ABSTRACT

It is the goal of this manuscript to describe and analyze a complete kinematic model for hybrid wheeled-leg rovers and its applicability to Sherpa, a flexible rover with a complex actuation system. Differential kinematic equations of the hybrid legs are combined to form the composite equation for the rover motion. The model captures the 6 DoF pose (position and orientation) while traversing uneven terrains for hybrid systems and independently actuated joints. The kinematics model is analyzed in order to correctly propagate rover pose as input for a pose estimator in localization. Initial results from simulation are discussed for Sherpa navigation kinematics towards efficient pose estimation and dead reckoning.

Key words: robot motion, wheel odometry, rover kinematics, dead reckoning and planetary rovers.

1. INTRODUCTION

Up to now planetary rovers deployed on extraterrestrial surfaces made use of passive suspension systems (mostly the "Rocker-Bogie" suspension). Wheeled mobile robots are more energy efficient than legged robots on hard and smooth surfaces while active articulated robots with sophisticated mobility systems enable traversal over uneven terrain. Development of hybrid wheeled-leg solutions for the next generation of more capable systems with active suspension are currently ongoing. The ATHLETE [WLB+07] family of rovers with completely active suspension or hybrid solutions with actively and passively suspended as in Scarab [BWW08] or Chariot1 are only some of the developments currently in progress.

Rover kinematics plays fundamental roles in design, dynamic modeling, dead reckoning, control and wheel slip detection. As the control of an actuated suspension system is more complex, a motion model of the chassis is required to correctly command the desired trajectory and propagate the pose of the wheels as well as to reduce slip by proper maneuvering [TM05][SSVO09]. Most efforts on kinematics have concentrated either on planar two-dimensional space, i.e., translation in the x-y plane and heading [Vol, GFASH09] or in more sophisticated systems with passive articulate joints [TM05]. Typically, the kinematics modeling can be solved by two methods, the geometric or the transformation approach. The geometric approach is more intuitive but it is restrictive to the particular platform lacking of generalization [CW90]. The transformation approach is general and consistent by applying a series of transformations and Jacobian matrices to relate motion in the joint space to the Cartesian space, which main contribution is by Muir and Newman [MN86].

Extensive research with different reasoning is available in literature. Alexander et al [AM89] present a planar rigid body model considering a variable number of wheels. Campion et al [CBDN96] classified ordinary mobile robots into five types taking into consideration generic parts of the model equations. Other research into wheel-ground contact angle and pose estimation of robots moving on uneven surfaces can also be found [LS07].

As of today, the challenges and problems of hybrid structures have not been extensively described. The approach presented in this paper extends [TM05, MN86] in order to solve the complete kinematics of hybrid wheeled-leg rovers. The methodology is applied to the particu-

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Figure 1: The fully integrated Sherpa robot in a lunar testing environment.
by the vector the particular leg kinematics in joints space represented by the transformation matrix $T_{C_i}$, the wheel contact frame

The actively control the angle.

For articulated rovers and it is more important for hybrid bile robots moving on flat terrains, it is a main distinction of degrees of freedom of each leg.

The wheel is considered to be a rigid disc. A key difference between planar and articulated rovers for uneven terrain is the wheel contact angle $\delta_i$ at each $C$-frame defined as the angle between the normal vector to the terrain plane and the wheel $z$ axis in $A$-frame (see Figure 3). Whereas the contact angle is always zero for planar mobile robots moving on flat terrains, it is a main distinction for articulated rovers and it is more important for hybrid wheeled-leg rovers which their suspension system allows actively control the angle.

The $C$-frame is related to the $A$-frame by the transformation matrix $T_{A_i,C_i}(\delta_i)$ defined as a rotation of the contact angle $\delta_i$ along the $y$ axis and a translation in $z$-axis defined by the wheel radius $r$. The corresponding transformation matrix is given in (where $c$ denotes cosine and $s$ sine):

$$T_{A_i,C_i}(\delta_i) = \begin{bmatrix} c\delta_i & 0 & s\delta_i & -rs\delta_i \\ 0 & 1 & 0 & 0 \\ -s\delta_i & 0 & c\delta_i & -rc\delta_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$  (1)

The leg forward kinematics solution relating the wheel contact point with respect to the body is defined by the matrix multiplication $T_{B,C_i}(q,\delta_i) = T_{B,A_i}(q)T_{A_i,C_i}(\delta_i)$. Hybrid rovers also provide rolling capability which entails a change of the $C_i$ frame over time increment $\Delta t$. The wheel motion is composite of a translation of the contact point along the $x$ axis by $r\eta_i + \xi_i$, where $q_{n,i}$ is the wheel rotation angle corresponding to the $i^{th}$ DoF of the leg $i$ and $\xi_i$ is the slip in the $x$ direction. The slip vector can be modeled in three dimensions including lateral slip $\eta_i$ along the $y$ axis and rotational slip $\xi_i$ along the $z$ axis. The resulting transformation matrix is (where $C_i$ is $C_i(k-1)$ and $C_i$ is $C_i(k)$):

$$T_{C_i,C_i} = \begin{bmatrix} c\xi_i & -s\xi_i & 0 & r\eta_i + \xi_i \\ s\xi_i & c\xi_i & 0 & \eta_i \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$  (2)

The transformation of the body frame $B$ with respect to the wheel contact point frame including the wheel rotation is:

$$T_{C_i,B} = T_{C_i,C_i}(\eta_i,\xi_i)T_{C_i,A_i}(\delta_i)T_{A_i,B}(q)$$  (3)

where $\varepsilon_i = [\xi_i, \eta_i, \zeta_i]$ is the slip vector and the matrix $T_{C_i,A_i} = (T_{A_i,C_i})^{-1}$ and $T_{A_i,B} = (T_{B,A_i})^{-1}$

Mobile robots are commonly commanded by desired velocities. The mapping between the rover Cartesian space rate vector $\dot{u} = \dot{u}_{B,B} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \\ \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix}$ and the joint space rate vector $\dot{q}$, the wheel rotation rate $\dot{q}_w$, wheel slip...
rate vector $\dot{\varepsilon}_{i}$ and the wheel-ground contact angle rate $\dot{\delta}_{i}$ is solved by the Jacobian matrix. The velocity kinematics is deduced by applying the transformation matrix and the derivation of the point position relative to a coordinate system. Defining the transformation of the rover body at time step $k-1$ ($\bar{B}$) to rover body at time step $k$ ($\bar{B}$) as $T_{B,B} = T_{\bar{B},C_{i}}T_{C_{i},C_{i-1}}T_{C_{i-1},B}$, the derivative is

$$
T_{\bar{B},B} = T_{\bar{B},C_{i}}T_{C_{i},C_{i-1}}T_{C_{i-1},B} + T_{B,C_{i}}T_{C_{i},C_{i-1}}T_{C_{i-1},B}
$$

Considering that for a general body in motion the position and orientation rates of $T_{B,B}$ are defined by the skew matrix:

$$
\dot{T}_{B,B} = 
\begin{bmatrix}
0 & -\dot{\phi} & \dot{\theta} & \dot{x} \\
\dot{\psi} & 0 & -\dot{\phi} & \dot{y} \\
-\dot{\theta} & \dot{\phi} & 0 & \dot{z} \\
0 & 0 & 0 & 0
\end{bmatrix}
$$

Equating matrices in Equation 4 and 5 the velocity kinematics is obtained. The equation can be reordered in order to have the leg Jacobian matrix $J_{l}$ of the form

$$
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{z} \\
\dot{\phi} \\
\dot{\theta} \\
\dot{\psi}
\end{bmatrix}
= J_{l}
\begin{bmatrix}
\dot{q}_{n}\n\dot{\varepsilon}_{i} \\
\dot{\delta}_{i}
\end{bmatrix}
$$

It defines the contribution of each leg to the body rover motion allowing the analysis of each joint to the resulting final velocity in $\dot{u}$. The $J_{l}$ matrix size is $6 \times (n+4)$ where $n$ corresponds to the DoF of the leg. Finally, the composite rover equations are obtained combining the Jacobian matrices for all legs into a sparse matrix equation as

$$
\begin{bmatrix}
I_{6} \\
I_{6} \\
\vdots \\
I_{6}
\end{bmatrix}
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{z} \\
\dot{\phi} \\
\dot{\theta} \\
\dot{\psi}
\end{bmatrix}
= J
\begin{bmatrix}
\dot{q}_{n} \\
\dot{\varepsilon}_{i} \\
\dot{\delta}_{i}
\end{bmatrix}
\equiv E\dot{u} = J\dot{p}
$$

where $E$ is a $6m \times 6$ matrix that is obtained by stacking $m$ $6 \times 6$ identity matrices, $\dot{q}$ is the $m(n-1) \times 1$ vector of rover joint angle rates, $\dot{\varepsilon}_{i}$ is the $m \times 1$ vector of wheel rotation velocities, $\dot{\varepsilon}$ is the $3m \times 1$ slip vector and $\dot{\delta}$ is the $m \times 1$ vector of wheel-ground contact angle rates. The rover Jacobian matrix $J_{l}$ is a $6m \times (mn + 4m)$ matrix obtained from the individual leg/wheel Jacobian matrices $J_{i}, i = 1, 2, ..., m$ and $\dot{p}$ is a $(mn + 4m) \times 1$ vector of composite angular rates for $m$ leg/wheels of the rover.

3. SHERPA ROVER

Sherpa [CDK11] is a hybrid wheeled-leg rover that is part of a multi-robot exploration system [CBLK10]. The rover is equipped with four legs with 4 DoF each, on these so called swing units are mounted the rover’s wheels with 2 further DoF, one for steering the wheel and one for driving the wheel, respectively.

Sherpa is a highly capable planetary rover that is intended to serve as the central mobile unit in a multi-robot exploration scenario. It is able to manipulate payload-items that can be used to build up scientific or infrastructural components as well as for enhancing the capabilities of the mobile systems. The manipulator on top of Sherpa is used for handling the payload-items and for locomotion support [DRC11].

The wheeled-legs that constitute Sherpa’s suspension system provide a total of 6 DoF each, summing up to 24 active DoF in the locomotion system. The first DoF ($q_{1}$) seen from the central body is called Thorax joint. The movement range is ±90° around the vertical axis. The Basal joint ($q_{2}$) is designed as a parallel structure, that is responsible for lifting the wheel. These two DoF are the main DoF for (re-)positioning the wheel with respect to the body. The two auxiliary DoF WheelTilt ($q_{3}$) and WheelFlip ($q_{4}$) are used to orient the Wheel to the ground. By positioning a designated foot plate on top of the WheelSteering ($q_{5}$), the WheelFlip can be used to flip over the whole wheel and use a secure foot point2. WheelSteering ($q_{5}$) and WheelDrive ($q_{6}$) are used for steering and driving the wheel respectively. Figure 4 and Table 1 details the DoFs.

3.1. Sherpa Kinematic Model

Figure 5 illustrates the coordinate frames of a single leg of Sherpa according to Denavit-Hartenberg (D-H) notation. The D-H parameters $\theta$, $d$, $a$ and $\alpha$ are presented in Table 2 with units radians and millimeters. The presence of a parallel structure in the leg requires the definition of a virtual axes ($B_{a2}$) which rotation angle ($q_{2}$)

2This feature is currently not implemented mechanically.
is the negative value of the Basal joint (Ba). Wheel Tilt frame is rotated Φ radians along the z-axis in order to avoid the elbow between the virtual Basal joint and the Wheel Tilt. Wheel Flip frame appears to be outside of the mechanical structure between the steering and its predecessor frame in the chain (WT) with a displacement of −HW F units along its x-axis. This choice of the coordinate frame ensures the minimum number of frames to represent the transformation between the wheel leg swing base (S) and the wheel contact point (C)

The resulting transformation from Sherpa body to the wheel contact point can be written as

$$T_{B,S}(q,δ) = T_{B,S}T_{S,A_i}(q)T_{A_i,C_i}(δ_i) \quad i = 1, 2, 3, 4$$ (8)

The transformation from the body frame (B) to the leg frames given by Equation 1 varies depending on the leg side. It results on a positive (right-side legs) or negative (left-side legs) 90° angle rotation along z-axis, which gives the following transformation matrices

$$T_{A_i,C_i}(δ_i) = \begin{bmatrix} 0 & cδ_i & sδ_i & -rsδ_i \\ -1 & 0 & 0 & 0 \\ 0 & -sδ_i & cδ_i & -rcδ_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad i = 1, 3$$ (9)

$$T_{A_i,C_i}(δ_i) = \begin{bmatrix} 0 & -cδ_i & sδ_i & -rsδ_i \\ 1 & 0 & 0 & 0 \\ 0 & sδ_i & cδ_i & -rcδ_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad i = 2, 4$$ (10)

It is noted that wheel-contact transformation depends on the articulated joints values q and the wheel-contact angle δ. The Jacobian matrices are calculated as explained in Section 2 using Equation 8. The computation of the velocity kinematics requires the derivative of transformation matrices, which for Sherpa rover there are a considerable amount of DoFs (10 DoF per leg coming from joints, wheel-ground contact angle and slip vector). The cascade velocity derivative corollary [MN86] is applied in order to simplify the derivation. Since $T_{B,S_i}$ (and therefore $T_{S_i,B}$) is independent of time, the time derivative of $T_{B,B}$ is

$$\dot{T}_{B,B} = T_{B,S_i}\dot{T}_{S_i,C_i}T_{C_i,B} + T_{B,C_i}\dot{T}_{C_i,S_i}T_{S_i,B}$$ (11)

where the first row represents the rate change of the wheel contact point at time $k - 1$ with respect to the body frame.
4. SHERPA KINEMATIC EQUATIONS

Different forms of rover kinematics can be obtained depending on the specific state of interest. This article focuses on two forms since the purpose is to properly model Sherpa rover kinematics towards an efficient pose estimation during path following. This will be done by describing useful forms of Equation 7 for Sherpa, referred as navigation kinematics and slip kinematics. Finally, uncertainty modeling and step-integration is performed to estimate rover pose over time using dead reckoning methods. Other forms of interest as leg-inverse kinematics and actuation kinematics to command desired rover velocities are also valuable to analyze [TM05], but they are beyond the scope of this paper.

4.1. Navigation Kinematics

Navigation kinematics relates rover pose rate to the joints and sensed rate quantities. The navigation kinematics is often referred as motion model and is the basics for dead reckoning systems. The objective of the method is to estimate the rover pose. Moreover, it is useful for the understanding of the role of different quantities contributing to the final rover pose.

In order to simplify the model, the navigation kinematics focuses on the navigation form of Equation 11 when Sherpa is rolling over its wheels and adapting its legs to the uneven terrain. Therefore, the first row of Equation 11 is set to be zero since any walking movements are analyzed for the purpose of this work. Joint angle measurements are available in Sherpa rover since absolute encoders are installed in each joint and relative encoders are available in all wheels for measuring wheel rotation rates. Sherpa rover is also equipped with an IMU that can provide information on the pitch and roll angle, since they are able to compensate for drift error by estimation of the gravity vector using accelerometers. This is not totally possible by the heading error. Sensor availability defines sensed and not-sensed quantities and Equation 7 separates as

$$[E_s \ E_n] \begin{bmatrix} \dot{\bar{u}}_s \\ \dot{\bar{u}}_n \end{bmatrix} = [J_s \ J_n] \begin{bmatrix} \dot{\bar{p}}_s \\ \dot{\bar{p}}_n \end{bmatrix}$$ (12)

Rearranging into not-sensed (right-side) and sensed (left-side) quantities, the resulting equation is obtained

$$[E_n \ -J_n] \begin{bmatrix} \dot{\bar{u}}_n \\ \dot{\bar{p}}_n \end{bmatrix} = [-E_s \ J_s] \begin{bmatrix} \dot{\bar{u}}_s \\ \dot{\bar{p}}_s \end{bmatrix} \equiv A\chi = B\gamma$$ (13)
where $A$ and $B$ are matrices dimensions depends on the sensing capabilities of the rover system which will direct influence on the existence of a solution. The study the rank of $A$ refers the sensing analysis of the navigation equations. There is no solution if the matrix $A$ has not full-rank and therefore the system is undetermined. However, if rank[$A|B]$ = rank[$A$] the system is determined and a unique solution exists. When the system is overdetermined, rank[$A|B]$ > rank[$A$], there is more than one solution and least-square method is applied to solve the equations minimizing the error. If the matrix $A$ has fully-rank and rank[$A|B]$ > rank[$A$], there is ample sensing because it provides extra sensing capabilities. This extra information is very useful for slip detection and error analysis where the equations are inconsistent [TM05].

All the joints angles and wheel rolling rates are sensed quantities, as well as the pitch $\phi$ and roll $\theta$ angles rates. The slip vector $\vec{e}$ is not a sensed quantity and the wheel-ground contact angles $\delta$ are defined here as unknown values even though some techniques can be used to estimate these angles [LS07] or by the installation of force sensors in wheel axles. Not-sensed quantities of the vector $\chi$ can then be removed for the navigation kinematics. The resulting matrices $E_n$, $E_s$, $J_n$ and $J_s$ have dimensions $24 \times 4$, $24 \times 2$, $24 \times 8$ and $24 \times 24$ respectively. The matrix $A$ and $B$ have dimensions $24 \times 12$ and $24 \times 26$ respectively and $\chi$ is a $12 \times 1$ vector corresponding to the not-sensed quantities and $\gamma$ is a $26 \times 1$ vector corresponding to the sensed quantities (i.e., rover joints, wheel rolling and pitch and roll angles). The solution for the Equation 13 is obtained using least-square method where the error vector is given as

$$e = B\gamma - A\chi$$

(14)

the solution is based on minimizing the error vector $E = e^T C e$, where $C$ is the constant matrix which could be the weighting matrix block diagonal, but for simplification here $C \equiv I$. The solution to Equation 13 is given by

$$\chi = (A^T CA)^{-1} A^T CB\gamma$$

(15)

The desired quantities of Sherpa pose $\dot{x}$ $\dot{y}$ $\dot{z}$ are extracted by taking the first element of the solution vector $\chi$. The least-square solution provide an optimal solution by minimizing the error $e$ in velocity. This solution is applicable to dead reckoning methods. A large error represents larger navigation uncertainty, while a small error implies a more accurate solution.

4.2. Slip Kinematics

The detection of the slip vector $\vec{e}$ is important to identify the terrain, correct odometry errors and reduce undesirable motions as well as detect the called ‘slip-sinkage effect’. Similar to the navigation kinematics, the slip kinematics equation can be obtained per each rover leg/wheel. No-sensed values are worked out together at the right-side of the equation and sensed values are in the left-side

$$[J_n - J_m] \begin{bmatrix} \dot{\epsilon}_i \\ \dot{\delta}_i \end{bmatrix} = [-I_s \ J_{is}] \begin{bmatrix} \dot{u} \\ \dot{q}_{ns} \end{bmatrix}$$

$$A_i \chi_i = B_i\gamma_i, \ i = 1, 2, ..., m$$

(16)

The analyses if the existence of a solution is similar to the navigation equations. The study the rank of $A_i$ refers the sensing analysis of the slip equations. There is no solution if the matrix $A_i$ has not full-rank and therefore the system is undetermined. The wheel slip rates could be fully detected if rank[$A_i|B_i\gamma$] = rank[$A_i$] or equivalent to express the residual error equal to zero as

$$A_i (A_i^T A_i)^{-1} A_i^T - IB_i\gamma_i = P(A_i) - IB_i\gamma_i = 0$$

(17)

where $P(A_i)$ is the projection matrix to the column space of the matrix $A_i$. When $P$ is coincident with the identity the error is zero and a unique solution is found for the slip vector. For Sherpa rover, it is assumed that rover pose $\dot{u}$ is know using sensor capabilities as visual odometry or inertial sensors. The wheel contact angle is unknown and the joint rate angles and wheel rolling rate are known. With this configuration the resulting matrices $I_s$, $J_{is}$ and $J_{ns}$ have dimensions $6 \times 6$, $6 \times 6$ and $6 \times 4$ respectively. The matrix $A_i$ and $B_i$ have dimensions $6 \times 4$ and $6 \times 12$ respectively, with not-sensed vector $\chi_i$ of dimension $4 \times 1$ and sensed vector $\gamma_i$ of dimension $12 \times 1$.

5. Experiments

Experiments with the real hardware are costly to perform and a proof-of-concept is needed as a first approach before testing with the real system. In order to evaluate the feasibility of the approach, a simulated terrain and the Sherpa rover in MARS (Machina Arte Robotum Simulans) [RKK09], a simulation and visualization tool for developing control algorithms and designing robots, is used. The simulator 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 simulation environment. The simulation provides true position and orientation values, as well as information about wheel contact points with the ground. It is not the purpose of this work to accurately model surface conditions, the wheel-terrain interaction is based on
simple models. The output of the simulated rover is the sensed quantities as joint-angle vector $q$, wheel rolling angles $q_n$, contact angles $\delta_i$ and ground truth for the pose vector $U$.

5.1. Position Estimate Uncertainty and Results

Determining the uncertainty associated with robot’s internal sensors is especially important since sensed values are usually corrupted by measurement errors. The uncertainty of the wheel-contact point is estimated with respect to the body frame. The information should be statistically relevant in order to be useful. A common assumption is to work with the first and second order centered moments of a calculated pdf $\rho_\nu$, which is the expectation value $\bar{\nu}$ and the covariance matrix $\sum_{\nu\nu}$ (std. deviation is detailed in Table 1). Each DoF in the leg is modeled as a random value in the direction of the joint rotation which affects to the final pose uncertainty as a composition of transformations.

The angle uncertainty is then treated as a couple $(\bar{\nu}, \sum_{\nu\nu})$. A classical first order approximation of Jacobians described by Pennec et al in [PT97] is used to model the resulted noise of a chain of transformations along the leg. Therefore, rigid motions and the handling of uncertainty are done by composition of noise covariance matrix instead of additivity. The detailed derivation of the method is not reported here for brevity and can be found in [PT97].

The same noise propagation is used in the dead reckoning process. The least-squared solution of the navigation kinematics is the exact solution for the rover velocities under wheel no-slip assumption. The dead reckoning update calculation is described as

$$ U(k) = U(k - 1) + \frac{\Delta t}{2} R_{W,B}(\dot{\hat{u}}(k) + \hat{u}(k)) $$

where $R_{W,B}$ is a rotation matrix from $W$-frame to $\hat{B}$-frame. It is assumed that the Sherpa motion is adequately modeled by constant accelerations since the robot is being actuated by constant force/torque generators in each sampling period $\Delta t$ (the same sampling period as the dead reckoning process). The dead reckoning integration is erroneous when wheel slip occurs and visual techniques could be used to estimate the wheel slip vector described in Equation 17.

Two tests are presented here: a squared path and a serpentine path performed on inclined flat terrain by $15^\circ$. Figure 6 depicts the pose estimator for the navigation kinematics and the dead reckoning method when the squared path is performed. An uncertainty of 0.12 m in x axis after 19 meters path is estimated considering internal errors coming from the encoders. Figure 7 show the pitch and roll angles propagation when initial pose is given and the angular rates $\dot{\phi} \dot{\theta} \dot{\psi}$ are not-sensed for a serpentine path. The navigation kinematics is used to estimate the change in attitude. Estimation of the wheel slip vector using Equation 17 is shown in Figure 8 demonstrating the applicability of the slip kinematics.
6. CONCLUSION

A methodology for the kinematic modeling and the pose estimation problem of a hybrid wheeled-leg robot is presented. Additionally, the wheel slip vector detection by the slip kinematics is also analyzed. The insight into kinematic modeling takes more importance for localization in space where methods can not make use of the Global Positioning System (GPS). Therefore, a six DoF solution in a three dimensional space is desirable for positioning during complex maneuvers and long term navigation by means of dead reckoning methods. The following objectives have been achieved. (1) Calculation of the leg/wheel forward kinematics and Jacobian matrices for the Sherpa rover. (2) Equations for the navigation and the slip kinematics for the Sherpa rover (3) Uncertainty modeling and propagation along the kinematic model due to measurement errors and (4) six DoF dead reckoning propagation. By using this method, all degrees of freedom are captured. Further analysis on the influence of each rover leg joint on the resulted robot pose is desired. Experiments with the real system should be performed to allow a more in-depth analysis in real environments.

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