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LOCOMOTION MODE TRANSITION STUDY OF GROUND HYBRID ROBOTS

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This paper proposes a criterion based method to make possible the autonomous locomotion mode transition of ground hybrid robots. The criterion is developed based on both the internal states of robots (energy) and the external environmental information (obstacle height), which has been verified via the energy consumption comparison of two simplified locomotion models of rolling and walking locomotion. A method to determine the conditions under which locomotion transition should be performed is also discussed.

Compared with current studies in this area, the novelty of the proposed method lies on considering external environmental information in developing the transition criterion, comparing and evaluating the alternative locomotion performance to determine the criterion threshold, and developing criteria based on generalizable robot parameters rather than particular designs, thus the proposed method can be implemented on various hybrid robots.

Keywords: Hybrid robots, Criterion, Energy consumption, Stair-obstacle negotiation, Locomotion mode transition.

1. Introduction

Locomotion control of Unmanned Ground Vehicles (UGVs) through an unknown environment is an ongoing challenge in mobile robotics. Hybrid robots have been proposed to achieve a high locomotion mobility by selecting the most appropriate locomotion among their multi-locomotion modes. The majority of the proposed hybrid robots in the past decades are Legged-wheeled/tracked systems because of their excellence in both locomotive efficiency and rough terrain negotiation capabilities [1].

The advantage of hybrid robots stems from their more than one locomotion modes. Locomotion transition can either be realized by “supervised autonomy” [2], where switch decisions are made by operators; or by autonomous locomotion mode transition, where robots switch their locomotion automatically. The former locomotion mode transition requires continuous operator-robot interaction, and operators need to have good situational awareness of the environment surrounding the robot which is not always available or reliable.

One of the first automatic locomotion transition research was the Russian Moon Rover wheel-walking vehicle [3], in which three solutions with different degree of automation, mechanics-only, pre-programmed, and an autonomous feedback solutions using sensors' information for the automatic locomotion transition were proposed [4].

Nowadays, the majority of hybrid robots locomotion transition are realized by high level control from operators [2], some other researches have been conducted combining both particular mechanical designs and pre-programmed solutions [5, 6]. One of the reasons autonomous locomotion mode transition is challenging is due to the fact that it requires reliable and efficient sensing measurement of the vehicle-terrain characteristic parameters. This can be realized via terra-mechanic formulations, however, the current terra-mechanics models are heavily computational expensive [7], thus they are inadequate to be directly used for the autonomous locomotion mode transition [4], especially when robots are required to perform a time critical task. Instead of using terra-mechanic models to measure vehicle-terrain characteristics directly, energy consumption has been used as a criterion to evaluate the transverse-ability of a particular locomotion mode [4, 8] in order to study the locomotion mode transition control.

In this paper, a comparison of the energy consumption of rolling and walking locomotion of a hybrid robot was studied. We simulated the simplified dynamic models of the two locomotion of the fully autonomous robot Cricket [9] shown in Figure 1 to negotiate stair type obstacles.

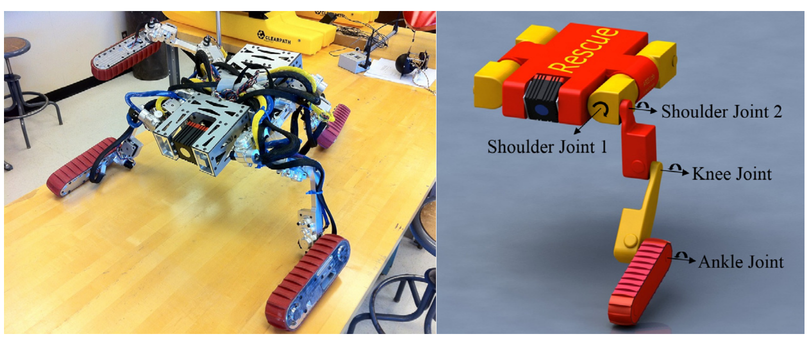

Figure 1. The Prototype of Cricket and Its Leg Joints Layout [9].

2. Dynamic Modelling

A one wheel-terrain model and a two-link leg with a wheel end model were developed as the simplified dynamic models for the rolling and walking locomotion of the robot (Fig. 1). These simplified models were used to characterize the track-terrain performances of the robot, the robot tracks were modeled as systems having several roller wheels and such simplified models were used in the dynamic modeling studies.

2.1. *One Wheel-terrain Model*

In order to determine the energy usage when the robot climbs a step size obstacle, a one wheel-terrain model was developed in a situation that only one of the wheels need to negotiate obstacles. The reason for this is the fact during the rolling process, robots move as traditional vehicles with their articulated legs (chassis) fixed to a particular configuration.

The wheel-stair negotiation was modelled in three stages: i) Stage 1 horizontal terrain rolling, ii) Stage 2 obstacle climbing, and iii) Stage 3 after obstacle rolling. These stages are illustrated in Figure 2, where all related forces, such as friction, torques etc. are analyzed to determine the energy consumption.

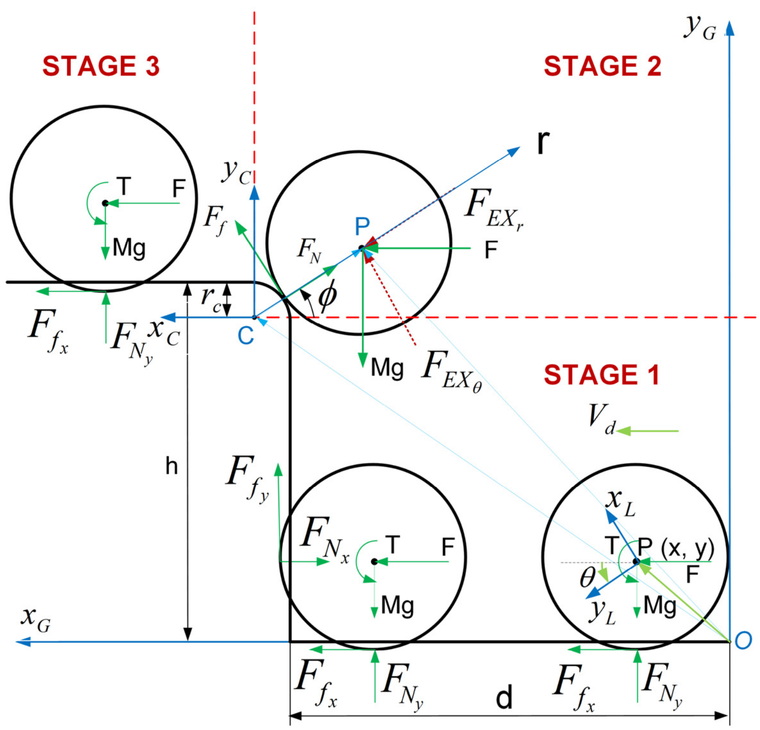

Figure 2. Three Motion Stages of One Wheel-terrain Model.

During the motion of wheels, deformations between the wheel and terrain were modelled as Mass-Spring-Damper (MSD) systems with spring coefficient k and damping ratio c in the horizontal (x-axis) and vertical (y-axis) directions as shown in Figure 3.

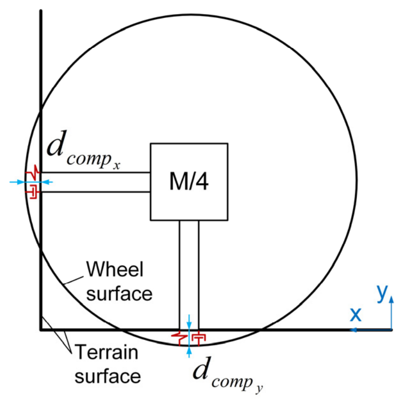

Figure 3. MSD Modelling of One Wheel-terrain Interaction.

2.2. *Articulated Leg Model*

A periodic gait was used to simplify the modelling of the walking locomotion. The walking gait was modelled as: i) lifting one wheel up to the stair, ii) getting the wheel braced on the stair, and iii) moving corresponding one quarter of the body up. One motion period ends when both the body and legs are moved up to the obstacle. In this climbing gait, the walking locomotion can be analysed by one simplified leg model as shown in Figure 4.

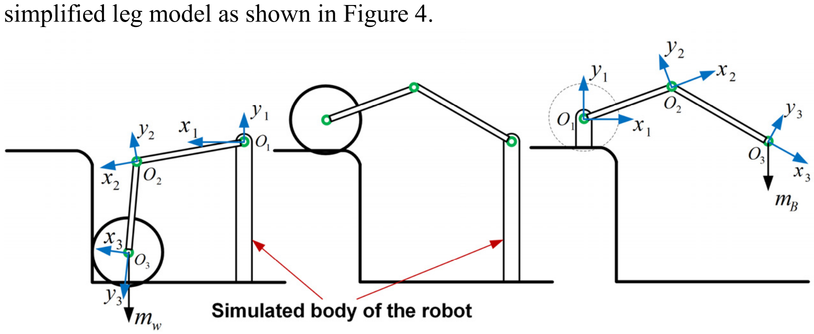

Figure 4. Three Stages of a Two Link Leg with an End Wheel Leg-stair Model.

The Decoupled Natural Orthogonal Complement [10] dynamic modelling algorithm was used to develop the dynamic model of the articulated leg. This method allows a direct elimination of constraint forces of the motion equations derived by Newton-Euler method to get the motion equations as same as derived by Euler-Lagrange method by multiplying a proper orthogonal complement velocity constraints matrix. Because of its recursive property, it is one of the most computational efficiency algorithms for multibody dynamic modelling [10], and thus used in this work to combine the advantage of NE's good for control and EL's merit for simulation [11].

3. Simulation

The energy consumption of the two locomotion modes were simulated and compared under different stair obstacle heights and simulation time combination. The simulation was executed in MATLAB. Both rolling and walking started right in front of the step obstacle, thus no energy consumption was recorded for the robot to be in position to climb the defined obstacles. Step heights ranged from 0 to 4 times of the wheel radius, and the simulation time during walking was defined to match with the simulation time when the robot rolled over the same obstacle.

The energy consumption of the associated DC motors (wheels and leg joints) in a time T was evaluated as [12]:

$$E = \int_0^T \left[f\left(\tau\dot{\theta}\right)\right] dt + \int_0^T I_a^2 R \, dt; \; f\left(\tau\dot{\theta}\right) = \begin{cases} \tau\dot{\theta} & when \; \tau\dot{\theta} > 0 \\ 0 & when \; \tau\dot{\theta} \leq 0 \end{cases} \tag{1}$$

The obtained results is shown in Figure 5, the x axis in the plot represents the obstacle height (meter), the y axis represents the simulation time (second), and the z axis represents the energy consumption (Joule), respectively. Each red dot in the plot represents an energy consumption.

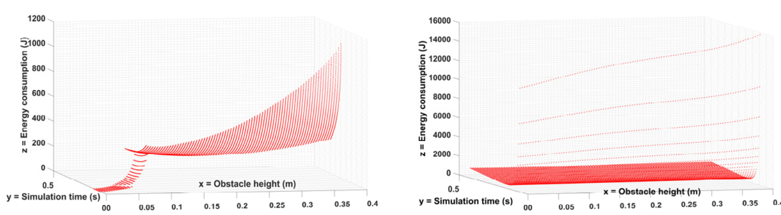

Figure 5. Energy Consumption Simulation of Rolling and Walking Locomotion.

The Figure 6 shows the energy consumption in the x-y plane. It shows that when obstacle heights were the same (the same terrain conditions) as shown in the blue squared data in rolling and walking locomotion modes, walking locomotion was both energy and time efficiency compared with rolling; and within the green squared data, walking was also considered to be more appropriate based on the energy consumption criterion.

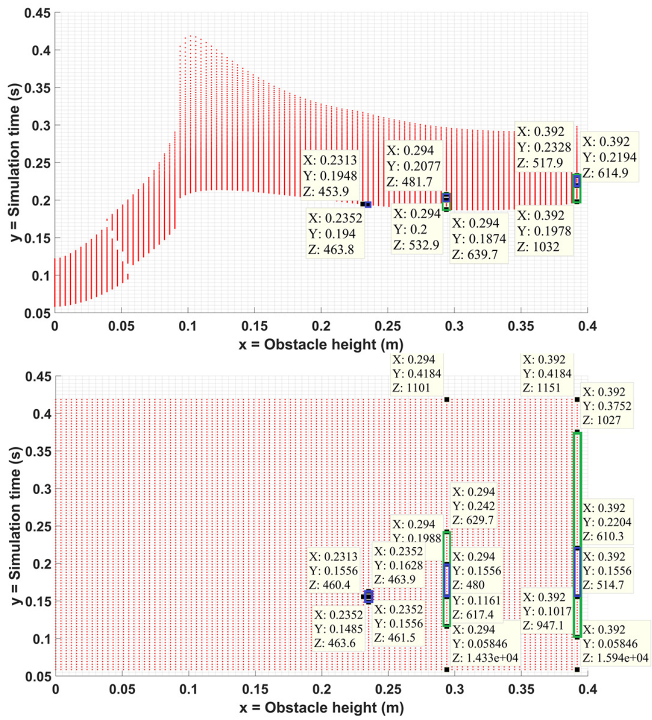

Figure 6. Energy Consumption of Rolling (upper) and Walking (down) in the x-y Plane view.

4. Autonomous Locomotion Mode transition

The primary locomotion mode of Legged-wheeled/tracked robots is rolling because of its energy and time efficient on flat hard terrain. The locomotion transition may happen on rough terrain when walking is more appropriate.

The energy performance knowledge of rolling and walking can be used to study the autonomous locomotion mode transition control. The proposed criterion based method is illustrated in Figure 7: the robot starts to move using a rolling locomotion, calculating the energy consumption in current situation (E_R); simultaneously, the criterion uses the environmental information gathered by sensors to calculate and predict the energy consumption that another alternative locomotion (walking) consumes in the current situation (E_W); then a threshold value (T_R) is determined by the energy prediction (E_W); and a decision-making process is executed following the rule that if $E_R > T_R$, this means walking is more appropriate compared with rolling, the robot switches from rolling to walking and continues walking for the next one vehicle length distance, after which the robot attempts to switch back to the rolling locomotion; otherwise if $E_R \leq T_R$, the robot keeps rolling.

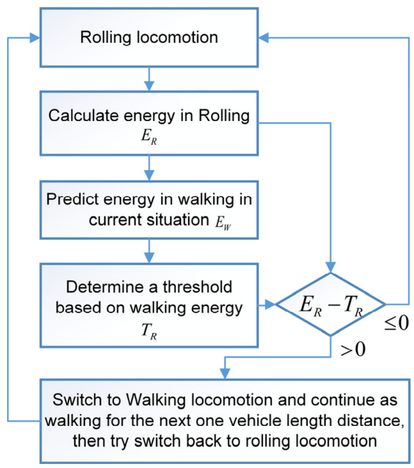

Figure 7. Autonomous Locomotion Mode Transition Flowchart.

In the proposed method, the threshold value T_R for locomotion mode transition from rolling to walking was determined based on the energy prediction E_W. Moreover, the optimization degree of the walking gait has a significantly effect in determining the threshold.

5. Conclusion and Future Work

The energy consumption performances of the rolling and walking locomotion of a hybrid robot were evaluated and compared. Based on the simulation result, walking locomotion can be more energy efficient, and even more time efficient compared with rolling when obstacle height is relatively high.

A criterion based method to study the autonomous locomotion mode transition of hybrid robots was also preliminarily discussed. The criterion was developed based on both the internal states of robots (energy) and the external environmental information (obstacle height).

The future work includes optimization of the method to determine the transition threshold, development of the criterion cost function considering the motion stability margin, and verification the proposed autonomous locomotion transition method on the hybrid robot Cricket.

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