Innovative design for wheeled locomotion in rough terrain
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Abstract
In our paper we present an innovative locomotion concept for rough terrain based on six motorized wheels. Using rhombus configuration, the rover named Shrimp has a steering wheel in the front and the rear, and two wheels arranged on a bogie on each side. The front wheel has a spring suspension to guarantee optimal ground contact of all wheels at any time. The steering of the rover is realized by synchronizing the steering of the front and rear wheels and the speed difference of the bogie wheels. This allows for precision maneuvers and even turning on the spot with minimum slippage. The use of parallel articulations for the front wheel and the bogies enables to set a virtual center of rotation at the level of or below the wheel axis. This insures maximum stability and climbing abilities even for very low friction coefficients between the wheel and the ground.

A well functioning prototype has been designed and manufactured. It shows excellent performance surpassing our expectations. The robot, measuring only about 60 cm in length and 20 cm in height, is able to passively overcome obstacles of up to two times its wheel diameter and can climb stairs with steps of over 20 cm.

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1. Introduction
Recent research in mobile robotics has mainly concentrated on autonomous navigation. These new technologies allow for reliable localization, obstacle avoidance and even autonomous map building in dynamically changing environment. However, mobility in very rough terrain is often very limited due to the absence of adequate locomotion concepts. Most of the existing surface locomotion concepts are based on wheels, caterpillars or legs and have not much evolved lately.

Walking machines (e.g. [1]) are well adapted to unstructured environment because they can insure their stability in a wide range of situations, but they are mechanically complex and require a lot of control resources. On a plane surface, they demonstrate low speed motion and high power consumption in comparison with the other solutions.

Caterpillars demonstrate good off-road abilities because of their stability and good friction coefficient during motion. Its advantages are simplicity and robustness, but the friction losses between the surface and the caterpillars when the robot is turning are high.

Wheeled rovers are the optimal solutions for well-structured environment like roads or flat and regular terrain. But off-road, their mobility is often very limited and highly depends on the type of environment and the typical size of encountered obstacles [2]. This is well studied for planetary
rovers, e.g. Sojourner [3], Rocky 7 [4] or Micro5 [5], which can typically overcome obstacles of their wheel size, if friction is high enough. Adding real climbing abilities to a wheeled rover requires the use of a special strategy and often implies dedicated actuators like for the Marsokhod [6] and Hybtor [7] or complex control procedure like for the SpaceCat [8] or for the Nanorover [9,10].

The classification we use in our lab to study locomotion concepts makes the difference between active and passive locomotion. Passive locomotion is based on passive suspensions that means no sensors or additional actuators to guarantee stable movement. On the other hand, an active robot implies a closed loop control to keep the stability of the system during motion. Under these definitions, Sojourner, Rocky 7 and Micro5 are passive robots; walking machines, Nanorover and SpaceCat are active robots; Marsokhod, Nanokhod and Hybtor are hybrid depending on their locomotion mode.

It is obvious that active locomotion extends the mobility of a robot but increases the complexity and needs extended control and power resources. With the actual performance of microprocessors, it is yet imaginable to perform active locomotion, which is one of our research axes. However, in many fields of application, power consumption, complexity and reliability are predominant criteria. This is especially the case for planetary rovers.

The lack of passive wheeled locomotion concepts with good climbing ability motivated us to develop and investigate this very promising area. Based on preliminary investigation, we started a project with the goal to build a wheeled robot:

a) having excellent off-road abilities: maximum gripping capacity and stability during motion in rough terrain;

b) able to passively overcome steps of 1.5 times its wheel diameter.

The result of this project is a first prototype that shows performances exceeding our expectations. It will be presented below.

2. Mechanical robot design

The Shrimp robot design is inspired from existing rover concepts. However, its main difference is the extended use of parallel suspension architectures [15] leading to a very smooth slope of the center of gravity (CoG) even when overcoming obstacles with vertical slopes (discontinuities). The robot is therefore able

![Fig. 1. (a) Schematic lateral view of the rover; (b) configuration of the wheels on ground.](image-url)
to move in very rough terrain with minimal motor power even if the friction coefficient with the ground is relatively low.

Using a rhombus configuration, the vehicle has one wheel mounted on a fork in the front, one wheel in the rear and two bogies on each side (Fig. 1). Although our bogies have a special geometry, it is the same basic principle as used for a train suspension: two wheels mounted on a support that can freely rotate around a central pivot between the two wheel axles.

The front fork has two functions: its spring suspension guarantees optimal ground contact of all wheels at any time and its particular parallel mechanism produce an elevation of the front wheel if an obstacle is encountered (Fig. 2).

The parallel architecture of the bogies and the spring suspended fork provide a non-hyperstatic configuration for the six motorized wheels while maintaining a high ground clearance. This insures maximum stability and adaptability as well as excellent climbing abilities. The robot is designed to keep all its six motorized wheels in contact with the ground on a convex ground up to a minimal radius of 30 cm and on a concave ground up to a minimal radius of 35 cm (Fig. 3).

The six DC-motors integrated in the wheels have a power of 1.75 W each and can be controlled individually. The total weight of the robot base is 3.1 kg including 600 g for the battery (12 V, 2 A h).

2.1. The bogies

The bogies are the first key components of the vehicle. They provide the lateral stability during the motion even on very rough terrain. To insure good adaptability of the bogie, it is necessary to set the pivot as low as possible and in the same time to keep a maximum ground clearance. This problem is solved by using the parallel configuration shown in Fig. 4 that has the virtual center of rotation of the bogie at the height of the wheel axis.

2.2. The front fork

As shown in Fig. 2, a trajectory of the front wheel with an instantaneous center of rotation situated under the wheel axis is helpful to get on an obstacle. The second goal for the fork is to provide maximum vertical amplitude for the wheel. To find the optimal configuration for the fork, a kinematics model was used (Fig. 5).
With the parametric equations of $\xi$, $\alpha$ and $\psi$ as function of the angle $A$:

$$
\alpha(A) = \frac{\pi}{2} - A + \phi,
$$

$$
\psi(A) = a \cos \left( \sqrt{b^2 + c^2} - 2bh \cos[\alpha(A)] \right),
$$

$$
\xi(A) = A - \psi(A).
$$

We have all elements to establish the movement of the wheel center $P$ as function of the angle $A$:

$$
P(A) = \begin{pmatrix} c \cos(A) + h \cos[\xi(A)] \\ c \sin(A) - h \sin[\xi(A)] \end{pmatrix}.
$$

The trajectory of the wheel center $P$ can now be plotted and analyzed for different parameters (Fig. 6). The horizontal line in Fig. 6 is the height of the wheel axis when the robot is on a horizontal plane. Note that the wheel center $P$ is moving backwards while the wheel is lifted. This enables lifting the front wheel while still moving forward.

### 2.3. Steering

The steering of the rover is realized by synchronizing the steering of the front and rear wheels and the speed difference of the bogie wheels (Fig. 1b). This allows for high precision maneuvers and even turning on the spot with minimum skidding.
3. Modeling

In order to analyze the interaction forces between the wheels and the ground during motion in rough terrain, we established various mathematical models of the robot. Since the robot is designed for slow speeds, we can analyze the wheel–ground interaction based on a static model. The simplest model that still allows analyzing the key concept of the proposed locomotion principle is presented in the following section.

3.1. Planar static model of the structure

To facilitate the analyses of the locomotion concept, we assume that the test obstacles are only two-dimensional and aligned with the wheel plane. Therefore, the two bogies are moving symmetrically and can be simplified to one bogie placed in the same plane as the front and rear wheel. Furthermore, the parallel structure of the front fork is modeled by a spring-suspended arm, which is rotating around the fixed center of rotation \( O_1 \) (Fig. 7). Even if this is a significant simplification, it has only minor influence on the basic principle of locomotion and still allows to demonstrate the basic concept.

If we assume an equal friction coefficient \( \mu \) for each wheel (\( R_i = \mu N_i \)), we can find the following five equations describing the static force equilibrium:

\[
N_1 (\Delta O_1^{(1)} + \mu \Delta R_1^{(1)}) = \tau_1 + m_1 g \Delta O_1^{(1)},
\]

Fig. 7. Simplified model representing the static interaction of the robot with the ground. The robot structure modeled by three subsystems, the front fork represented by a spring suspended arm rotating around \( O_1 \), the bogie rotating around the center point \( O_2 \) and the robots main chassis with the real wheel. The total mass of the robot is modeled by the central body mass \( M \) and the four masses \( m = m_i \) of the individually motorized wheels.
\[ N_2(\mu \Delta O_2^R + \Delta O_2^R) + N_3(\mu \Delta O_3^R - \Delta O_3^R) = 0, \]

\[ N_1(\mu \cos \gamma_1 - \sin \gamma_1) + N_2(\mu \cos \gamma_2 - \sin \gamma_2) + N_3(\mu \cos \gamma_3 - \sin \gamma_3) = 0, \]

\[ N_1(\mu \sin \gamma_1 + \cos \gamma_1) + N_2(\mu \sin \gamma_2 + \cos \gamma_2) + N_3(\mu \sin \gamma_3 + \cos \gamma_3) + N_4(\mu \cos \gamma_4 - \sin \gamma_4) + N_5\left(\mu \cos \gamma_5 - \sin \gamma_5\right) \]

\[ = 6mg + Mg, \]

\[ N_4(\Delta O_4^R - \mu \Delta O_4^R) = \tau_1 + mg(\Delta O_4^R_1 - \Gamma_1) - Mg\Delta O_4^R \]

where \( \tau_1 \) is the internal torque around \( O_4 \) due to the front fork suspension, \( \Delta O_4^R \) the shortest distance of the point \( j \) to the line spanned by the force vector \( i \) and \( \Gamma_1 \), the projection of the vector \( \overrightarrow{O_2O_1} \) in \( x \)- and \( y \)-direction, respectively.

Through the above equations, we can numerically find the normal contact forces \( N_i \) of each wheel and the required friction coefficient \( \mu \) as a function of different situations of the robot in the terrain.

3.2. Simulation of a quasi-static step climbing

The simplified model was used to analyze a step climbing sequence of the robot that is considered as an important benchmark test for a locomotion structure. As can be seen in Fig. 8, the friction coefficient \( \mu \) for climbing a step of 16 cm is always below \( \mu = 0.5 \). In comparison, a locomotion system with only four fixed wheels (car-like) would require a friction coefficient of \( \mu = 1 \) to climb the same obstacle. Furthermore, it can be shown that the friction coefficient required to climb a step is only around 35% higher than that climbing a ramp that is formed by the step height and the length of the robot. This shows clearly that the locomotion concept is able to smooth the movement of the center of gravity during step climbing. This can also be seen in Fig. 13.

Fig. 8. Required friction coefficient \( \mu \) during step climbing. The four segments of the curve are linked with the climbing of the four wheels.

In our case the maximum value of around \( \mu = 0.5 \) is needed when the second of the bogie wheel starts to climb the step. However, this strongly depends on the spring constant \( C \) and wheel arrangement.
4. Experimental results

4.1. Motion in structured environment

4.1.1. Step climbing

One goal of the new locomotion concept was to passively overcome a step of at least 1.5 times the wheel diameter. Figs. 9 and 10 depict a motion sequence of the robot climbing a step. First, the front fork gets on the step (Figs. 9b and 10b), compressing its suspension spring. This relieves the load on the bogie wheels and thus eases the bogie to climb (Figs. 9c and 10c). When the second bogie wheel is in contact with the wall, the bogie turns around the upper corner of the step. At this time, the center of gravity reached almost its final height (Figs. 9d and 10d). Finally, the last wheel can easily get on the step, dragged by the other five wheels.

As the two bogies are independent from each other, it is even possible to climb the step if the robot is not approaching perpendicularly or if only one bogie encounters a step. Although it was designed to climb steps up to 17 cm, the vehicle is able to climb even steps of twice its wheel diameter (22 cm).
4.1.2. Stair climbing
Impressed by its step climbing abilities, we tested the robot also for stairs climbing (Fig. 11). Due to a good correlation between the bogie size and the step dimensions, the vehicle is able to climb them nearly effortlessly. This is impressive if it is considered that the 1.75 W motors are controlled in open loop.

4.2. Unstructured environments
4.2.1. Off-road abilities
The rover demonstrates excellent stability in both smooth and rough terrain. It can move with a lateral or frontal inclination of up to 40° (Fig. 12a and b) and is able to overcome obstacles like rocks even with a
4.3. Movement of the CoG

The sequential rising of the CoG provided by the consecutive action of the wheels mainly influences the climbing ability.

Fig. 13 shows the trajectory of CoG for a step climbing of 17 cm. The CoG rises to 10% of the final height when the front wheel is on the top of the step (Fig. 13b). Then the first bogie wheel, supported by the suspension of the front fork, rises the CoG to 50% (Fig. 13c). The second bogie wheel and the rear wheel contribute each for approximately 25%. The trajectory clearly demonstrates that the mechanical structure transforms sharp underground structures with steep slopes to a smooth movement of the CoG. This is the key idea, which makes the system much better than other concepts.

4.4. Influence of the friction coefficient

As already demonstrated by the simulation in previous section, the required friction coefficient between the wheels and the ground are largely reduced by the proposed locomotion concept. In order to verify this also by experiments, we reduced the friction coefficient of some wheels by covering the tires with a plastic film tape. The measured static friction coefficient between the uncovered wheels and a wooden step was 0.81 and reduces to 0.23 with the tape coverage. The rover was able to climb easily the wood step with the front and the rear wheel covered (bogies uncovered) or with the bogies wheels covered (front and rear wheel uncovered).

As we expected, the robot was not able to climb the step anymore with all wheels covered by tape. Nevertheless there is a large number of parameters which are not optimized on this first prototype like the weight distribution or the control of the individual motors. This will for sure improve the climbing ability of the robot.

5. Conclusion and outlook

In this paper we presented an innovative, wheeled rover which provides excellent climbing and steering capabilities. Based on a parallel architecture allowing for high ground clearance and excellent stability, the vehicle is able to passively overcome steps of twice
its wheel diameter, to climb stairs or to move in very rough terrain. These capabilities are mainly provided by the parallel architecture of the front fork and the bogie in combination with non-hyperstatic contact of all its wheels with the ground.

This robot is therefore a perfect candidate for planetary exploration or terrestrial applications in the field of mining, construction, agriculture, post-earthquake assistance or demining.

Beside the studies of this new mechanical design, we are also interested to use it for investigating outdoor navigation. For this purpose, we mounted different sensors such as a stereo vision head, inclinometers and range sensors on the rover (Fig. 14). A laptop running Linux is used as the main controller. Our aim is to adapt different techniques for obstacle avoidance and path planning. Currently we are porting and testing the CMU Mars autonomy navigation algorithm [12] on the Shrimp. This system is based on several modules that each vote for the next best action to perform.

The local planner, called Morphin, evaluates the best trajectory based on a traversability map just ahead of the vehicle. The global planner evaluates the cost of travel to the goal using the D* algorithm. Finally, the arbiter module combines the recommendations from D* and Morphin to choose the best action to send to the robot’s motion controller.

Since Shrimp has good climbing capabilities, it is interesting to overcome surmountable obstacles rather than avoiding them. Indeed this reduces the time of travel and in some circumstances can even be the only way to reach the goal. Overcoming obstacles introduces new challenges. In rough terrain the rover has to deal with important changes in orientation and acceleration, wheel slippage and chocks. Thus the standard assumption on the rover dynamics are not valid anymore. For these reasons, a particular attention should be paid on choosing the sensors and the sampling frequency must be adjusted to deal with high frequency signals. Furthermore, position tracking becomes more difficult in such environment. The most common method for the position estimation when no absolute positioning system such as GPS or beacons are available is through dead reckoning. It is generally based on inertial sensors and/or odometry. The drawback of this method is that it accumulates errors very fast. Other techniques based on images and called ego-motion are known to be more accurate [13,14]. They give very good results when combined with absolute angle sensors over long distances. The error can be less than 2% and its growth is linear.

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References

Roland Siegwart (1959) received his M.Sc. ME in 1983 and his Doctoral degree in 1989 at the Swiss Federal Institute of Technology (ETH), Zurich. After his Ph.D. studies, he spent one year as a post-doc at Stanford University where he was involved in micro-robots and tactile gripping. From 1991 to 1996, he worked part time as R&D director at MECOS Traxler AG and as a lecturer and deputy head at the Institute of Robotics, ETH. During this time, he was mainly involved in magnetic bearings, mechatronics and micro-robots. Since 1997, he is a full professor for Autonomous Systems and Robotics at the Swiss Federal Institute of Technology, Lausanne (EPFL). His current research interests are robotics and mechatronics, namely high precision navigation, network base robotics (Internet, space exploration), human–robot interaction, all terrain locomotion and micro-robots. He lectures various courses in robotics, mechatronics and smart product design at the two Swiss Federal Institutes of Technology and is cofounder of several spin-off companies. Roland Siegwart published more than 80 papers and is member of various scientific committees. He namely represents Switzerland in the International Federation of Robotics (IFR) and the Advisory Group for Automation and Robotics (AGAR) of the European Space Agency (ESA).

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