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Research paper

Design and terramechanics analysis of a Mars rover utilising active suspension

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ABSTRACT

Wheeled rovers have a limited ability to traverse soft terrains and climb loose slopes. This study proposes a wheel-step rover with a modified active rocker-bogie suspension. The rocker and differential shaft fixed to the rocker are divided into three parts and reconnected via a novel angle-adjusting mechanism. The mechanism, which is driven by a single motor, widens and narrows the angle between the two rocker parts periodically to generate a wheel-step motion. Moreover, it adjusts the angle between a rocker part and differential shaft part to keep the bottom side of the rover body parallel to the ground. When fully stretched, the suspension lowers the bottom side horizontally to the lander platform. The mechanism also cooperates with a brake added between a rocker part and bogie to lift the sunken wheels separately. The strategies of wheel-step motion, wheel lifting, and suspension folding/unfolding are practicable as validated by prototype tests. Experiments show that the active suspension considerably enhances the rover's ability to escape from a dune or a crater. The proposed suspension is an important attempt in improving the design of Chinese Mars rovers.

1. Introduction

Mars is the most probed planet in the solar system because it is the most likely to contain extra-terrestrial life and it contains rich minerals that are rare on Earth. The development of science and technology has allowed major space powers to launch spacecraft and other vehicles to Mars. The space agencies of USA [1–4], Russia [5], China [6], Europe [7], India [8], and Japan [9] plan to send their own probes/rovers to Mars. An increasing number of scientists have focused on the design of mobile rover systems. Some have researched the existing Lunar and Martian rovers for many years and obtained several configurations, including wheeled robots, wheel-step robots, and legged robots.

Wheeled robots have a higher efficiency than legged robots, but their mobility is relatively poor. Wheel-step robots can use both wheeled and legged motion, providing good efficiency for travelling over flat ground and traversing on rugged ground. Previous Mars rovers were typically wheeled rovers with increased mobility provided by specially designed suspension and wheels. The USA have successfully landed four rovers on the Martian surface, but two rovers launched by the Soviet Union unfortunately crash-landed. The structures of those rovers are described in some papers [10–13]. The four

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Nomenclature

fs_2	Length of single step in forward wheel-step motion (m)
rs_2	Length of single step in backward wheel-step motion (m)
d_c	Horizontal distance between centre of mass and axle of front wheel (m)
d_r	Horizontal distance between rocker pivot and axle of front wheel (m)
d_b	Horizontal distance between bogie pivot and axle of front wheel (m)
d_{fm}	Horizontal distance between axle of front wheel and axle of middle wheel (m)
d_{mr}	Horizontal distance between axle of middle wheel and axle of rear wheel (m)
d_{bm}	Horizontal distance between bogie pivot and axle of middle wheel (m)
d_{bf}	Horizontal distance between bogie pivot and axle of front wheel (m)
h_c	Vertical distance between centre of mass and axle of front wheel (m)
l_1	Length of front rocker (m)
l_2	Length of rear rocker (m)
l_3	Length of front bogie (m)
l_4	Length of rear bogie (m)
α_1	Branch angle between rear rocker and vertical line (°)
α_2	Branch angle between front rocker and vertical line (°)
α_3	Branch angle between front bogie and vertical line (°)
α_4	Branch angle between rear bogie and vertical line (°)
φ_m	Branch angle between front rocker and rear rocker (°)
δ_r	Angle between front rocker and horizontal line (°)
$\bar{k}$	Expected transmission ratio of planetary gear train
k	Actual transmission ratio of planetary gear train
n_{fw}	Rotation speed of front wheel (rpm)
n_{mw}	Rotation speed of middle wheel (rpm)
n_{rw}	Rotation speed of rear wheel (rpm)
J_1	Revolute joint between front rocker and output shaft of differential mechanism
J_2	Revolute joint between rear rocker and output shaft of differential mechanism
sg	Sun gear
rg	Ring gear
cr	Planetary gear carrier
Com/C	Centre of total mass
O_1	Rocker pivot
O_2	Bogie pivot
W_1	Axle of front wheel
W_2	Axle of middle wheel
W_3	Axle of rear wheel
r	Radius of wheel (m)
d	Diameter of wheel (m)
h_1	Ground clearance of body (m)
h_2	Height of body (m)
$\bar{d}$	Average height of obstacles (m)
q	Maximum diameter of branch angle-adjusting mechanism (m)
L	Total length of rover (m)
α_{10}	Initial value of α_1 (°)
α_{11}	Terminal value of α_1 (°)
α_{20}	Initial value of α_2 (°)
α_{21}	Terminal value of α_2 (°)
p	Correlation coefficient
s	slip ratio, $s = \frac{\omega r - v}{\omega r} (\omega r > v, 0 \leqslant s \leqslant 1)$
θ_1	Entrance angle of wheel (°)
θ_2	Exit (left) angle of wheel (°)
θ_m	Angle of maximum stress (°), $\theta_m = (c_1 + c_2 s)\theta_1$
b	Width of wheel (m)
$\sigma(\theta)$	Normal stress (kPa)
$\sigma_1(\theta)$	Normal stress in entry area (kPa), $\sigma_1(\theta) = (k_c/b + k_\varphi) r^n (\cos\theta - \cos\theta_1)^n$
$\sigma_2(\theta)$	Normal stress in exit area (kPa), $\sigma_2(\theta) = (k_c/b + k_\varphi) r^n \{\cos[\theta_1 - \frac{\theta - \theta_2}{\theta_m - \theta_2}(\theta_1 - \theta_m)] - \cos\theta_1\}^n$