Locomotion Modes for a Hybrid Wheeled-Leg Planetary Rover

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***Abstract*— This paper introduces locomotion modes for the planetary rover Sherpa[1]. The rover's locomotion system consists of four wheeled-legs, each providing a total of six degrees of freedom. The design of the active suspension system allows a wide range of posture and drive modes for the rover. Self-locking gears in the suspension system allow to maintain the body height without the need of actively driving the actuators. Thus, energy-efficient wheeled locomotion and at the same time high flexibility in ground adaption and obstacle negotiation are possible, as well as high payload capabilities. Furthermore, the rover will be equipped with a manipulator arm explicitly designed to be used for locomotion support. Thus, all degrees of freedom of the system can be used to enhance the locomotive capabilities. This paper gives an overview of the mechanical design of the rover, kinematic considerations for movement constraints on the wheel contact points are presented. Based on these constraints, the wheel motions due to the commanded velocities of the platform can be calculated, taking into account the flexible posture of the rover. A first set of possible locomotion modes for the rover is presented in this paper as well.**

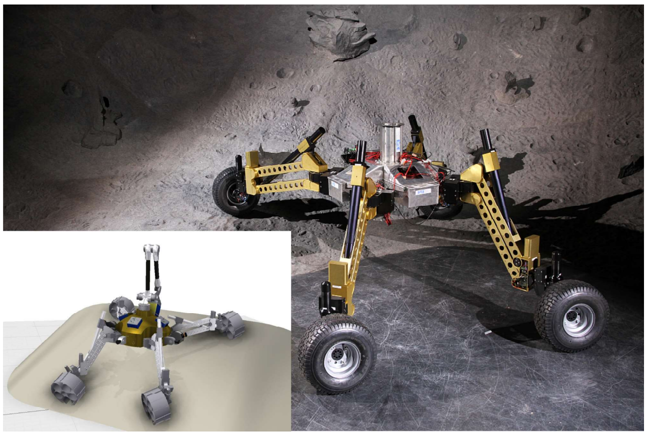

Fig. 1. Current state of the integration study of Sherpa in DFKI's artificial crater environment. The active DoF are used in a way that the central platform is horizontally aligned. The inset depicts the CAD model of the rover.

I. INTRODUCTION

Today, extraterrestrial exploration is conducted nearly exclusively by robotic means. This includes satellites for remote sensing (e.g. *LCROSS* [1]) as well as surface deployable probes (e.g. *Phoenix Lander* [2]) and mobile exploration robots (e.g. *Spirit* and *Opportunity* [3]). In order to investigate a planetary terrain closely, mobility has to be provided to allow for collecting scientific samples from various locations. Canyons and impact craters are of special scientific interest, but these terrains are also challenging for locomotion systems. Thus, these areas can only be accessed with sophisticated mobile devices.

Mobile systems that have been deployed up to now on Mars and Moon make use of passive suspension systems. The rocker-bogie system, used for example in *Pathfinder*, the *Mars Exploration Rovers*, and also implemented for the *Mars Science Laboratory* [4], is a sophisticated suspension system for a wide range of terrains. However, experiences with the Mars Exploration Rovers show, that a robot with a purely passive suspension system has limitations for instance in stuck situations, as appeared when *Spirit* drowned in a spot of soft soil [5]. Furthermore, the size of the obstacles that can be overcome is limited to the range of a wheel diameter.

An active suspension system overcomes these limitations and can maintain the advantages of wheeled locomotion such as energy efficiency. With the *ATHLETE* family of rovers, NASA/JPL introduced a rover with wheels mounted on a six degrees of freedom (DoF) (*ATHLETE*) and a seven DoF (*Tri-ATHLETE*) leg [6], respectively. This rover is able to use its wheels for locomotion in moderate terrain, whereas the DoF of the legs can be used for egression off the landing unit and overcoming big obstacles. The robot is meant to serve as crew assistant and cargo transporter on the Moon. Furthermore the robot can be used to transport habitat modules, thus serving as a mobile platform for heavy loads. The final version of ATHLETE aims at limb sizes of 4 m length.

Scarab [7] is a four wheeled rover that combines a classical bogie suspension with an active DoF to enhance the ability to climb and drive along slopes. Furthermore, the control of the body height as well as the roll angle of the robot is possible. The system is designed to work in places of perpetual darkness at the lunar poles in order to search for deposits of water ice.

Outstanding surface mobility can be provided by legged locomotion, since the foot contact points do not need a constant trajectory on the ground plane but can be placed arbitrarily within the workspace of the leg, enabling walking machines to climb even vertical surfaces [8]. However, purely legged locomotion suffers the disadvantage of complexity and worse energy efficiency compared to wheeled locomotion. This makes legged robots more suitable for relatively short traverses in extreme terrains [9] [10].

The combination of wheeled and legged locomotion provides the possibility to combine the advantages of both approaches. In the RIMRES-project [11] we pursue this approach on different levels: (1) We combine two separate

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[1] Sherpa: Expandable Rover for Planetary Applications

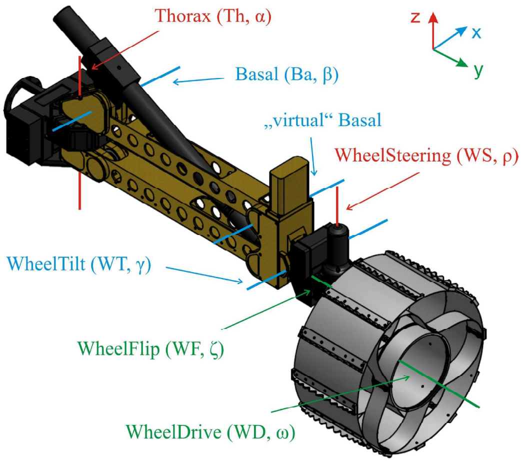


Fig. 2. The four DoF of a swing unit and two DoF for actuating the wheel. The virtual Basal DoF results from the parallel kinematic. All angles are shown in their respective zero position.

systems, namely a wheeled rover (Sherpa, Fig. 1) and a legged scout (CREX[2]) into one multi-robot system. (2) The rover that is responsible to carry the scout to the crater rim is designed with an active suspension system to be highly manoeuvrable itself and to transport the scout safely to the crater rim.

Sherpa is designed to transport moderate loads. Its main tasks are transporting the scout robot to scientific interesting places and setting out science packages. Since Sherpa is embedded into a heterogeneous multi-robot system another design issue is the compatibility with the hardware developed for the multi-robot system RIMRES. A distinct new feature of the robot is its ability to use the robotic arm for multiple purposes: (1) Manipulating payload-items, fig.3, (2) using the embedded camera for system supervision (hazard cam) and (3) active locomotion support.

This paper is structured as follows: In Section II, the mechanical design of Sherpa is briefly described. Section III presents kinematic considerations based on the wheel contact point's motion restrictions. Section IV presents a subset of manually designed postures and drive modes for Sherpa to give a first insight into the locomotion capabilities of the system. The last section concludes the paper and gives an outlook on the next steps of the work with Sherpa.

II. DESIGN OVERVIEW

Sherpa is a four wheeled rover that is capable to connect tightly to a legged scout robot via an electromechanical interface beneath the body [12]. The same interface is used to transport payload items in the four payload bays that are oriented around the central manipulator tower. The manipulator itself makes use of the interface for manipulating the payload items. The whole design of Sherpa is driven by the need to safely carry the legged scout and to manipulate the payload-items. Table I provides some of the key values of Sherpa.

[2]Crater Explorer

TABLE I
KEY DIMENSIONS OF SHERPA

Description	Value
Max. ground clearance	711 mm
Min. ground clearance (Wheels above body)	-189 mm
Propellant torque per wheel	59 Nm
Max. speed of wheel drive	$165° \frac{1}{s}$
Expected mass	≈ 200 kg
Additional Payload	≈ 60 kg
Length of fully stretched arm	1772 mm

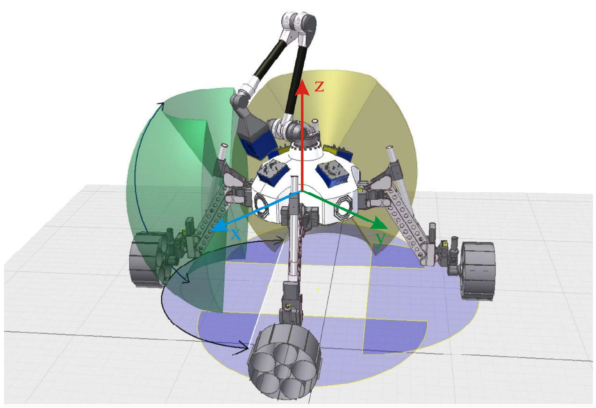


Fig. 3. Movement range of the two main DoF of Sherpa's active suspension system, depicted for two legs. The two DoF result in a spherical shape of the workspace of the swing unit. The thorax movement range for all four and the combination of basal an thorax for two of the swing units is shown. The manipulator is shown with one payload item attached, in each of the four payload bays around the manipulator base is another payload item mounted.

Currently, the hardware integration is ongoing, Fig. 1 depicts the state of the integration. The first drive modes have been implemented for the real system, however, intensive testing and verification is still work in progress.

A. Active Suspension System

The suspension system makes use of actively controllable swing units in order to change the posture of the robot or to lift a wheel off the ground and replace it in a suited place. Short passages of ambulating locomotion are possible. Fig. 2 shows one swing unit with all joints in zero position and the naming of the joints. The Basal joint has a "virtual counter joint" resulting from the usage of a parallel structure. The possible range motion of the two main degrees of freedom of Sherpa's swing units is depicted in Fig. 3. The Thorax joint has a range of ±90°, whereas the Basal joint has a moving range of ±60°, resulting in a maximum vertical stroke of 900 mm. The combination of the auxiliary DoF WheelTilt and WheelFlip can be used to orient the wheel towards a slope.

The DoF are driven by highly reduced gears for supporting the rover without the need for actively maintaining the body height. All four DoF of a swing unit use brushless DC motors with a planetary gear. For further reduction and a self-locking feature, worm gears (Thorax, WheelFlip) and spindle drives (Basal, WheelTilt) are used. The actuators only have to be driven when a change in the locomotion system is desired. Thus, the energy efficiency of wheeled locomotion is maintained.

In order to adapt to the ground on a smaller scale, passive suspension is provided through springs and adaptive flexible wheels. Sherpa's wheels make use of adaptronics in order to sense the properties of the interaction of wheel and surface and to actively adapt the stiffness of the wheels to the actual situation[3]. This will reduce the danger of digging to deep into the ground and get stuck in loose surface material. In case the rover is stuck nonetheless, the active suspension system can be employed to lift the leg out of a sand pit or a comparable situation.

For each DoF of a swing unit, an absolute position sensor is used to be able to measure the deflections of the springs in the passive part of the suspension system. In the mounting point of the swing units to the body, a customized force-torque load cell will be employed to measure the loads that are acting on a swing unit. These measurements can be used for load balancing between the legs and to detect stuck situations, contact with obstacles, and alike.

B. Manipulator Arm

The manipulator arm is designed to be used for various applications: (1) Manipulation of payload items, (2) Supervision of the rover and its closer surroundings, (3) Locomotion support by shifting center of gravity (COG) and using the manipulator arm as an additional leg.

For manipulation and assembly tasks, the arm is equipped with an electromechanical interface which is also used for connecting payload items as well as rover and scout. This interface provides mechanical, electrical, and data connection between two units of the RIMRES system [12].

As proposed for a tracked robot in [13] or a planetary rover in [14], a robot's manipulator arm can also be used for locomotion support. This can improve the locomotive abilities of the system, thus increasing the robustness of the system in unknown environments.

From the beginning of the design phase, the manipulator arm of Sherpa is meant to be a multi-functional tool as stated above. In order to support the rover's weight, considerable torques have to be generated by the manipulator joints. In an evolutionary approach using a physical simulation environment in combination with CMA-ES[4], the optimal joint lengths and required torques for the given use-cases were determined.

Fig. 3 shows the resulting design of the manipulator as mounted on the rover. Currently, the mechanical construction of the first and second joint as well as of the connecting link is finished based on the simulation results. The second joint will be driven by two parallel brushless DC motors in order to generate the required torques for supporting the rover's weight. The link lengths are chosen in a way, that the arm is able to reach the surface over an attached payload item in a radius of 900 mm around the center of the body when the rover has maximum ground clearance ($\beta = 60°$).

Since the manipulation interface is not designed to withstand the loads that occur during the support of the rover, the wrist of the manipulator arm is moved aside and a dedicated footplate is used for ground contact.

III. KINEMATIC CONSIDERATIONS

In this section, the movement constraints at the contact points of the wheels are used to deduce the wheel orientations and velocities for given commanded velocities. Furthermore, it is shown how the orientation of the wheels (including the robot's posture in Thorax and Basal joints) affects the general mobility of the robot.

A. Assumptions

For the calculations conducted in this section, the wheels are assumed to experience no slippage or skidding. The calculations in the following are derived from [15] and extended to Sherpa's flexible morphology.

The three-dimensional vector ξ^W describes the pose of the robot with respect to the fixed world coordinate frame.

$$\xi^W = \begin{pmatrix} x^W \\ y^W \\ \theta^W \end{pmatrix} \quad \text{and} \quad \dot{\xi}^W = \frac{d}{dt}\xi^W = \begin{pmatrix} \dot{x}^W \\ \dot{y}^W \\ \dot{\theta}^W \end{pmatrix} \tag{1}$$

With the orthogonal rotation matrix $R(\theta)$, the coordinates can be transformed into the body frame. Note that the superscript ^{B} is omitted for the body coordinates in the following. For planar movements, the body frame's z-axis can be assumed to be collinear with the world frame's z-axis without loss of generality. Thus, $\dot{\theta}$ is the rotational velocity of the robot around its z-axis. The origin of the body frame is located in the geometric center of the robot, fig. 4. $\dot{\xi}^B$ is used as input vector of the currently active drive mode (section IV) for commanding the robot's velocities.

$$\xi^B = R(\theta) \cdot \xi^W \tag{2}$$

$$\mathrm{R}(\theta) = \begin{pmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3}$$

B. Description of Wheel Motions

In the following, the dimensions and angles needed for setting up the movement constraints on the rover's wheels are illustrated. The values are depicted in fig. 4. As also depicted in fig. 2, α_i, β_i and ϕ_i describe the angular positions of the Thorax, Basal and WheelSteering joint, respectively. The point $\mathcal{PWS}$ is the position of the WheelSteering axis. The length of the connecting line from the robots center $\mathcal{O}$ to $\mathcal{PWS}$ is denoted l_i. The length l_i is dependent on both, α and β. However, note that the calculations presented here are projected into the x-y-plane of the robot, so the z-component of $\mathcal{PWS}$ can be neglected in this case.

$$l_i = \sqrt{(x_{\mathcal{PWS},i})^2 + (y_{\mathcal{PWS},i})^2} \tag{4}$$

[3]The wheels are currently under development by the project partner DLR-RY: Institute of Space Systems, Bremen, Germany. The rubber wheels in Fig. 1 are a substitute for first experiments with the active suspension system.

[4]Covariance Matrix Adaption Evolutionary Strategy

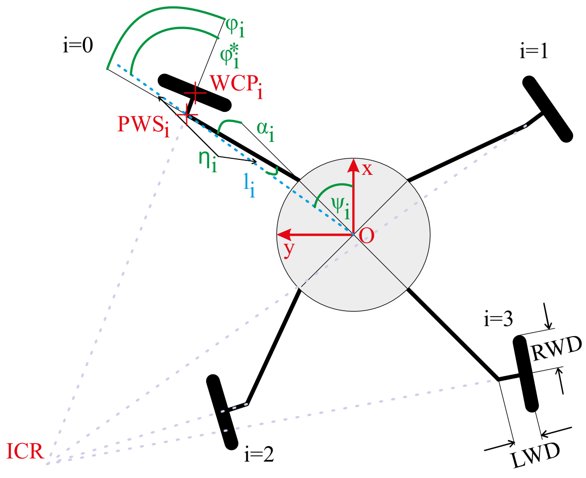


Fig. 4. Schematic view of Sherpa in arbitrary pose for kinematic calculations. α_i: angle of the thorax joint; φ_i: angle of the wheel steering DOF to swing unit; ψ_i: angle of connection line from origin to wheel contact point; l_i length of that line.

The angles ψ_i are the angles between l_i and the x-axis of the robot.

$$\psi_i \;=\; \arctan 2(y_{\mathcal{PWS},i}, x_{\mathcal{PWS},i}) \qquad i = \{0, \dots, 3\} \tag{5}$$

To be able to proceed with the calculations as proposed by Campion et. al [15], we introduce the *virtual steering angle* φ_i^*, measured between the wheel axis of wheel i and l_i, fig. 4. The connection between the virtual steering angle and the actual steering angle φ is given by eqn. (6).

$$\varphi_i = \varphi_i^* - \eta_i \tag{6}$$

The angle η can be calculated using simple geometric dependencies:

$$\eta_0 \;=\alpha_0 - \Psi_0 + \frac{\pi}{4} \tag{7}$$

$$\eta_1 \;=\alpha_1 - \Psi_1 - \frac{\pi}{4} \tag{8}$$

$$\eta_2 \;=\alpha_2 - \Psi_2 + \frac{3\cdot\pi}{4} \tag{9}$$

$$\eta_3 \;=\alpha_3 - \Psi_3 - \frac{3\cdot\pi}{4} \tag{10}$$

With these terms defined and the no slip-condition, the following two constraints for velocities along the wheel plane and orthogonal to the wheel plane can be established for the four wheels ($i = 0, \dots, 3$), where ω_i denotes the turning speed of wheel i.

Constraints along wheel plane:

$$\begin{pmatrix} \sin(\psi_i + \varphi_i^*) \\ \cos(\psi_i + \varphi_i^*) \\ l_i\,\cos(\varphi_i^*) + \mathrm{LWD} \end{pmatrix}^T \dot{\xi} - \mathrm{RWD}\,\omega_i - \mathrm{LWD}\,\dot{\varphi}_i = 0 \tag{11}$$

Constraints orthogonal to wheel plane:

$$\begin{pmatrix} \cos(\psi_i + \varphi_i^*) \\ \sin(\psi_i + \varphi_i^*) \\ -l_i\,\sin(\varphi_i^*) \end{pmatrix}^T \dot{\xi} \qquad = 0 \tag{12}$$

In difference to [15], the velocity of the off-centered wheel adds to the motion along the wheel plane, since Sherpa's wheel is orthogonal to the lever (LWD; denoted d in [15]) and not parallel, as in the castor wheels described by Campion et al.

For simplification, the velocity $\dot{\alpha}$ of the thorax joint has been omitted here. It is assumed that in each calculation step, the posture of the robot can be regarded as fixed. However, the posture is still included in the calculations, since l_i is dependent of α_i and β_i.

C. Robot Control with Flexible Suspension System

For a given velocity vector $\dot{\xi}$ the angle φ_i^* can be calculated from constraint (12), the required wheel velocity ω can then be calculated from constraint (11). Effectively this means, that the wheels will be oriented according to the instantaneous center of rotation (ICR) for a given $\dot{\xi}$, see also section IV-C.1.

$$\varphi_i^* \;=\; \arctan \frac{-1\cdot(\cos\Psi_i\cdot\dot{x} + \sin\Psi_i\cdot\dot{y})}{\cos\Psi_i\cdot\dot{y} - \sin\Psi_i\cdot\dot{x} + \dot{\Theta} l_i} \tag{13}$$

$$\omega_i \;=\; \frac{\sin(\Psi_i + \varphi_i^*)\dot{x} + \cos(\Psi_i + \varphi_i^*)\dot{y}}{\mathrm{RWD}} - \frac{(\cos(\varphi_i^*) l_i + \mathrm{LWD})\,\dot{\Theta} - \mathrm{LWD}\dot{\varphi}_i}{\mathrm{RWD}} \tag{14}$$

D. Restrictions to Robot Mobility

The constraints (11) and (12) can be written under the following matrix form to summarize the constraints for all four wheels:

$$J_1\,\dot{\xi} + J_2\,\omega + J_3\,\dot{\varphi} = 0 \tag{15}$$

$$C_1\,\dot{\xi} \qquad = 0 \tag{16}$$

In which the matrices J_1 and C_1 are defined as follows. J_2 and J_3 are diagonal matrices containing the wheel diameters RWD and the offset length LWD on their diagonal, respectively.

$$J_1 \;=\; \begin{pmatrix} \sin(\psi_0 + \varphi_0^*) & \cos(\psi_0 + \varphi_0^*) & l_0\,\cos(\varphi_0^*) + \mathrm{LWD} \\ \sin(\psi_1 + \varphi_1^*) & \cos(\psi_1 + \varphi_1^*) & l_1\,\cos(\varphi_1^*) + \mathrm{LWD} \\ \sin(\psi_2 + \varphi_2^*) & \cos(\psi_2 + \varphi_2^*) & l_2\,\cos(\varphi_2^*) + \mathrm{LWD} \\ \sin(\psi_3 + \varphi_3^*) & \cos(\psi_3 + \varphi_3^*) & l_3\,\cos(\varphi_3^*) + \mathrm{LWD} \end{pmatrix} \tag{17}$$

$$C_1 \;=\; \begin{pmatrix} \cos(\psi_0 + \varphi_0^*) & \sin(\psi_0 + \varphi_0^*) & -l_0\,\sin(\varphi_0^*) \\ \cos(\psi_1 + \varphi_1^*) & \sin(\psi_1 + \varphi_1^*) & -l_1\,\sin(\varphi_1^*) \\ \cos(\psi_2 + \varphi_2^*) & \sin(\psi_2 + \varphi_2^*) & -l_2\,\sin(\varphi_2^*) \\ \cos(\psi_3 + \varphi_3^*) & \sin(\psi_3 + \varphi_3^*) & -l_3\,\sin(\varphi_3^*) \end{pmatrix} \tag{18}$$

The rank of the matrix C_1 is an indicator for the mobility of the robot system [15]. If $rank\,[C_1] = 3$, no motion of the robot is possible, since $\dot{\xi} = 0$ is needed to fulfill constraint (16), thus the rank has to be less than 3; due to the dimensions of C_1, the rank is always less than or equal to 3.

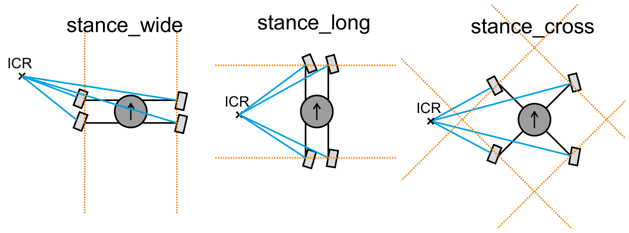


Fig. 5. Three basic stance modes and the dependency of ICR-singularities of the stance mode. When the ICR is moved across a line, at least one wheel has to flip to the opposite end point in a realignment phase.

When the wheels are not coordinated in a way, that the normals of the wheels cross in one singular point (the instantaneous center of rotation, ICR), clearly no directed movement is possible. This is also reflected in the fact that for such configurations $rank\,[C_1] = 3$ (we assumed no slipping motion of the wheel's contact point).

When for instance a point turn is commanded, $\varphi_i^* = 0$ and thus $rank\,[C_1] = 2$. Note that the commanded value of φ_i^* is independent of α and β, which means that the movement is possible for each posture of the corresponding swing unit. However, the real commanded value φ_i obviously is dependent on the posture of the swing unit.

IV. POSTURE AND DRIVE MODES: LOCOMOTION USING ALL DOF

This section first gives definitions of the terms *behavior*, *posture mode*, and *drive mode* as used in this work and then presents some of the possible posture and drive modes for Sherpa.

A. Definitions

Behavior A behavior is a process that is implemented in the robot's operating system. A behavior controls the robots actuators and/or collects sensor data.

Posture Mode A posture mode is a behavior that controls the robot's extremities in order to achieve a goal such as keeping the robot's center of gravity within the stability margin of the support polygon. The posture is not fix, it can be adapted to changes in the environment.

Drive Mode A drive mode is a behavior that is commanding the robot's actuators in a way that the robot moves in the fixed world coordinate frame.

Locomotion Mode A locomotion mode is a combination of drive and posture modes that is used for propelling the robot.

B. Posture Modes for Sherpa

By presenting a basic set of posture modes, this section provides an insight into the flexibility of Sherpa's suspension system. As given in the above definition, posture modes are used for adapting the robot's pose to the environment, for example to facilitate locomotion in slopes. Different posture modes can be combined by different merging functions. The robot's operating system MONSTER [16] allows writing multiple joint position/velocity commands to one single hardware driver using an appropriate merge function.

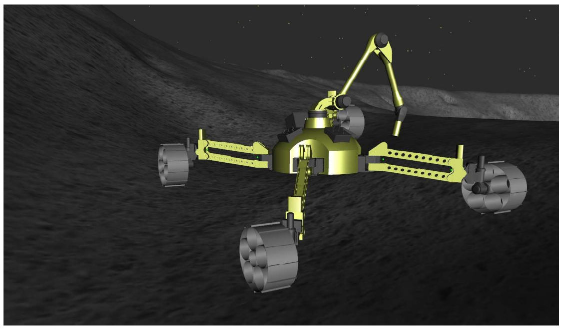


Fig. 6. Roll and pitch adaption for locomotion in slopes. The picture shows a screenshot taken from the physical simulation where the main body's roll and pitch angle are kept below 1°. The manipulator arm is oriented towards the slope.

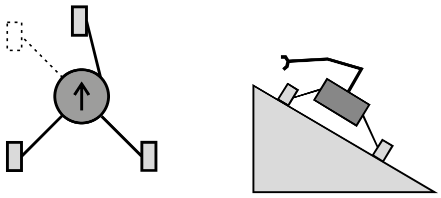
1) Posture Stance: Fig. 5 illustrates three possibilities of the basic posture mode *stance*. This posture mode varies the support polygon of the robot. Narrow passages can be passed in a long stance, while the wide stance can be used to overcome medium sized craters or boulders without needing to traverse them with any wheel. For varying the stance, this posture mode controls the thorax angle of the legs. The regular stance mode for Sherpa has been chosen as a cross shaped footprint. A relatively high stability is ensured with this posture, while high flexibility concerning changes of the posture is achieved.

2) Posture Roll/Pitch: The posture mode *roll/pitch* keeps the roll and pitch angle of the robot within specified boundaries. This posture mode is important for negotiating moderate slopes and during traversing rugged terrain. If the body angles are kept approximately constant, mechanical stress induced into the manipulator arm mounting can be reduced. Fig. 6 shows a snapshot from the physical simulation environment, where Sherpa controls its roll and pitch angle by adapting the height of the wheels. The input for this posture mode is given by an inertial measurement unit. For the real system, the measurements of a force-torque load cell in the shoulder (currently under development) can be included additionally.

In principle, this posture mode can be superimposed with other posture modes. When the wheels are lifted (due to the morphology, a pure z-motion is not possible), stress might be induced in the structure. However, by combining the movements in the first two joints, the circular motion around the x-axis (Basal joint) can be transformed into a circular motion around the y-axis. In projection to the ground plane, this is a straight movement along the x-axis of the robot. This movement can easily be compensated by adapting the turning speed of the respective wheel.

3) Posture Tripod: Driving in a tripod configuration is necessary, if a wheel drive or wheel steering actuator fails. Then, the robot does not have to drag a malfunctioning wheel behind, which would affect energy efficiency and stability. If needed, the leg can still be used in some kind of stepping motion, where steering and/or wheel drive actuator are not needed. In order to increase the stability of the tripod stance, this posture mode can be combined with the posture *manipulator balance*.

4) Posture Manipulator Balance: This posture mode makes active use of Sherpa's manipulator arm to support locomotion so as to increase the stability of locomotion. For this posture mode, the relation between COG and spanned support polygon is constantly checked. If the COG moves to close towards the border of the support polygon, an appropriate action of the arm is taken in order to move the COG back towards the center of the support polygon. The arm is not kept in a fixed pose, since its pose is constantly adapted to compensate for the movements of the rover in the terrain.



(a) Tripod posture: If a wheel unit fails, the robot can lift the corresponding leg.

(b) Using the manipulator for balancing the center of mass

Fig. 7. The posture modes *Tripod* and *Manipulator Balance*

C. Drive Modes for Sherpa

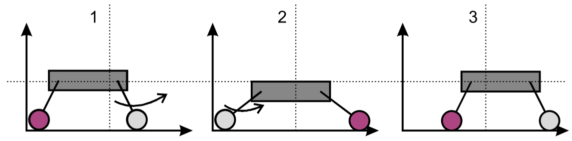
In this section, a subset of possible drive modes is presented. The drive modes are combined with the posture modes (and optional reflexes) into locomotion modes. Some drive modes are incompatible with certain posture modes. Only one drive mode is possible to be active at a time, while various posture modes can be activated simultaneously with the drive mode.

1) Omnidirectional Control: The instantaneous center of rotation (ICR) is a common tool to describe the translational and rotational movement of a rigid body as a purely rotational movement. It is also widely used in order to control wheeled vehicles, the control approach is not limited to flat terrains [17]. The ICR follows the rover movement and in each time instant, the ICR is the current center of rotation of the rover's body. By steering the wheels in order to cross their normals of their respective wheel plane in the ICR, a smooth trajectory following of the robot is made possible. Generally, for Sherpa all kinds of postures are compatible to the *ICR control*.

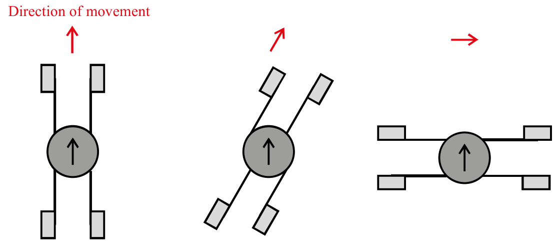
In case of Sherpa, there is no fixed geometry concerning the suspension system, i.e. the footprint of the robot is time-varying. Thus, the calculations for the wheel orientations always have to be adapted to the current posture mode of the robot, cf. section III.

A second issue arises with the mechanical design of the wheel modules. Since it is not possible to turn the wheel freely in 360°, several lines of singularities exist. If the ICR is moved across such a line, the wheel theoretically has to move in zero time from one limit to the opposing one (resulting in a 180° turn in 0 s). Fig. 5 illustrates the change between the singularity lines for three different stance modes.

For an ICR that temporarily reaches the singularity line, a correction movement with the thorax joint can avoid the singularity. When the ICR is set completely on a different side, the robot has to stop and re-orient the wheels in order to move on with the new ICR.



(a) By keeping one pair of wheels fixed with respect to the ground (colored wheel) the grip of the system is increased. The basal joints account actively for propelling the system.



(b) "Omnidirectionality" of inch worming behavior: Due to the flexibility, inching can be executed in arbitrary directions. The arrow depicts the x-axis of the robot's body frame

Fig. 8. Drive mode *inch worming* and direction variations

2) Inch Worming: The drive mode *inch worming* utilizes the fact that in this mode at least two wheels have fixed ground contact at all times to reduce the slippage of the vehicle [7]. Fig. 8(a) depicts the three steps of this drive mode: (1) The rear wheels are fixed and the body is lowered by rolling over the front wheel pair. (2) At the lowest point, the front pair of wheels is kept fixed, while the rear wheels roll forward and the body hight is increased. (3) The procedure repeats itself.

Due to the flexibility of Sherpa's locomotion system, an arbitrary direction for this mode is possible. The Thorax joints are aligned in a way that ensures the desired direction of motion, fig. 8(b). First tests with the real system on a supporting frame proved that the inch worming mode can be used in an arbitrary 2D direction.

3) Stepping with Manipulator Arm Support: In general the active suspension system also allows stepping or walking motions. These can be useful when obstacles have to be overcome or single wheels have to be freed from stuck situations. To support stability, the manipulator arm can be used to stabilize the robot at the spot where the swing unit is lifted. The stepping behavior should only be used for short traverses and to free the robot since it is expected to be less energy-efficient than rolling motions.

The scheme for this locomotion behavior is as follows: (1) Place the manipulator's footplate close to the wheel that is next to be lifted, (2) lift the wheel and place it according to the desired direction of movement, (3) when the wheel is on the surface again, move the manipulator to the next wheel that is to be lifted and start the procedure again.

Since the manipulator arm is designed to support the rover when two wheels are lifted, it should be possible to mount even obstacles that are higher than the 900 mm maximum vertical stroke of the rovers legs. However, this has still to be verified with the real system when the integrated manipulator arm is available.

V. CONCLUSION AND OUTLOOK

In this paper, posture and drive modes for the planetary rover Sherpa are introduced. By combining a drive mode with one or more posture modes, a locomotion mode for the rover is realized. The presented modes are an initial set that has been manually designed and partially implemented in a physical simulation environment and on the real system.

The design of the robot facilitates a multitude of postures and drive modes that can be implemented for locomotion in various terrains. Furthermore, the manipulator arm on the robot is explicitly designed for locomotion support. The possibilities for using the arm for locomotion include shifting of the COG to enhance the stability during the traverse of slopes. Furthermore, actively incorporating the arm into locomotion patterns is possible, so it can be used, for example, to support the rover when a leg is in a stuck situation.

The wheel configuration space for smooth movements without slipping and skidding under the constraint of a variable locomotion system is presented. In the next steps the model will be extended for application in rough environments.

The presented locomotion modes will be extended and evaluated experimentally in various terrains with the real system. Up to now the implementation has been validated on flat laboratory floor. The comparison of the results from the locomotion experiments in relevant terrain then feeds into a locomotion mode controller, which will be responsible for choosing the appropriate locomotion mode for the current terrain based on a metric that incorporates stability, maneuverability and energy considerations.

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