}$
7	θ_6	Length of end effector (DH7D)	0	0

new generation by changing the parameters of the parents. A mutation rate defines how much the new individuals differ from the parents. While decreasing the mutation rate the evolution emerges into one solution. We already gained experience with CMA-ES by optimizing locomotion patterns of walking robots [14], [13].

Since CMA-ES does not provide any means of bounding the search space, the object variables are optimized in $\mathbb{R}$. In consideration of the parameter value limits imposed by the robot hardware, we chose to use a function that projects the whole space of real values onto a range that the robot controller can handle. The mapping function $P : \mathbb{R} \to [x_m, x_m + x_a]$ is defined by the chain $x \to u \to v \to w$ given as:

$$u = x \bmod 2x_a \tag{1}$$

$$v = \begin{cases} u, & \text{if } u \leq x_a \\ 2x_a - u, & \text{if } u > x_a \end{cases} \tag{2}$$

$$w = v + x_m \tag{3}$$

where x is the parameter chosen by CMA-ES, u and v are temporarily used, x_a is the amplitude of the mapping, x_m is the minimum value, and w is the mapped parameter used for the evaluation. This projection function is continuous, which is important for the learning algorithm. The absolute value of its derivative is constant wherever this derivative exists. This is done to avoid negative effects on the performance of the learning algorithm that can result from nonlinearly projecting the learned values onto the control-value space. Such a nonlinear projection like a modulo function could cause the fitness landscape to become more fragmented, making it more difficult for an evolutionary method to find a global minimum.

B. Morphology Parameters

In our approach we divide the evolutionary development into a coarse and fine optimization. The coarse optimization is used to find a morphology which seems to be quite optimal. Hence, a huge search space is used with a high mutation rate to decrease the possibility to miss good morphologies. Thus, the convergence rate is slower and the resulting end resolution lower. If the majority of many evolutions finds morphologies in a closed range, one can start a fine optimization. The fine optimization takes the morphology of the coarse optimization as a starting point to define a new range around the found link lengths. By decreasing the search space and the mutation rate, a solution with higher accuracy can then be found in shorter time.

Table II shows the range of each parameter during coarse and fine optimization. The minimum values are limited by constructional constraints whereas the maximum values are freely chosen.

TABLE II
RANGE OF PARAMETERS

Parameter	Coarse Optimization	Fine Optimization
DH1D	500 mm - 800 mm	500 mm - 650 mm
DH1A	0 mm - 500 mm	0 mm - 300 mm
DH2A	234 mm - 984 mm	600 mm - 900 mm
DH3D	0 mm - 300 mm	30 mm - 130 mm
DH4A	0 mm - 300 mm	30 mm - 130 mm
DH5D	234 mm - 984 mm	600 mm - 900 mm
DH7D	300 mm - 600 mm	300 mm - 400 mm

C. Evaluation

The fitness value to evaluate a set of link lengths N is defined as the cumulative sum of the torques for each joint during the time of motion of the manipulator T,

$$f(x) = \sum_{i=1}^{T} \sum_{j=1}^{N} t_{ij}^2 \tag{4}$$

where t_{ij} is the torque at time i for joint j. There exist several approaches to determine the torque. Instead of using an analytical model, we preferred to use a real-time simulation. In this simulation, a route consisting of several way points is defined which covers all proposed use cases. The needed torques are measured until all way points are reached. This approach allows us to easily change constraints like angular limits, velocities, or constructional changes. In addition, it is possible to see the tested configurations online.

The used simulation software is MARS (Machina Arte Robotum Simulans). MARS is an in-house developed simulation and visualization tool for developing control algorithms and designing robots. It consists of a core framework containing all main simulation components, a GUI, OpenGL-based visualization, and a physics core that is currently based on ODE [18] which simulates the acting forces and resulting torques. Physics and GUI are implemented as modules connected via interfaces with the core. By choosing this implementation, the graphics can run without physics and vice versa. Additionally, a communication module is implemented. Furthermore, it is possible to include customized controllers for a robot.

Sherpa has to be abstracted into simple physical shapes to minimize the computational effort. Complex stiff parts are reduced to simple primitives. Nevertheless, positions and masses of the body parts are modeled accordingly to the physical robot. Especially, the payload items on top of the rover are precisely placed since small changes here could lead to different manipulator arm morphologies. Torques of the simulated joints are specified as can be expected from the real rover to achieve the same moving behavior. The joint limits and angular velocities are set accordingly to the input constraints.

The way points on the route cover all proposed use cases. Following key way points have to be reached to guarantee the functionality of the tested manipulator arm morphology.

1) The manipulator arm establishes ground contact as specified in the requirements and partly lifts up the rover. This is achieved by reaching over a payload item which is attached to a docking port (Fig. 4(a)). The end effector is folded aside to prevent damage of the EMI.

The housing of the fifth joint is used to establish ground contact.

2) The adjacent legs are lifted up and placed on different spots to show a solution how to resolve a dangerous situation, i.e., when the rover got stuck.
3) A payload item is grasped from a docking port which simulates an energy supply pack with a mass of 5 kg.
4) The payload item is moved around in a way that maximum torques are created especially to stress the three wrist joints (Fig. 4(b)).
5) The payload item is stacked on another one to prove that the kinematic configuration can reach this point (Fig. 1).

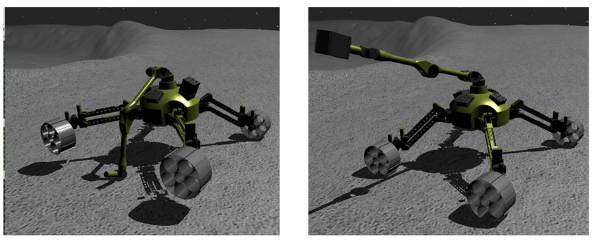
During this defined route, all joint torques are measured as shown in Fig. 5. On the one hand, the measurements provide a good indication of the required joint torques. On the other hand, the sum of the average joint torques is used as fitness value of the tested morphology.

If a morphology cannot reach a way point, a penalty M_P is imposed instead of using the average torque as fitness value. This prevents a good rating of morphologies which do not need high torques until failing a way point. The computation of the penalty is shown in (5). N is the number of failed way points and N_{compl} is the quotient of the remaining distance to the next way point and the overall distance between these two way points. Each passed way point reduces the penalty by factor M_B. The maximum penalty M_{PMax} should be chosen accordingly to the number of way points and the expected fitness value of a successfully passed way point route.

$$M_P = M_{PMax} - M_B \cdot (N - N_{compl}) \tag{5}$$

D. Optimization Farm

The evolutionary process is split in order to increase the evaluation speed of complex behaviors in simulation. An evolution server is designed that places all individuals of one generation into a virtual data space. A client is implemented by a simulation that takes an individual out of the virtual data space, performs an evaluation, and returns a fitness value of the individual into the data space. So, the evaluation of individuals can be done on several computers in parallel. After receiving all fitness values, the evolution server performs the selection of the best individuals and creates the next generation by mutating the parents.



(a) Lifting the rover (b) Handling a payload item

Fig. 4. Use cases covered during way point route in MARS simulation

IV. OPTIMIZATION RESULTS

A. Optimization Convergence

The proposed method is able to find a configuration of link lengths which require minimal joint torques to accomplish the pre-defined tasks. The fitness value runs into local minima but finally converges. Fig. 6 shows an example during fine optimization. All seven variable link lengths are varied over the given ranges defined by the mapping function. Some link lengths converge to the physical constraints indicating that some constructional improvements could be made to further optimize the overall result. At the beginning, major changes are applied by the algorithm whereas at the end only small changes help to find a solution of the predefined accuracy.

We ran many evolutions to test the reproducibility of the approach. Because the fitness landscape is not known, it is of our interest to see whether the algorithm runs into different minima meaning the algorithm is not suitable or different configurations exist which create similar results. First, we started the coarse optimization where the parameters were varied in big steps across a large search space. After 43 evolutions we limited the search space around the found optimum of the coarse optimization and switched to the fine optimization with small parameter changes. During coarse optimization we discovered that some evolutions converge to different minima indicating that the proposed algorithm can run into local minima. But 90% of these trials emerged into very similar solutions indicating that the global minimum was found. The following fine optimizations always emerged into very similar optimums (Fig. 7). The standard deviation of the fitness value is 0.097 Nm. The standard deviation across all link lengths of 5.77 mm is caused by noise of the joint torque measurements and by inaccuracies of the used real-time simulation. On average, 101 generations, each consisting of nine individuals, were needed per evolution. The final link lengths are listed in Table III.

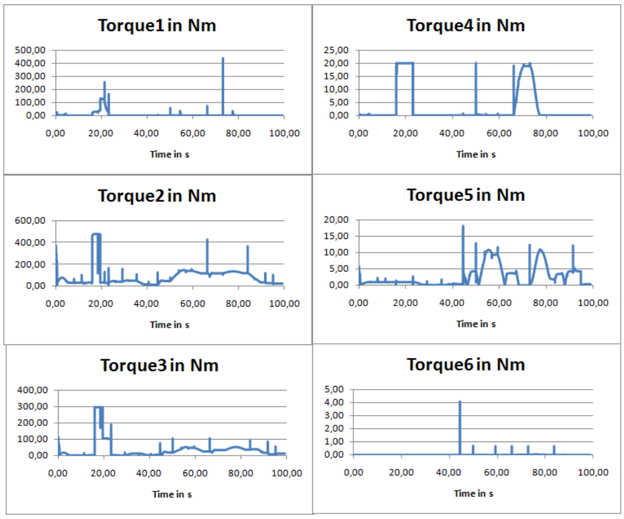


Fig. 5. Example of torque measurements during defined way point route

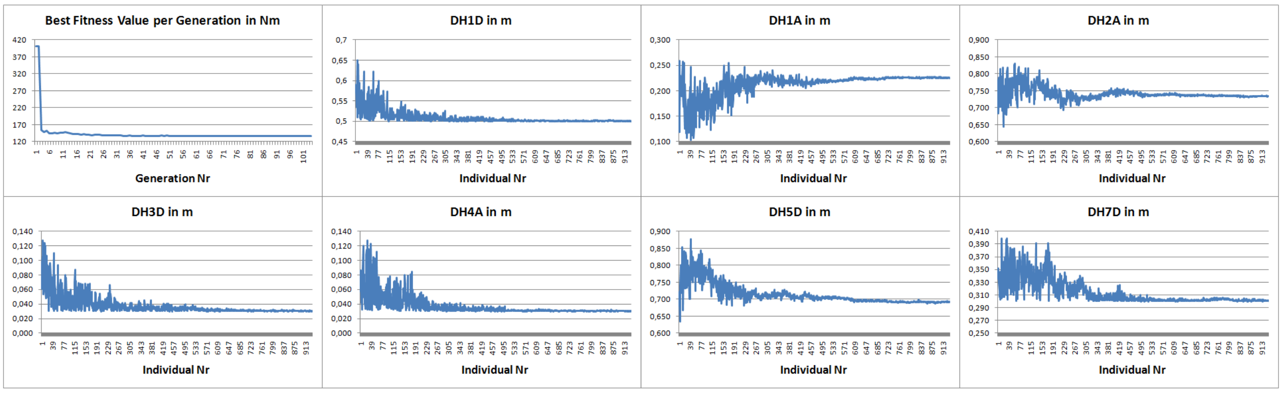


Fig. 6. Convergence of the fitness function and the corresponding link lengths

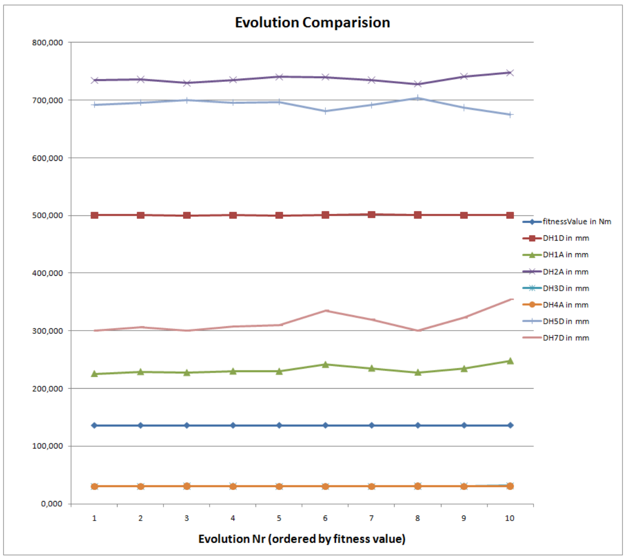


Fig. 7. Comparison of 10 evolutions during fine optimization in fitness value and link lengths

TABLE III
RESULTING LINK LENGTHS OF OPTIMIZATION

DH1D	DH1A	DH2A	DH3D	DH4A	DH5D	DH7D
500 mm	225 mm	735 mm	30 mm	30 mm	695 mm	300 mm

B. Interpretation of the Results

The results show that a centralized second joint is not beneficial. Adding a cantilever allows to shorten the upper and lower arm (Fig. 8). In this way, the cantilever structure takes some additional torque but the second and third joints are relieved, e.g. when the arm is straight in horizontal pose. An appropriate height of the manipulator tower combined with the right cantilever helps the manipulator arm to touch the ground even over a docked payload item. In addition, the cantilever increases the toggle lever effect. Thus, if the manipulator arm touches the ground near the body, it is able to lift the rover with reduced torque by stretching the third joint. The small elbow displacement is needed to increase the positive angle limit of the third joint allowing the manipulator

Fig. 8. Manipulator arm design based on optimization results. The left end is the first joint that is incorporated into the rover's central tower. The right end is the end effector without EMI.

arm to grasp payload items from the docking ports. A further increase would enlarge the needed torques.

According to the results of the optimization, upper and lower arm have similar lengths, which is also true for a human arm that is evolutionary developed as well. The length of the last link DH7D should be chosen as short as possible. The minimum border of the mapping function is the optimum (Fig. 6) because this length just increases the torques when handling payload items. The length is not needed to touch the ground because the end effector has to be folded aside when using the manipulator arm as an additional leg. The tower height should be kept as short as possible but is limited by the rover design.

V. CONCLUSION AND OUTLOOK

An optimized manipulator arm morphology was found which needs minimum torques to manipulate payload items and to lift one side of a 200 kg rover. CMA-ES in combination with a real-time simulation was used. Seven link lengths were analyzed regarding their effect on the torques needed to fulfill pre-defined use cases. In general, this method can easily be expanded to more parameters, e.g. pose of docking ports, size of payload items, and cross sectional dimensions.

A coarse optimization is used to find the best solution in a large search space by starting new evolutions many times. 90% of 43 evolutions emerged into solutions in a very closed range, indicating that a global optimum was found. A following fine optimization takes this proposed optimum and refines the resolution with a smaller search space. The results of these ten evolutions had a standard deviation across all link lengths of 5.77 mm.

The optimization shows that a cantilever is of advantage. The tower height and the last link length should be as short as possible. A small elbow displacement is needed to increase the moving range of the third joint. Upper and lower arm have similar lengths.

Another outcome, the simulation delivers expected torques of a worst case scenario which can be used for the joint construction. The approach can easily be adapted to constraint changes, which might occur during construction phase. Then, a new optimization has to be conducted. However, the active chassis of Sherpa as well as the central structure are already designed and manufactured, thus no critical changes are expected.

The evolutionary approach to find an optimal manipulator morphology was just the first step in the design of Sherpa's manipulator arm. In future, the mechanical design has to be finalized. The first two joints as well as the cantilever are mechanically designed, the third joint and the wrist joints are nearly finished. Then the manipulator arm can be integrated and put into operation. Due to the modular design of Sherpa, the arm can be used without being attached to the rover. Thus, manipulation procedures can be developed independently from the basic locomotion of the rover. Finally, after mounting the manipulator arm on the rover, methods for locomotion support including the arm will be implemented.

VI. ACKNOWLEDGMENTS

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