Wheeled actively articulated modular vehicle for locomotion on difficult terrain

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ABSTRACT

Robotic systems for evolution over natural and unstructured environments have to face to various types of difficulties, which are related to the ground conditions (obstacles, collapses and slopes clearance) and to the mission constraints (mechanical integrity, velocity displacement, low energy consumption, etc).

The proposed paper describes an original design for a dynamically reconfigurable locomotion system and the associated control techniques. The system performances are evaluated by the use of a simulation system, which integrates the multibody dynamics of the system and basic interaction with the environment.

1 INTRODUCTION

Missions for mobile robots are numerous and various. They concern several types of environments such as mining, agriculture, forestry, military locomotion and exploration of planetary surfaces. Robots must have to face to varying types of terrains: obstacles, collapses, slopes, …

During the past decades, several researches have been developed on one hand in wheeled actively articulated vehicles and on the other hand in self-reconfigurable modular systems. Concerning wheeled systems, most of them have been designed for planetary exploration such as the Wheeled Actively Articulated Vehicle (1) at the Ohio State University, the Actively Articulated Six Wheeled Vehicle Concept (2) at JPL-NASA, the eight wheeled rover Octopus (3) developed at EPFL and the hybrid wheel-legged Hylos (4) at LRP.
The evaluation of performances of off-road vehicles has been studied first by many authors, (13), (14). Three indices of performance are generally used to determine optimal configuration

parameters: *trafficability*, *manoeuvrability* and *terrainability*. Configuration for trafficability should minimize power expenditure due to losses from soil compaction or other phenomena associated to motion resistance. The manoeuvrability is the ability to change a robot's heading, avoid obstacles and navigate through cluttered environments.
Modular systems have been also developed to adapt their modes of locomotion, in function of terrains, by changing automatically their topology: Polybot (5-9), M-TRAN (6-7-8), …
Each module has its own hardware and software, driven and steered units, sensors, communication links, power unit, kinematics, path planning, obstacle avoidance, sensor fusion, and control system. The advantages of this modular technology include reduction of system costs, application flexibility, system reliability, scalability and survability.

In addition to generating traction and changing the vehicle's heading, locomotion may carry the robot through rough terrain. Terrainability is the locomotion's ability to negotiate rough terrain features without compromising the vehicle's stability and forward progress.
The background analysis enables to release problems related to locomotion on rough terrain in terms of adaptability, obstacles clearance, environment perception, sensors using, contact model. One way to obtain a maximal adaptation to environment difficulties is to develop mobile robot based on reconfigurable modular system.
One approach in the design of such systems consists in the use of modular and dynamically reconfigurable locomotion systems. The issue lies in mechanical design, control development and internal mobility that allow the system to dynamically and automatically reconfigure itself for complex tasks of locomotion as obstacles clearance or varied environmental topologies.
Firstly, we will describe in this paper the proposed mechanical design. Next, we will present in section 3 the different modes of locomotion associated to this kinematic design. Finally, some preliminary simulation results will be presented in section 4.

2 MECHATRONICS OF THE MODULAR CONCEPT

The proposed kinematic design is based on the assembly of similar modules, which are made up of an actively articulated wheeled axle. This is illustrated in figure 1 which shows the reconfiguration capacity of this modular-based system.

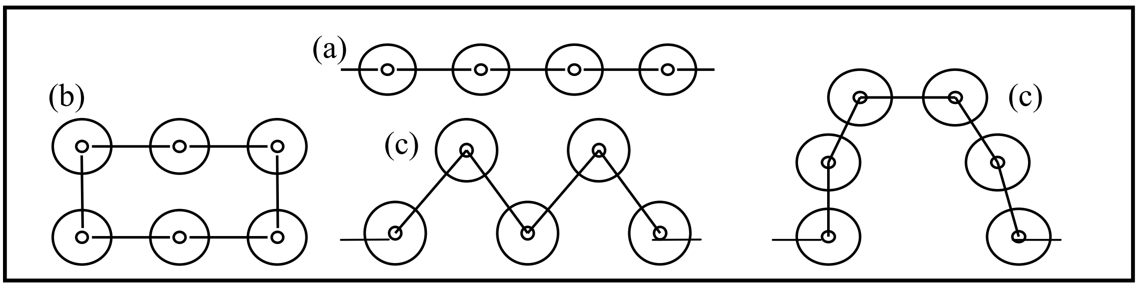


Fig. 1: Various locomotion modes

Each module is composed by an axle equipped with two cylindrical wheels and two arms, which are actively articulated by means of a single motor (fig. 2). Every arm has two passive revolute joints along the roll and yaw directions, which allow respectively maximum adaptation to the terrain 3D-surface and the manoeuvrability (steering) of the system. The roll joints are sustained by means of flexible elements although the yaw joints are free.

This module has a simple kinematic structure and only three actuators. Other active elements will be integrated to connect and to disconnect dynamically the modules between them.
The active joints along the pitch direction enable the system to maximize adaptation to terrains and also to actively negotiate obstacles and environment difficulties. These mobilities allow the clearance of frontal discontinuities (fig. 4), which is not possible with passive joints (Genbu (10)).
The problem of obstacles clearance must be based on an estimation of both contact points positions and the local geometry of the ground surface. These measures are very important for motion control of the system and for planning of locomotion modes.
Environment mapping methods based on vision are difficult to use in the low level control because they need accurate localization. Another system (Octopus (3)) proposes tactile wheels with infrared sensors to measure the contact position along the rolling tread. This system allows also the detection of multiple contacts per wheel.

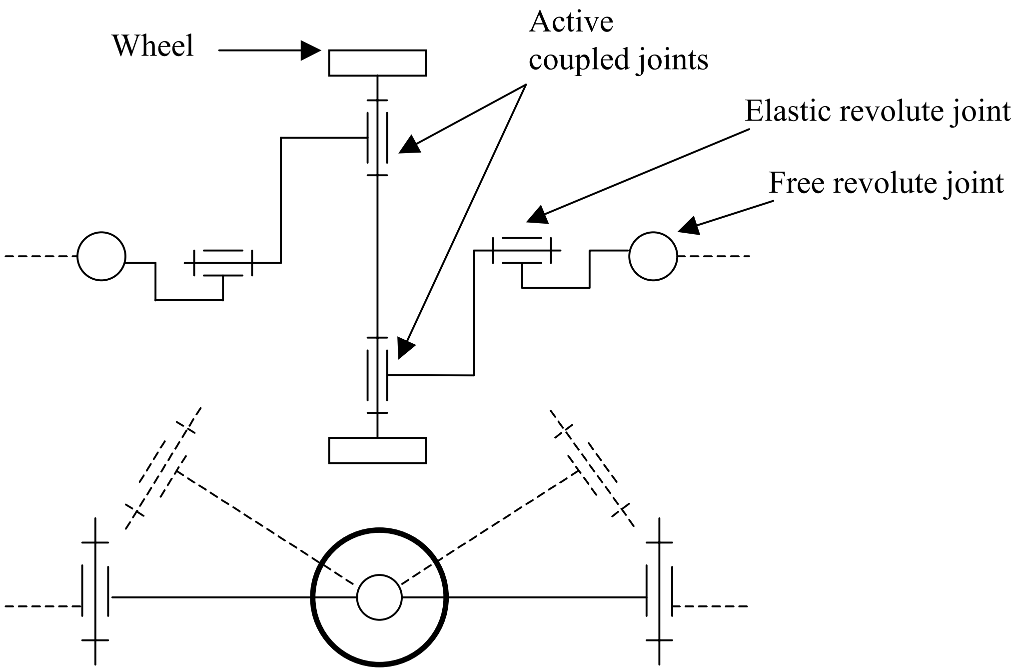


Fig. 2: Module kinematics (top view and side view)

We present an original system (fig. 3) to estimate the ground profile. It is composed of two casters placed in front of the first axle and close to each wheel plane. They are linked to the axle with two prismatic joints and a revolute one, coupled with springs and dampers systems. The measurement of joints displacements and angles permits the computation of the ground profile along the motion direction. This system can be used for displacement velocity measure and then for wheel slippage estimation. The measure on the vertical spring allows calculating the ground profile until a given declivity. Beyond this declivity threshold, the measurements on the horizontal spring and on revolute joint make possible the obstacles detection.

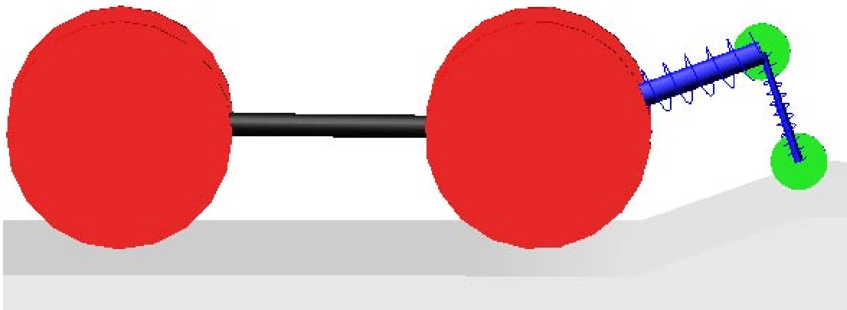


Fig. 3: Concept of ground profile perception

3 LOCOMOTION MODES

The proposed articulated system uses self-reconfiguration to create structures, which perform different locomotion gaits or modes. For locomotion in rough terrains, a modular robot must be able to reconfigure itself to clear obstacles, slopes, collapses or difficulties with different geometry. These structures combine internal mobilities, wheel's rolling and provide different locomotion modes as continuous rolling mode, in caterpillar mode, legged mode and peristalsis. More complex locomotion can be obtained by the combination of two or more of these basic modes (fig. 1). These modes are principally bio-inspired.

3.1 Rolling mode

The **rolling mode** is the simplest locomotion mode (fig. 1-a). It is based on wheel motion and uses all contact possibilities with the ground in order to obtain the maximum traction and the minimum energy consumption. The number of modules for this locomotion mode is not preset. The structure can be composed of, at least, 2 modules to perform a stable configuration and controllable motion. This topology enables cooperation between robotic systems, assembly or separation.

The obstacles can be cleared by this type of topology by controlling wheels velocity, arms joints to raise an axle for example (fig. 4). This mode of locomotion is the basic one and is the object of the simulation presented in the next section.

This locomotion mode seems to be the simplest in terms of control. However, it is not suitable for locomotion on granular and soft grounds, as rolling motion can produce in this case high sinkage and high rolling resistance.

3.2 Caterpillar mode

The **caterpillar mode** corresponds to the left drawing on fig. 1-b. It is a particular locomotion mode for mobile robot. It is inspired by the locomotion of modular robotic systems as M-TRAN (8) or Polybot (5), which do not have wheels. They compensate for this lack by a wheel configuration to move. Initially, we suppose that the wheels must be locked during caterpillar locomotion. The system only uses arms motion to perform a rolling-like displacement.

Thereafter, we will consider the combination of the caterpillar mode and the rolling mode to improve the displacements performances. It will require an efficient control strategy to combine the advantages of these two modes.

3.3 Peristaltic mode

The **peristaltic mode** corresponds to the middle drawing on fig. 1-c. This locomotion mode is similar to that of Marsokhod robot (12). This topology requires preferably an odd number of modules. Internal mobilities of arms are coordinated in a sequential way with the rolling mobilities (locked or towed) of wheels to perform this motion. This type of locomotion is particularly interesting for navigation on granular and sandy slopes. The control of this locomotion mode is based on a simple kinematic model.

3.4 Legged mode

The **legged mode** is derived from the peristaltic mode with fewer contacts with the ground. This mode can be used for obstacles with high dimensions or for high density of rocks. However, it needs more complex control stability, which must be based on load distribution optimisation and force balance. This configuration needs high actuator torques and will be considered to choose actuator performances.

4 SIMULATION RESULTS

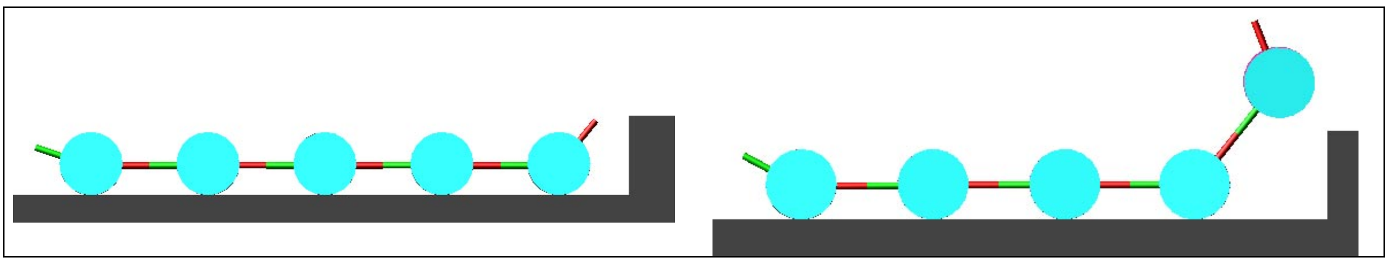
We carry out a dynamic simulation with ADAMS tool. This section will first present a simulation of a step clearance with five modules system. Next, we will show simulation results of ground profile estimation based on casters system, which is presented in section 2.

4.1 Stair clearance

Figure 4 illustrates different steps of a stair clearance by using a hybrid mode combining rolling and peristalsis. The number of modules was chosen arbitrarily and the height of the stair was taken higher than the wheel height.

This figure shows the strategy of the step clearance. We propose here a sequence of actions to realize the movement. Initially, the system must raise the first arm to avoid collision with the obstacle. When a contact with the vertical part of the step is detected, the first axle is raised while the vehicle goes on. Then, the first wheel is posed on the horizontal high part of the step. The contact is detected by using a force sensor equipped on the axle. The forces components give the contact geometry (vertical or horizontal obstacles).

The same process is used for the rest of the system: as soon as a wheel contact is detected, the axle is raised to clear the obstacle.



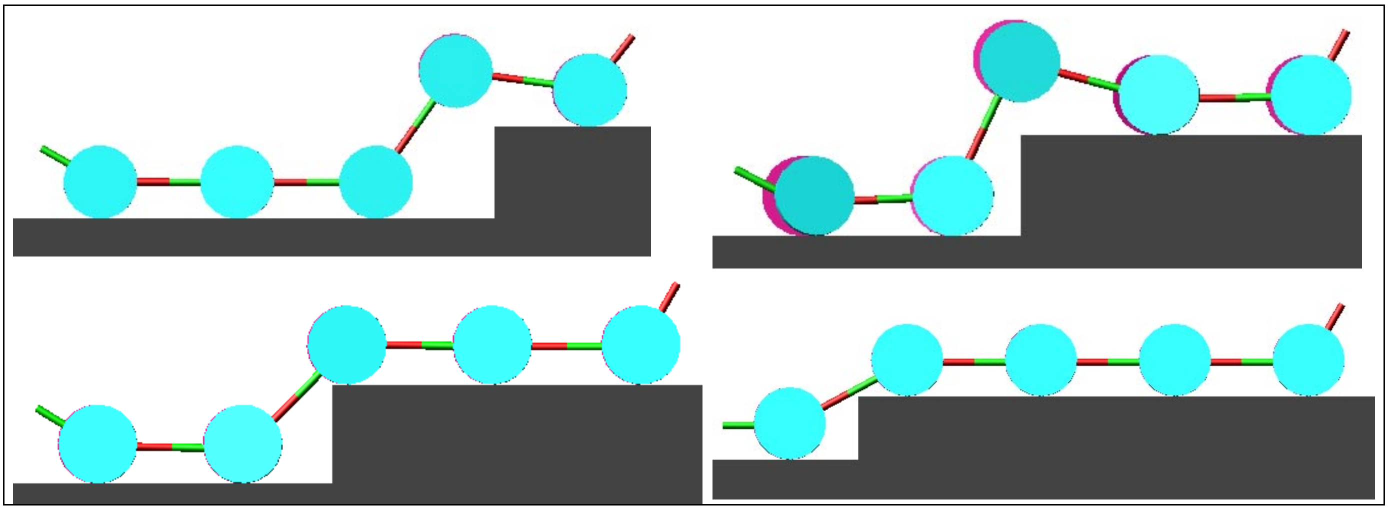


Fig. 4: Actions sequence for the step clearance

4.2 Profile estimation

This part shows simulation results on ground profile estimation using casters system presented in section 2. This information is very important to actively negotiate the ground difficulties. This information, coupled with relative positions between axles, will be used to estimate the contact position of each wheel with the ground.

Figure 5 represents with the continuous line the real ground profile and with the dotted one the estimated profile. The result shows that, in first approximation, the estimated profile is quite close to the real one. The accuracy of the estimation should be improved by means of an optimisation of spring stiffness and damper coefficients of the sensors. This optimisation should be developed for typical ground profiles and for nominal displacement velocity.

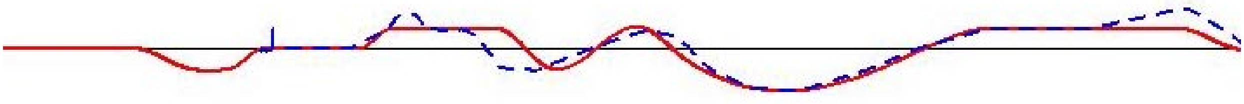


Fig. 5: Ground profile estimation (continuous: real profile, dotted: estimated profile)

5 CONCLUSIONS AND FUTURE WORKS

In this paper, an original concept of mobile robot for high adaptation to terrain difficulties has been presented. This system is based on modular components, which are able to perform self-reconfiguration. We have described some concepts concerning mechanical design, ground-contact detection. We have presented simulation results for stair clearance using both rolling and peristaltic modes.

We are currently developing the mechanical design of the system and particularly the connexion system between the modules based on a male/female assembly. This kind of assembly can be considered as universal one as each axle is symmetric in the saggital plane and has the ability to perform a half-turn. Future works will deal with evaluation of performances of the different locomotion modes. The three indexes of performance (manoeuvrability, trafficability, terrainability) will be used to compare these modes for different environment conditions.

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