An Active Suspension System for a Planetary Rover

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Abstract

This paper reviews the design of the hybrid wheeled-leg rover Sherpa[1]. Focus is set on the mechanical design of the suspension system that is constituted by four independently controllable legs with a wheel mounted at each leg. Achievements and drawbacks of the current design are outlined and lead together with the new application range to a revised design of the suspension. The new design and its modular actuation components are presented in this paper.

1 Introduction

Autonomous robots for exploration of extraterrestrial surfaces require reliable and robust locomotion systems. Passive suspension systems such as the well-known rocker bogie system which is applied for example in all successfully deployed Mars rovers so far [9, 8, 10] provide high motion capabilities with low control complexity. The passive suspension allows to negotiate obstacles in the size of the order of a wheel diameter of the rover. With passive suspension no extra efforts in controlling the configuration of the suspension system or its reaction to the ground are necessary, since the mechanical structure adapts to the external loads.

A major drawback in passive suspension systems becomes obvious in situations where the vehicle is stuck, for example in soft soils. Relieving the vehicle might become difficult or impossible without external intervention.

Compared with passive suspension, active suspension systems come with a higher cost concerning the control of the adaption to the ground. However, these systems provide a high maneuverability and reconfiguration capabilities that are not possible with purely passive suspension. Depending on the layout,

[1] Sherpa: Expandable Rover for Planetary Applications

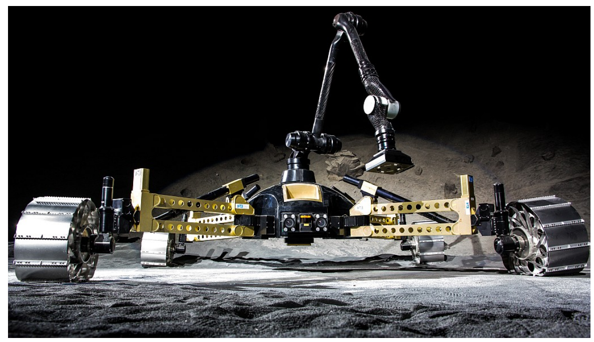

Figure 1. Sherpa in low stance mode. The body is very close to the ground and a wide footprint is adopted.

the suspension can be used in substantially different ways to propel the robot. Apart from mere adaption to the ground, the suspension system's actuators can be used to actively take part in the robot's movements [3] and, for example, to increase the traction on the ground [1]. On a higher complexity level of the suspension, wheels that are mounted on leg-like structures even enable the robot to exhibit undulating locomotion capabilities, resulting in a reconfiguration space of the locomotion system from driving to walking [6]. As described with the skating motions of the RollerWalker system [3] the locomotion modes are not necessarily discrete driving vs. walking. Rather, a potential for mixed modes or gradual mode changes is created using active suspension systems.

Not only rough terrain robots benefit from reconfigurable suspension: In indoor environments a change of the footprint allows high stability when needed, for example, in heavy load manipulation (i.e. health care robots) while compact configurations facilitate driving through narrow passages such as, for example, doors or crowded hallways [4].

Active suspension systems are defined by employing actuators for changing the kinematics of the suspension. The Sample Return Rover (SRR) [7] and Scarab [1] are both four wheeled systems that make use of one bogie on each side of the robot. The bogies are connected via a differential. Furthermore, one active degree of freedom (DoF) per bogie is used to reconfigure the suspension system. In case of the SRR, the main purpose of actively controlling the suspension system is to increase the rover's tipover stability by actively shifting the center of mass (CoM). Scarab, as well as the SRR make use of a shoulder joint to actively change the footprint of the system. Apart from increasing the stability in slopes the suspension system allows alternative motion modes and is used to lower the body for increased stability for subsurface drilling. For the SRR not only the suspension system is considered for locomotion purposes but the manipulator can be used to stabilize the robot in slopes (i.e. by shifting the CoM).

The ATHLETE family of rovers makes use of a highly actuated suspension system. It can be considered to be constituted by legs that are equipped with wheels at the ground contact points [6]. This configuration allows high adaption capabilities to irregular ground. Even discontinuous paths can be realized, since active lifting of the wheels off the ground is possible. This further increases the possibilities of motions and obstacles that can be negotiated. Using tool adapters mounted at the driving axes of the wheels, a leg of the system can be used as manipulator as well.

An important role in the flexibility of terrain negotiation plays the possibility of decoupling path following from the attitude of or attitude changes in the suspension system. High level control such as autonomous navigation should provide a path planning through the terrain ahead and a path following process. An appropriate suspension system controller can then provide a decoupled control of path following and terrain adaption by posture changes [5]. In order to enable path following in rough terrain, the posture of the suspension system is actively changed decoupled from high level commands.

In the remainder of this paper, the rover Sherpa (Fig. 1) will be highlighted in Section 2. Apart from benefits of the system, drawbacks are outlined as well, leading to a mechanical re-design of the suspension system as described in Section 3. In Section 4 a conclusion and an outlook on the next development steps are provided.

2 Sherpa Review

The hybrid wheeled rover Sherpa was initially developed within the project RIMRES [11]. It features

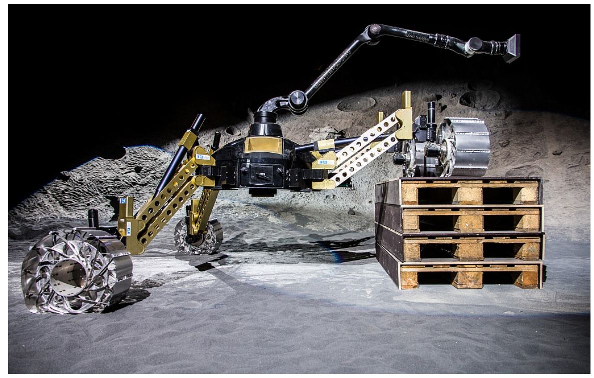

Figure 2. Benefits of negative ground clearance: Sherpa stepping onto a high obstacle. The manipulator was used to support the rover while lifting the wheel onto the obstacle.

an active suspension system for increased maneuverability and a multi-purpose manipulator arm that can be used for both, manipulation and locomotion purposes. The suspension system is constituted by four independent legs each equipped with a wheel, Figure 2.

The design of the suspension system uses active and passive suspension on different scales. Flexible metal wheels are employed to cope with ground irregularities on a small scale (several centimeters) and to provide high traction in soft soils. Springs in the lifting actuators of the rover form a kind of serial elastic actuator that copes with bigger irregularities below one wheel diameter. Big obstacles and body leveling in sloped terrain are dealt with by actively actuating the suspension system.

Sherpa has a maximum ground clearance of 711 mm. The ground clearance can be altered with the active suspension. This allows Sherpa even to put the central body to the ground and lift the wheels 189 mm off the ground, resulting in a negative ground clearance. In square footprint configuration, the edges of the square have a length of 2100 mm in high stance and 2500 mm in low stance (as shown in Fig. 1). Overall the system has a mass of approximately 160 kg.

A design point that proved to be beneficial is using self locking gears in the actuator design of the suspension. Due to this construction, Sherpa is able to maintain its body height without expending electrical energy. High additional payloads are realizable. A maximum of 90 kg impact load was successfully tested on Sherpa. A drawback is, however, an estimation of the load of a leg based on currents in the individual joints is not possible.

The wide range of motions of each single leg allows a wide range of postures (footprint/body height and attitude combinations) the robot can achieve. A change of stance width can be used for narrow passages, the center of mass of the robot can be shifted with respect to the support polygon etc. The manipulator can be used for locomotion i.e. serving as a fifth leg. This further increases the flexibility of the rover.

The chosen control approach for regular driving [2] is able to cope with the loss of one wheel. More precisely, no reconfiguration of the controller is necessary. If a wheel has a failure, the leg can be lifted off the ground, the remaining three legs are rearranged for a stable stance and the controller can work identically with three wheels as it did with four wheels.

The passive flexibility as described above allows to control the robot with a comparatively low number of sensors for the locomotion software-layer. Joint positions/speeds and a gravity sensor in the body are enough for basic terrain adaption. However, a sophisticated load balancing between the wheels/legs would need, for example, force-torque sensors for each leg since this information is not available by comparing the single joint's loads (due to the self locking gears).

A non-optimal point in the current design turned out to be the arrangement of the individual joints in a leg. Currently the first two joints (DoF0 and DoF1, c.f. Fig. 3) are responsible for the main positioning of the wheel contact point in x, y, and z coordinates. Consequently, the wheel cannot be freely positioned in the whole workspace of the leg. Furthermore, the second set of joints (DoF2 and DoF3, c.f. Fig. 3) does not have a considerable effect on the actual position of the wheel. Those DoF are intended to tilt and flip the wheel for proper steering in slopes and to provide a foothold with the wheel being lifted off the ground. During experiments with the system it became obvious that the flexible wheels sufficiently adapt to slopes so that the two DoF were used sparsely.

While the offset of the wheel from the steering axis allows the wheel to support the steering motion, at the same time the re-orientation of the wheel during steering imposes a movement of the wheel-ground contact point (WCP) relative to the rover. Thus, wheel steering is always coupled to a x,y-movement of the WCP within the rover's body coordinate frame. This imposes control issues when adapting the footprint during locomotion.

Thorough analysis of the mechanical structure and the distribution of loads originating from the wheel contact points revealed potential for weight reduction in the mechanical structure of the legs. Since most of the mechanical loads are carried by the linear actuator (lift DoF) and the upper beam of the parallelogram, it is possible to reduce stiffness and thus the mass of the lower beam.

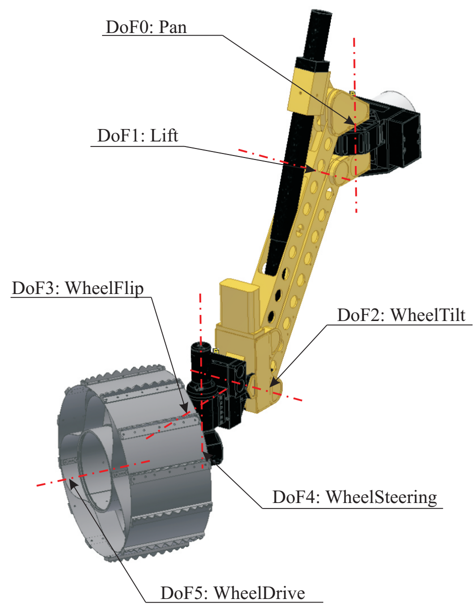

Figure 3. One leg of Sherpa's suspension system with numbering and naming of the degrees of freedom.

Since four of the in total six actuators of each leg are clustered close to the wheel, a rather unflexible geometry of the leg is achieved. This results in the above mentioned coupling of DoF and in a non compact stow position of the robot. The minimum volume envelope of Sherpa is with front and back legs stretched forward and backward, respectively at $2.25\,m \times 0.8\,m \times 1.35\,m = 2.43\,m^3$. Figure 4 illustrates the minimum volume configuration for Sherpa.

Sherpa was designed as a member in a heterogeneous robotic team in which a six-legged robot can be attached to the bottom interface of its central structure [11]. In the original scenario, the flexibility of the legged robot was exploited and allowed an autonomous docking manoeuver. For the docking process, Sherpa did not need to control its body attitude independently in several DoF; adapting the body height and limiting the roll and pitch angle were sufficient for successful docking maneuvers.

In the new application range also passive payloads shall be picked up with the electromechanical interface. In the new scenario, Sherpa is used to deploy

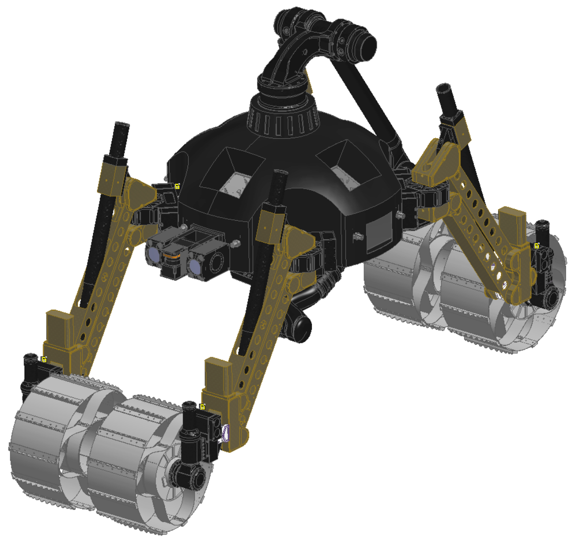

Figure 4. Sherpa in its minimal volume configuration. Due to the clustering of four out of six actuators at the end of each leg, more compact configurations are not possible.

base camps in a lunar logistics chain [12]. These base camps constitute node for (geological) sample storage and are planned to be used as communication relays and for energy harvesting in a multi robot scenario.

The placement of base camps and the pickup of those passive structures requires a higher maneuverability of the central body than currently possible. For precise docking of the two corresponding interfaces, the rover's body-attitude should be controllable in all 6 DoF independently, which is not possible with the current design of the suspension.

3 Sherpa-Redesign

Based on the drawbacks as indicated in the previous chapter, a redesign of Sherpa's suspension system is currently executed. The main focus is to further increase the flexibility of the suspension system and trying to reduce the weight at the same time. In order to reduce the development effort, a modular actuator concept shall be used.

3.1 Suspension design

The new leg design is shown in Fig. 5. As previously described, the wheel flip function (DoF3 in Fig. 3) was rarely used and therefore subducted in the new design. The WheelTilt actuator of the old design is exchanged for a second lifting actuator ('outer actuator'), resulting in a knee in each of Sherpa's legs. The new knee couples a set of two parallel structures that are coupled as main actuators for controlling the height and the width of Sherpa's footprint, Figure 5.

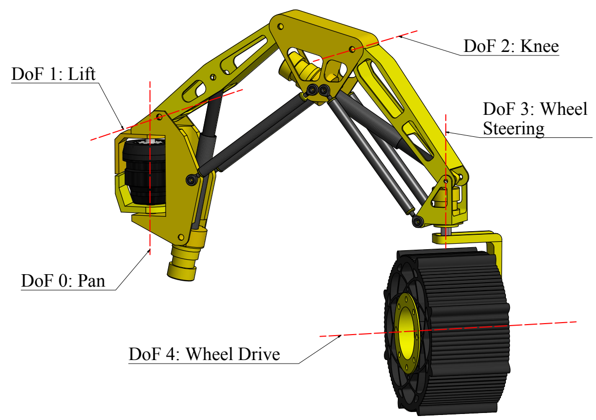

Figure 5. New leg design for Sherpa based on two serial aligned parallel kinematics

The linear actuators are installed in such a way that they experience tensional forces while the wheel has contact with the ground. This leads to a stiffer system compared to the original Sherpa design where the actuator has to provide a push-force and mechanical slackness leads to high position variance.

The new rover design in the regular driving pose is shown in Figure 6. With the proposed suspension design, the wheel contact point (WCP) can be moved $\approx 800\,mm$ in vertical direction. Due to the introduced knee, the wheel can be lifted independently from movements in x-y plane which is not possible with the original Sherpa suspension. Depending on the body height, a shift of up to $\pm 250\,mm$ is possible. When moving all legs synchronously, this results in an according body lean in the horizontal plane. Figure 7 depicts the movement range of the wheel contact point (WCP).

To measure the wheel loads (force and torque), a six DoF sensor will be installed between the drive motor and fork-type wheel attachment. The sensor input will be used for improved load balancing and terrain adaption. The additional sensor input is expected to facilitate the rover's terrain adaption capabilities and stability due to explicit load balancing.

The original version of Sherpa's suspension did not allow compact storage volumes. A compact stow volume is desired to be realizable with the new design. This demonstrates a possible launching configuration

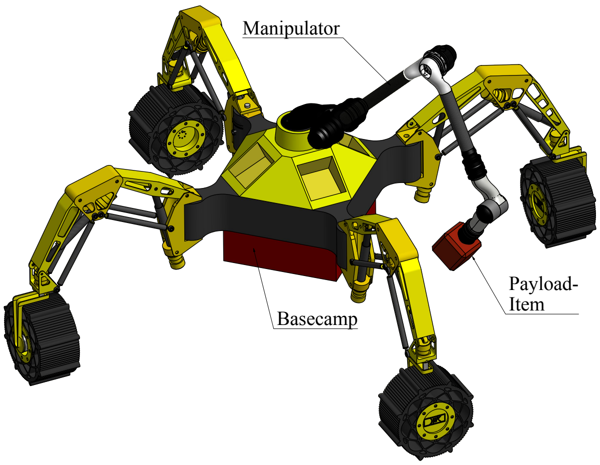

Figure 6. New rover suspension design. The suspension is shown in the normal pose: A cross shaped suspension alignment and at medium body height.

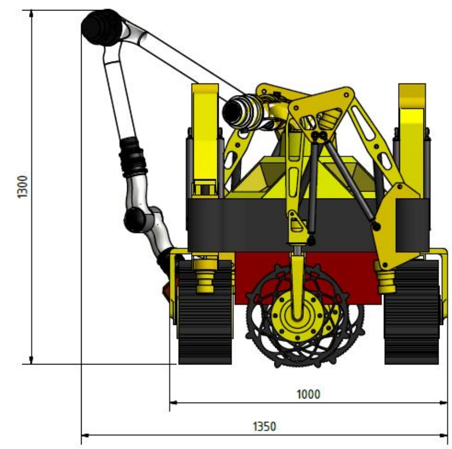

Figure 8. New stow pose of Sherpa. Note that the manipulator is unchanged in this design and might be adapted in a later development stage. Indicated dimensions are in mm.

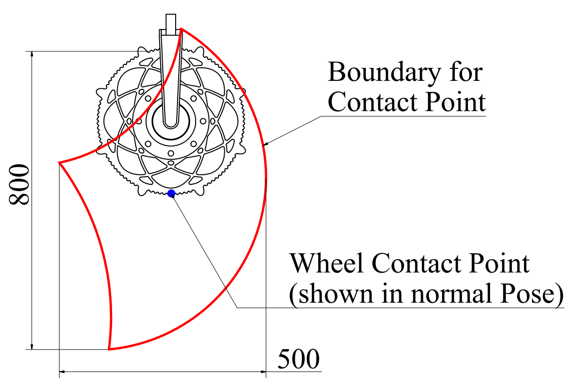

Figure 7. Movement range for the wheel contact point using DoF1 and DoF2. DoF0 has a movement range of $\pm 135°$ that creates a toroid of the denoted cross section. Normal pose denotes the expected nominal driving position (WCP in center of movementrange) in cross shaped stance. Dimensions are in mm.

and in terms of practical use facilitates transporting the rover for experimentation. The new suspension design with the newly introduced knee allows a way more compact bounding box than the original Sherpa suspension, Figure 8 shows Sherpa in the new stow configuration. Its new minimal volume envelope is approximately $1.0\,m \times 1.35\,m \times 1.3\,m = 1.76 m^3$

3.2 Modular Actuator Design

A set of modularized actuators of different power classes has been developed at the author's institute, these modules are used for the Sherpa redesign, reducing the number of different actuators in the system for improved maintenance and control. Basic components of the actuator modules are electronically commutated internal rotor DC motors of different classes and accompanying ellipto-centric gears of varying gear reductions in single or two stage configurations. For a better maintainability of the electronics, each actuator module has its own electronic stack with a base-board which provides all necessary connector plugs without any active components. Main sensors for position, speed and torque control are two magnetic encoders implemented on the drive side and the gear side, respectively as well as a bi-directional current measurement in each motor phase. For communication between the actuator modules and the central control electronics a high speed daisy chained serial communication is used with a communication speed up to $320Mbit/s$. Additionally temperature monitoring is implemented to avoid overheating of the motors.

From the experiences with the initial Sherpa design and using simulation tools, the required mechanical power for each DoF is estimated. The result is that both linear actuators and the steering actuator do require a comparable power and therefore can be based on the same motor module. The pan actuator has to provide a very high torque and therefore will be designed around a two stage cycloid gear. The same motor size as the leg pan actuator can be used for the wheel drive, but due to lower torque requirements a single stage gear is appropriate.

In the design phase it could be shown that the modular concept offers a great reduction in development time and costs. However, a drawback in modular devices with discrete performance classes are weight and efficiency. In case of Sherpa's suspension redesign, costs and time where favored over explicitly for this system developed actuator modules.

For the linear actuators in the legs, a relatively high rotational speed is required, therefore RoboDrive ILM50×8 motors (nominal speed: $5500rpm$) are used. For wheel steering, an ILM50×14 offers higher torque at lower speeds (nominal speed: $3500rpm$). Advantageous on the modular actuator concept is that the same casing can be used for both type of motors. For the wheel drive and the leg pan actuators, higher power is required, therefore ILM70×10 is used.

All of the actuators use HarmonicDrive gears to match the motors' speed and torque to the given requirement. For the linear actuators self-locking is desired, therefore ball-screw type screwjacks can not be used. Instead, ACME-type spindles get driven by an HarmonicDrive Series 17 gear, the same type which is used for the steering actuators. To provide the required torque, a two staged gear (double HarmonicDrive combination) is used for the leg pan actuator.

4 Conclusion and Outlook

4.1 Conclusion

This paper gives an overview of the current state of the exploration rover Sherpa. Current drawbacks are outlined and a new design improving the suspension system is proposed. The mechanical fabrication of the new components is currently in progress.

The original design of the suspension system featured some degrees of freedom (DoF) that were used sparsely, since the employed flexible wheels proved to exhibit a sufficient adaption to the ground that was planned to be done by two of the six DoF per leg. In the new design these DoF are thus subducted. For improving the independence of the wheel contact point's x, y, and z-coordinate, an additional knee joint is introduced. Furthermore, the offset of the wheels to their steering axis is removed to decouple steering direction from the positioning of the wheels ground contact point in the rover's coordinate frame.

The joints in the new suspension system are designed as modular units that can be adapted in terms of motor power and gear reduction. This reduces design efforts and facilitates maintenance of the system.

4.2 Outlook

The original rover motion control system (MCS) was ported into the Rock framework and is currently re-structured to exploit the tools and workflow provided by this framework. To exhaust the systems' capabilities, a distributed control software architecture is applied to the rover, allowing autonomous or semi-autonomous modes as well as full manual control by a mission operator. The underlying rock component model bases on the Orocos real time toolkit. Rock provides all tools required to set up and run robotic systems with a wide range of well tested modules for sensors, actuators and high-level operations like path planning or map generation.

Within rock, an encapsulated motion control will be implemented. The MCS is structured in different layers, e.g. a *motion generation* layer, the *motion control* layer or the *MCS core* layer. In the *motion generation* layer, high level inputs are used to generate the locomotion of the robot and the motions associated with reconfiguring the suspension system. These are feed forward modules, mainly transforming the inputs to desired outputs in the form of wheel orientation, wheel speed, and foot print.

The *motion control* layer takes the outputs of the *motion generation* layer and modifies the values based on the chosen control modes (e.g. terrain adaption). The terrain adaption controller changes the wheel contact point so as to actively adapt to changes in the terrain. This is achieved by estimating the loads expected from each of the legs in the current configuration and varying the height of the WCP in order to achieve this load. This ensures proper ground contact for all the wheels even when terrain changes. Roll/pitch adaption controls the body roll and pitch such that the body is leveled with respect to the gravity vector or, if desired, is parallel to the inclined ground. Still the operator can modify any given value with an offset, if required.

In the *MCS core* layer, the inverse kinematics are calculated in order to generate the appropriate joint commands from the cartesian commands generated in the layers before. Safety modules implement a self collision avoidance or a center of mass (CoM) stability checker to prevent damages to the hardware. A trajectory interpolator generates smooth joint reference trajectories taking into account speed and acceleration limits. The output of these module is sent as reference to the robot's joints. In the current state, the joints internally make use of cascaded position-speed-current control, which can actively limit the maximum position, speed, and currents, ensuring a safe operation.

The future Sherpa will benefit from its increased range of motion combined with additional sensors to allow reactive actions to given situations. Improving the overall outcome of a certain mission remains one of the main intention and will be achieved by reducing the operational risks due to more autonomous functionality like navigation and planning introduced by the rock framework.

Acknowledgment

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