Locomotion modes of a hybrid wheellegged robot

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Abstract

The main objective of this paper is to compare and evaluate the performance of several locomotion modes of an hybrid wheel-legged robot. Each studied locomotion mode is described, compared and evaluated according to the same criteria, which are the gradeability - i.e. the climbing ability - and the power consumption. A hierarchical scheme dedicated to the selection and the control of each locomotion mode is also presented.

Keywords

gradeability, stability, controllability, power consumption, multi-modal locomotion, wheel-legged robot.

1 Introduction

Autonomous exploration missions require mobile robots that can carry out high performance locomotion tasks while insuring the system integrity. For applications such as planetary and volcanic exploration or various missions in hazardous areas or construction sites, the locomotion performance is of first importance.

Vehicle motion on uneven surfaces involves complex wheel-ground interactions that are related to the geometrical and physical soil properties. Therefore enhancing the locomotion performance in such environment requires the design and control of innovative locomotion systems.

Due to their ability to adapt their posture and to cross over high terrain discontinuities, legged systems have been considered for a long time (and are ever considered) as a possible way to increase the field of accessible terrains for autonomous vehicles.

More recently, wheeled systems with passive suspension systems have been introduced (see for example the Nomad [10], Shrimp [11], Nexus [15] robots or the Rocky rovers [13]) to enhance the terrain adaptability and allowing these vehicles to address more challenging terrain including ground discontinuities that are higher than the wheel radius.

Between these two classical categories of locomotion mechanisms, hybrid robots are articulated vehicle with active internal mobilities or hybrid wheel-legged vehicles like Azimut [9], GOFOR [12], SRR [8] and HyLoS [3] robots. With these redundantly actuated systems[1], the internal mobilities can be used to improve the stability and/or the wheel traction leading to a global rough-terrain mobility enhancement.

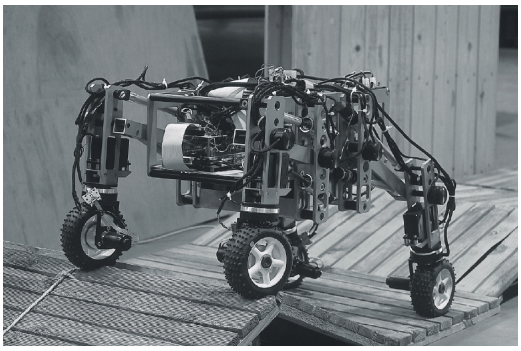


Fig. 1. HyLoS Robot

Hybrid wheel-legged robots like Workpartner [7] or HyLoS [3] can also combine different locomotion modes. We believe that one of the key factor of autonomous exploration mission's success is the ability of the system to automatically adapt its configuration and locomotion modes to the local difficulty of the traversed terrain.

In this paper, we describe the three main locomotion modes of the hybrid wheel-legged robot HyLoS (see Fig. 1). The locomotion performance in terms of gradeability and power consumption is compared for each mode.

The knowledge of the locomotion performance of the system will then be used in an on-line hierarchical control scheme based on two main loops: an internal loop dedicated to the locomotion mode regulation and an external loop dedicated to the switching between different locomotion modes as a function of the current geometrical and physical soil properties.

[1] the number of actuated degrees of freedom is greater than the dimension of the system workspace

2 Locomotion modes description

2.1 Pure rolling mode (mode 1)

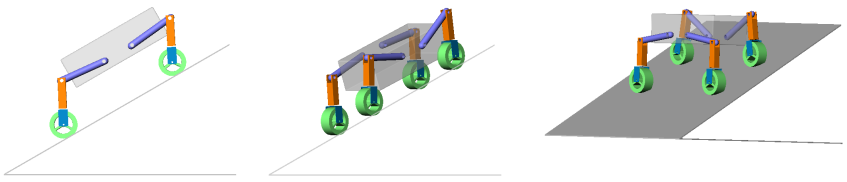
This is a trivial mode where the internal mobilities of the system are not used. On ground without irregularities and discontinuities like road, it is the most efficient locomotion mode (in obvious condition that the leg transmission mechanisms are irreversible or passively blocked).

2.2 Rolling mode with reconfiguration (mode 2)

In this case, the internal active mobilities are used to optimize the posture in order to enhance the locomotion performance. The used criteria are the tipover stability margin and the wheel-ground contact force balance.

A suboptimal posture of the robot that optimize the normal component of contact force is defined [6]. The normal forces balance is optimized by assuming the distribution of vertical component of contact forces. Because of the particular design of HyLoS this correspond to maintain the roll angle φ to zero, and to configure each leg in such way that projected distances between contact points and the platform center of gravity are equal. The other posture parameters that are the ground clearance z_g, the pitch angle ψ and the nominal wheelbase are specified by a high level controller with respect to the platform task (vision, manipulation). Here ψ is defined to make the longitudinal vehicle axis parallel to the slope.

This locomotion mode is adapted to irregular ground without discontinuities like sloping ground or rough terrain. A graphical representation of this posture for different slope configurations is given to Fig. 2.



$\theta_s = 0$ deg. $\theta_s = 45$ deg. $\theta_s = 90$ deg.

Fig. 2. Rolling mode with reconfiguration for different slope configurations

2.3 Peristaltic mode (mode 3)

This mode is similar to one used by worms. It consists in moving the system mass by using its inner mobilities (traction of wheels is used only to move the leg). It exists a lot of different cyclic gait motions to move the robot in this mode. In this study, we choose one cyclic gait in which each pair of wheels in the frontal plane moves only when the other one is firmly braced to the ground (see Fig.3). This mode is well adapted for locomotion on non-cohesive soils [1].

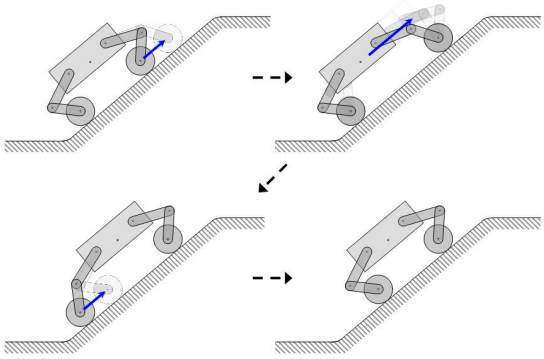


Fig. 3. Peristaltic mode

3 Locomotion modes performance

In this section advantages and disadvantages of each locomotion mode are studied with respect to different performance criteria. Considered criteria are the gradeability (i.e. the maximum slope that a vehicle can climb without compromising the vehicle's stability or it's ability to move forward) and the power consumption.

A rolling resistance model, issue from Terramechanics equations generating wheel sinkage due to soil compaction, has been implemented to take this phenomena into account. This resistance force is expressed by Bekker [2] as:

$$R = b\left[(k_c/b + k_\phi)\frac{z^{n+1}}{n+1}\right] \tag{1}$$

where z is the wheel sinkage given by:

$$z = \left[\frac{3W}{b(3-n)(k_c/b + k_\phi)\sqrt{D}}\right]^{\left(\frac{2}{2n+1}\right)} \tag{2}$$

In theses equations, W is the load, b is the contact width, D is the wheel radius and k_c, k_ϕ, n are the Bekker's parameters of the ground pressure behavior. Traction force T, for a rigid wheel, is also given by Bekker:

$$T = (Ac + W\tan\phi)\left(1 - \frac{K}{sl}\left(1 - \mathrm{e}^{-\frac{sl}{K}}\right)\right) \tag{3}$$

where K is the shear deformation modulus, s the shear displacement due to wheel-slippage, c the soil cohesion, A the contact area, ϕ the friction angle, and l the length of contact area.

3.1 Evaluation of Gradeability

This criterion is based on the evaluation of the stability and the controllability limits for each locomotion modes according to the slope angle η. The stability limit is defined as the max angle η_s for which the contact is loss in at least one wheel ($F_n = 0$) and the controllability limit is the max angle η_c when one of the reaction force leaves the friction cone ($|F_t| = \mu F_n$). They are evaluated as function of the robot yaw angle θ from 0 to 360°. These two parameters (θ and η) define all the possible slope configuration (Fig. 4).

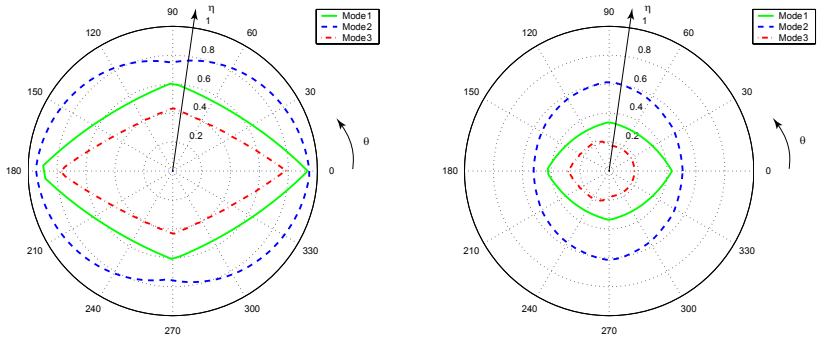


Fig. 4. Evaluation of Gradeability of different locomotion modes on hard soil

The results show an obvious superiority of mode 2 in terms of stability and controllability compared with other locomotion modes. Unlike locomotion mode 1 and 3, controllability limit of mode 2 increases when θ approaches to banked angles (90° and 270° values). Moreover its value is significantly higher for this mode than for the others (with factor three against mode 1 and six against mode 3). This is due to the reconfiguration capability which is more important in banked slope than frontal slope.
Concerning locomotion mode 3, the stability limit shows an interest mainly

in the frontal direction ($\theta = 0°$). Besides, this is the standard configuration of the mode 3. However controllability limit for mode 3 is not significant because, as previously described at section 2.3, the robot displacement is based on the motion of internal mobilities instead of the traction of wheels.

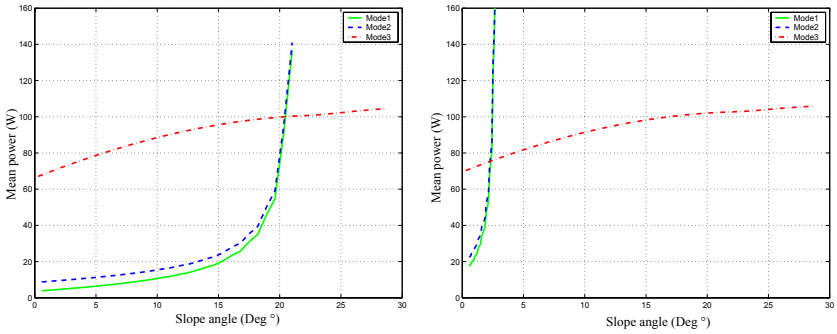
3.2 Evaluation of Energy Consumption

The second criterion consists in an evaluation for each locomotion mode of the energy consumption of the vehicle moving on a frontal slope. In order to compare average power or global energy, the calculus is done for constant distance and constant speed. For this evaluation we consider two terrains with different physical properties whom parameters are listed in Table 1. Then we compute the mean power consumption to travel a constant distance for different slope angles.

Type	n	K_c (kN/m^{n+1})	K_ϕ (kN/m^{n+2})	c (kPa)	K (cm)	ϕ (deg)
Hard soil	0.2	2.56	43.12	1.38	0.75	38
Soft soil	0.8	16.5	811	3.17	2.71	25.6

Table 1. Bekker's parameters for the two studied terrain (from Wong [14])

The results are showed in Fig. 5. Each plot represents the mean power consumption as function of slope angle. The advantage of peristaltic mode is clearly demonstrated for non-cohesive soils and/or terrain with high slope angle. Whereas mean power becomes rapidly infinity for pure rolling mode due to important slippage, peristaltic mode stay practically constant for any kind of ground. However on hard soil with low slope angle ($< 10°$), pure rolling mode presents advantage to have a low energy consumption.



Hard soil Soft soil

Fig. 5. Evaluation of Power Consumption on two kinds of ground

4 Control scheme

The overall control scheme of HyLoS is hierarchically divided into two main loops. The external loop is based on a stereovision system that produces digital elevation map and texture information. Its aim is to identify the crossed terrain properties and select the most appropriated locomotion mode, and control the switch between each modes. The overall control scheme is depicted Fig. 6.

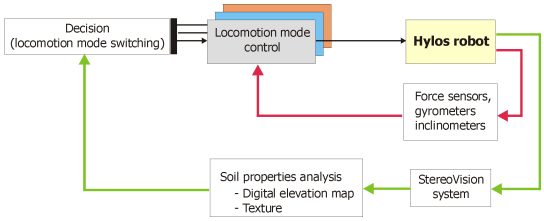


Fig. 6. Overall hierarchical control structure

The internal loop is dedicated to the control of the selected locomotion mode. The loop relative to locomotion mode 1 is based on traction control. For the rolling mode with reconfiguration, this loop consists of a velocity model-based posture control which is described in [4, 5] (see Fig. 7). The loop relative to the peristaltic mode is based on sequential motion generator.

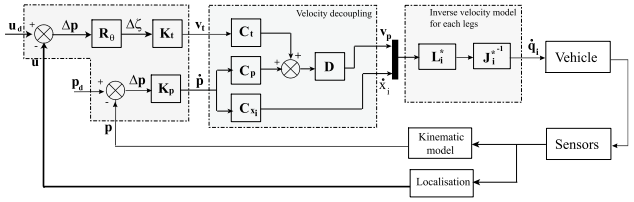


Fig. 7. Posture control scheme

5 Conclusion

The external control loop selects and switches between different locomotion modes. This selection is based on stereovision information and the measure of the locomotion performance.

The performance of each mode on different soils have been evaluated and compared with criteria that are gradeability and power consumption. In terms of energy consumption, peristaltic mode seems to be the most adapted ones on

non-cohesive soils and/or terrain with high slope angle whereas both rolling modes are more suitable for hard soil with low slope angle. And rolling with reconfiguration mode is clearly superior in terms of gradeability.

However evaluation of locomotion modes performance is limited since it is done considering quasi-static notion. This will be improved in future work by performing dynamic simulation of the different locomotion modes.

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