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Stair-climbing and Energy Consumption Evaluation of a Leg-tracked Quadruped Robot

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Abstract— **This paper proposes an energy consumption criterion to realize the locomotion mode transition of hybrid ground robots, which particularly focuses on gait and energy analysis of a leg-tracked quadruped robot. The proposed criterion uses both the internal states of the robot and the external environmental information to determine the most energy efficient locomotion mode. The criterion is proposed based on the knowledge of the energy consumption of the studied robot to negotiate stairs of varying heights in the walking locomotion mode.**

I. Introduction

In the past decade, various hybrid robots have been proposed due to their high locomotion mobility by selecting the most appropriate locomotion mode to negotiate surrounding environment [1]. Because of their excellence in both locomotive efficiency and rough terrain negotiation ability, the majority of the proposed ground hybrid robots are legged-wheeled/tracked systems [2]. In order to realize the autonomous locomotion mode transition of different locomotion modes of hybrid robots, some researches evaluated several generic performances of the individual locomotion modes including energy consumption [3, 4], stability margin [5], and time efficiency [6]. Based on these studies, diverse locomotion transition criteria were proposed [3].

The hybrid robot employed in this paper, Cricket [7, 8] was designed as a fully autonomous leg-tracked quadruped robot (Fig. 1). The two main locomotion modes are rolling and walking. Rolling indicates all four tracks are used for propulsion with the four articulated legs either fixed to particular configurations or moveable to change the configurations to improve the system's stability. Walking includes all sub-locomotion that involves articulated legs movement. Thus regular walking on flat terrain, and climbing negotiation of rough terrain are both categorized as walking locomotion.

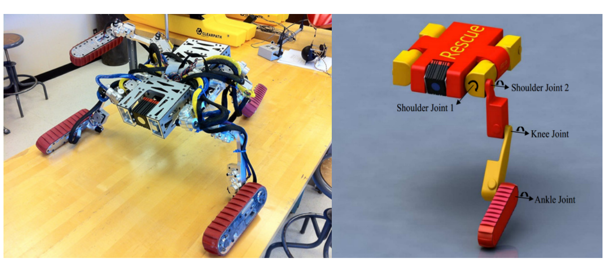

Figure 1. The prototype of Cricket and its leg joints layout [7]

This paper is organized as follows: Section II explains the kinematics and dynamics calculation of the Cricket robot. Section III introduces the proposed climbing gait design used to analyze the proposed energy consumption criterion. Section IV shows energy consumption evaluation simulations of stair negotiation of different stair heights. And section V concludes the paper.

II. Kinematics and Dynamics

A. Kinematics

The climbing gait design includes body adjustment and leg movement, both of which involve inverse kinematics calculations. The kinematics was developed by attaching coordinate frames to every link of the four legs and the body. The attached frames of each link can be chosen arbitrarily, however, it is convenient to follows some rules so we can describe the parameters of links and joints completely and uniformly. A link is specified by two parameters, its length a_i and its twist α_i. Joint can also be described by two parameters, the joint offsite b_i and the joint angle θ_i.

The first commonly used and well known method in robotics area is Denavit-Hartenberg (D-H) method [9]. Besides the originally standard D-H method, a modified D-H method is also commonly used. The root of the difference between the standard and modified D-H method lies where the coordinate frames are attached to each link. In standard D-H method the coordinate frame is attached to the far (distal) end of each link, while in the modified D-H method the coordinate frame is attached to the near (proximal) end of each link. This causes the difference of kinematic conventions, thus the transformation matrix between two successive frames.

In this paper, the standard D-H method as shown in Fig. 2 was employed.

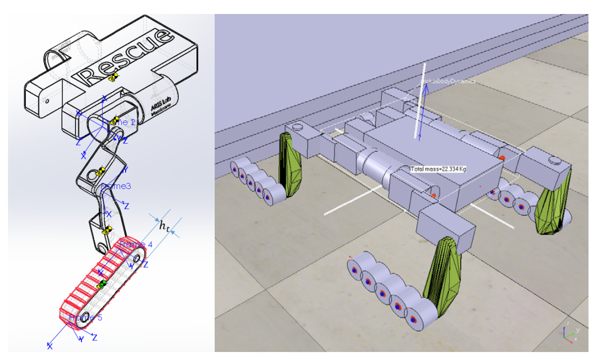

Figure 2. Frames assignment of leg links and V-rep simulation model

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The D-H parameters of the front left leg are listed in Tab. 1. Parameters of the other three legs are similar (with signs difference only) due to the Cricket's symmetrical mechanical design.

TABLE I. D-H PARAMETERS OF THE FRONT LEFT LEG

Link	b_i	θ_i	a_i	α_i
1	0	θ_1	0	$\pi/2$
2	$b_2 = 0.102$	θ_2	$a_2 = 0.133$	0
3	$b_3 = 0.0185$	θ_3	$a_3 = 0.185$	0
4	$b_4 = 0.0285$	θ_4	$a_4 = 0.2196$	0

The homogeneous transformation matrix [9] between Cricket's track tip and the shoulder frames of reference was calculated as:

$$ {}^1T_5 = {}^1T_2\ {}^2T_3\ {}^3T_4\ {}^4T_5 = \prod_1^5 {}^iT_{i+1} = \begin{bmatrix} c_1c_{123} & -c_1s_{234} & s_1 & (b_2+b_3+b_4)s_1 + c_1(a_2c_2+a_3c_{23}+a_4c_{234}) \\ s_1c_{234} & -s_1s_{234} & -c_1 & -(b_2+b_3+b_4)c_1 + s_1(a_2c_2+a_3c_{23}+a_4c_{234}) \\ s_{123} & c_{123} & 0 & a_2s_2+a_3s_{23}+a_4s_{234} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

where s_i and c_i represents $\sin\theta_i$ and $\cos\theta_i$, respectively; s_{ij} and c_{ij} represents $\sin(\theta_i+\theta_j)$ and $\cos(\theta_i+\theta_j)$, respectively; and s_{ijk} and c_{ijk} represents $\sin(\theta_i+\theta_j+\theta_k)$ and $\cos(\theta_i+\theta_j+\theta_k)$, respectively.

A fifth-order polynomial of time in (2) and its first and second derivatives [10] were used to define a smooth trajectory of the joint, satisfying six constraints, i.e. position, velocity, and acceleration at the initial and final states as:

$$ \theta(t) = a_0 + a_1t + a_2t^2 + a_3t^3 + a_4t^4 + a_5t^5 \quad (2) $$

B. Dynamics

In order to handle the robot dynamics effectively, one of the built-in physical engines of a robotics simulation software package V-rep, Vortex [11] was used. The simulated data generated by V-rep when the robot was controlled to negotiate step-shape obstacles were read to MATLAB where the data analysis including energy consumption calculations were performed.

III. CLIMBING GAIT DESIGN

In order to analyze the locomotion's energy consumption during walking, a climbing gait was designed to negotiate stairs with height of h_t, $2h_t$, $3h_t$ and $4h_t$, where h_t indicates track height as shown in Fig. 2. Because the fours leg weighs more than 60% of the total system weight, the legs movement have a non-negligible effect on the center of mass (COM) position. As a result, the system stability need to be considered when designing the climbing gait. Fig. 4 shows an illustrative top down view of the COM and feet-ground contact positons movement of the vehicle, in which the circle at each corner of the rectangle represents the corresponding foot-ground contact, the half bolded circle inside the rectangle represents the COM, arrows indicate displacement vectors. The number i $(i = 1, \dots 11)$ is used to indicates the movement sequence of the first move leg, i^* represents the movement sequence of the following move leg, and i^C represents the movement sequence of the COM. The movement c of Phase 1 and movement d of Phase 2 in Fig. 4 are used to explain the legs and body movement elaborately as in Fig. 3 i) and ii), respectively.

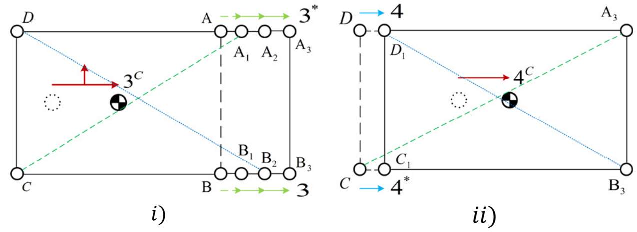


Figure 3. Power consumption of stairs climbing negotiation

In Fig.3 i), the body is moved forward and up (represented as red arrows and numbered as 3^C), the front foot-ground contacts have a forward displacements (A to A_1, B to B_1) because of the body forward movement (represented as light green dashed arrows). In the proposed gait, for the front legs, the right leg always moves first; for the rear legs, the left leg always moves first. When the front right leg moves from B_1 to B_2, the supporting polygon changes from A_1B_1CD to A_1CD; then the front left leg moves from A_1 to A_2, the supporting polygon changes from A_1CD to B_2CD. The movement of the front legs (B_1 to B_2 and A_1 to A_2) is defined as one front leg movement loop and represents as one unit light green arrow. In Fig.3 i), the front legs moves two movement loops. In Fig.3 ii), the body is moved forward (represented as red arrows and numbered as 4^C) to gain more stability margin. Then the rear left leg moves from D to D_1, the supporting polygon change from A_3B_3CD to A_3B_3C; the rear right leg moves from C to C_1, the supporting polygon changes from A_3B_3C to $A_3B_3D_1$. The movement of the rear legs (C to C_1 and D to D_1) is defined as one rear leg movement loop and represents as one unit light blue arrow.

The stability was guaranteed by checking that the COM fell inside the supporting leg-ground polygons in Fig. 4. The designed climbing gait is described in three Phases (Phase 1, Phase 2, and Phase 3) shown Fig. 4, the description of each sub-phase (a, b, c etc.) follows with the corresponding movement.

The proposed climbing gait has the following characteristics:

i. The body of the robot was constantly moved to a position with a greater stability margin before the following legs movement

ii. During the obstacle negotiation, the body movements didn't consider sideways motion and only forward and backward motions were used in order to have bigger feet-ground contacts during the first two climbing phrases. In the third phase, when obstacle height was high, bigger than $3h_t$, sideways body movements were used as shown in Fig. 4, this was due to the fact the stability cannot be achieved by just forward and backward body motions.

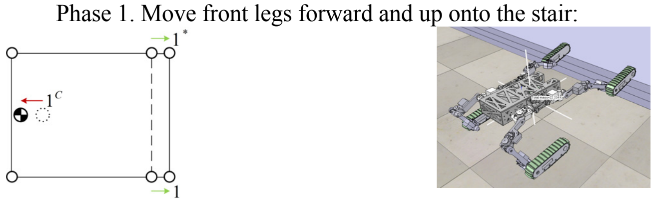
The proposed climbing gait was verified to achieve a smooth climbing motions with stair heights ranging from h_t to $4h_t$.

IV. ENERGY CONSUMPTION EVALUATION

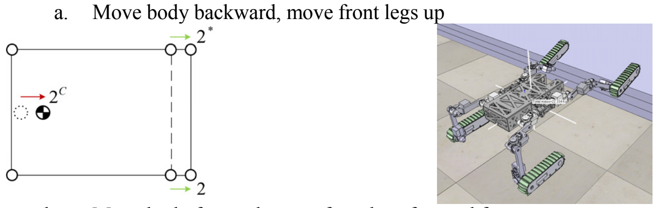
The energy consumption was evaluated by running the climbing (Section III) in V-rep, the simulated joints' torque and angular velocity data were sent to MALTAB.

Initial Position:

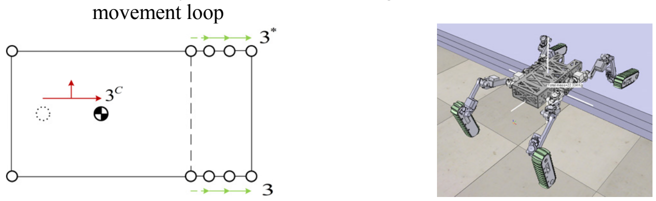
Phase 1. Move front legs forward and up onto the stair:



a. Move body backward, move front legs up

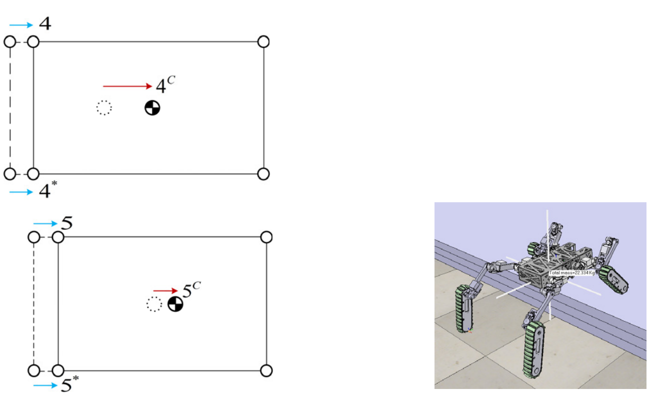


b. Move body forward, move front legs forward for one movement loop

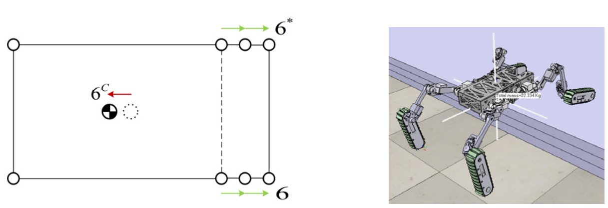


c. Move body up and forward, move front legs forward for two movement loop (dashed lines indicate feet-ground contacts displacement because of the forward body movement)

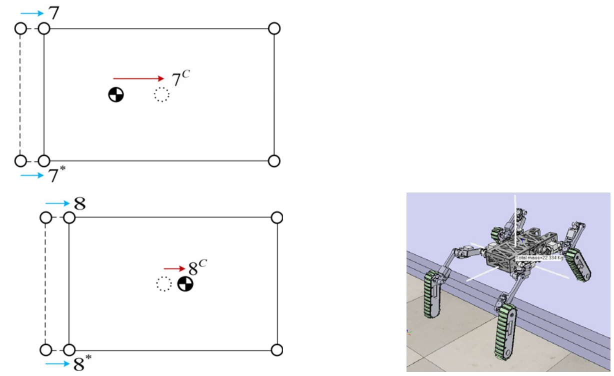
Phase 2. Move forward on the stair:



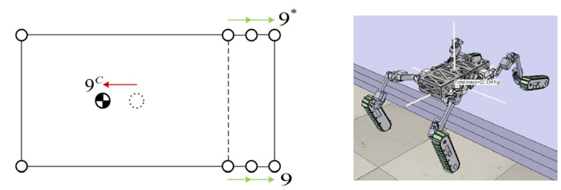
a. Move body forward, move rear legs forward



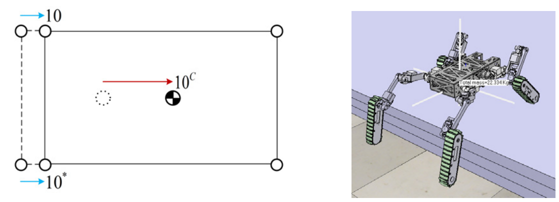
b. Move body backward, move front legs forward for two movement loop



c. Move body forward , move rear legs forward

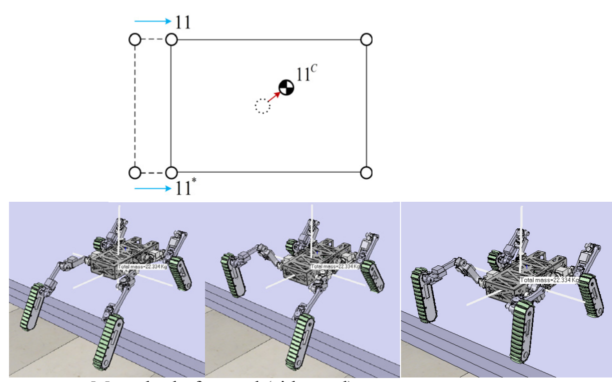


d. Move body backward, move front legs forward for two movement loop



e. Move body forward , move rear legs forward

Phase 3. Move rear legs up and forward onto the stair:



a. Move body forward (sideward)
b. Move rear legs forward and up onto the stair

Figure 4. The top view and simulation of the stair negotion gait

A. *Distance Normalized Energy Calculation*

The method used to evaluate the energy consumption of electrical actuators is explained first. For a DC motor, the energy consumed during a time T can be evaluated by [10]:

$$E = \int_0^T U_a I_a \, dt = \int_0^T \tau\dot{\theta} \, dt + \int_0^T I_a^2 R_a \, dt \quad (3)$$

where U_a and I_a are the applied voltage and armature current, respectively. Here, τ indicates the joint torque, $\dot{\theta}$ represents the joint angular velocity, and R_a is the armature resistance. Furthermore, I_a can be calculated by:

$$U_a = K_{emf}\dot{\theta} + I_a R \quad (4)$$

where K_{emf} represents the back electromotive force constant (emf). The joint torque τ can be derived as:

$$\tau = K_t I_a \quad (5)$$

where K_t denotes the torque constant.

In (3), the first term is the mechanical energy and the second part calculates the energy loss because of heat emissions. Although a negative value for the first term of (3), i.e. mechanical energy indicates a gain in energy supplied by external forces, DC motors cannot store this energy. Therefore, the energy consumed by the DC motors during a time T can be calculated as:

$$E = \int_0^T \left[f\left(\tau\dot{\theta}\right)\right] dt + \int_0^T I_a^2 R \, dt \quad (6)$$

where $f\left(\tau\dot{\theta}\right) = \begin{cases} \tau\dot{\theta} & when\ \tau\dot{\theta} > 0 \\ 0 & when\ \tau\dot{\theta} \le 0 \end{cases}$.

Instead of using energy consumption directly, the distance normalized energy (E/s) is used to compare energy efficiencies of different locomotion modes [3]. So the walking energy E_{walk} can be calculated as:

$$E_{walk} = \frac{\sum_{j=1}^{n}\sum_{i=1}^{m} E_i}{s} \quad (7)$$

where E_i represents energy consumption of the actuated joint i, s denotes the distance travelled by the robot, n is the leg/wheel number, m is the actuated joint number on each leg.

In this paper, the energy consumption during the stair negotiation of the robot can be evaluated by combing (4), (5), (6) and (7), the result is expressed as:

$$E_{walk} = \frac{\sum_{i=1}^{n} E_i}{s} = \frac{\sum_{i=1}^{n}\left(f(\tau_i\dot{\theta}_i) + \frac{\tau_i^2}{K_t^2}R_a\right)dt}{\sum V_{body}dt} \quad (8)$$

where dt denotes the simulation time step; $\dot{\theta}_i$, τ_i and V_{body} represents angular velocity, joint torque, and body velocity readings, respectively.

B. Simulator Parameters Setting

A Cricket simulation model and stairs environment were created in V-rep as shown in Fig. 2. The model parameters, including mass, inertia tensor, and motors were taken from the mechanical design of the Cricket shown in Fig. 1.

The simulation accuracy mainly depends on physical engines of the simulator and the model establishment. The physical engine used in this work was Vortex as it was observed to produce high fidelity dynamics simulation with high accuracy. The developed dynamic model was also proven to be accurate in many basic tests simulations.

C. Energy Consumption Evaluation

The energy consumption evaluation was conducted by running simulations using the proposed climbing gait to negotiate stairs with height of h_t, $2h_t$, $3h_t$ and $4h_t$. The horizontal travelled distance for the four stair negotiations were the same, thus the energy consumption evaluated by (8) was plotted in Fig. 5, in which the x axis indicates the simulation time (s), and the y axis represents the energy consumption (J) in every simulation time interval.

It can be seen from the legends in Fig. 5 that the differences of the energy consumption and the distance normalized energy consumption of walking negotiation of various heights stairs are small, this is due to the fact that the joint accelerations were held constant within the walking gait between tests leading to differences in the time required to overcome obstacles of differing heights (36s, 41s, 41.45s, and 42s for h_t, $2h_t$, $3h_t$, and $4h_t$ stair height respectively) – higher obstacles took longer to step over as shown in Fig. 5. Moreover, the same leg stride length and height were also defined in the walking gait, so the difference of energy consumption came only from the negotiation time and the body adjustments heights. Since the leg weighs more than 60% of the system, the energy consumption difference was small in the simulations.

In order to show the energy consumption intensity of the same motion phase of the different heights stair negation, the simulation time and power consumption were presented in the normalized form with respect to the total amount of time required to overcome the obstacle shown in Fig. 6, in which the x axis indicates the normalized simulation time, and the y axis represents the power consumption (Watt).

In Fig. 6, it can be observed that the power consumption of $1h_t$ height stair negotiation was even higher compared with $2h_t$ height stair negotiation, this is correct since the power consumption was plotted with respect to the normalized simulation time of each individual stair negotiation, and the negotiation time of four stair are different, the power plot of different stair negotiation can only reflect the power consumption of each stair negotiation motion. However, it can be concluded that the climbing gait for low height obstacle need more optimization to reduce the energy consumption.

D. Locomotion Mode Transition Method

The energy performance of walking stair negotiation simulation knowledge can be used as the criterion to realize the locomotion mode transition. The primary locomotion mode of Cricket is rolling because of its energy and time efficiency on flat hard terrain. From the energy consumption simulation results, it can be concluded that the walking locomotion have a more energy consumption advantage in high obstacle height negotiation, so the locomotion transition may happen on rough terrain when walking is more energy efficient compared with rolling.

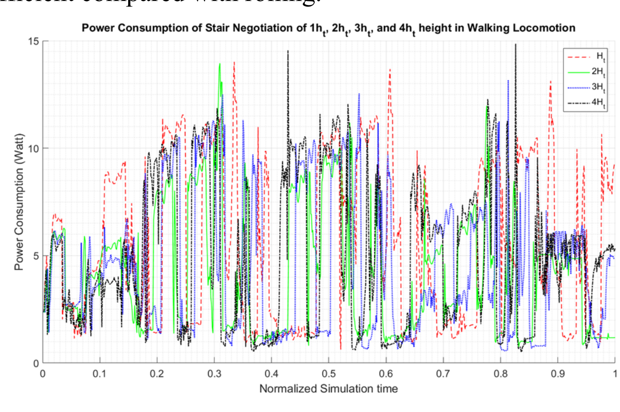


Figure 6. Power consumption of stairs climbing negotiation

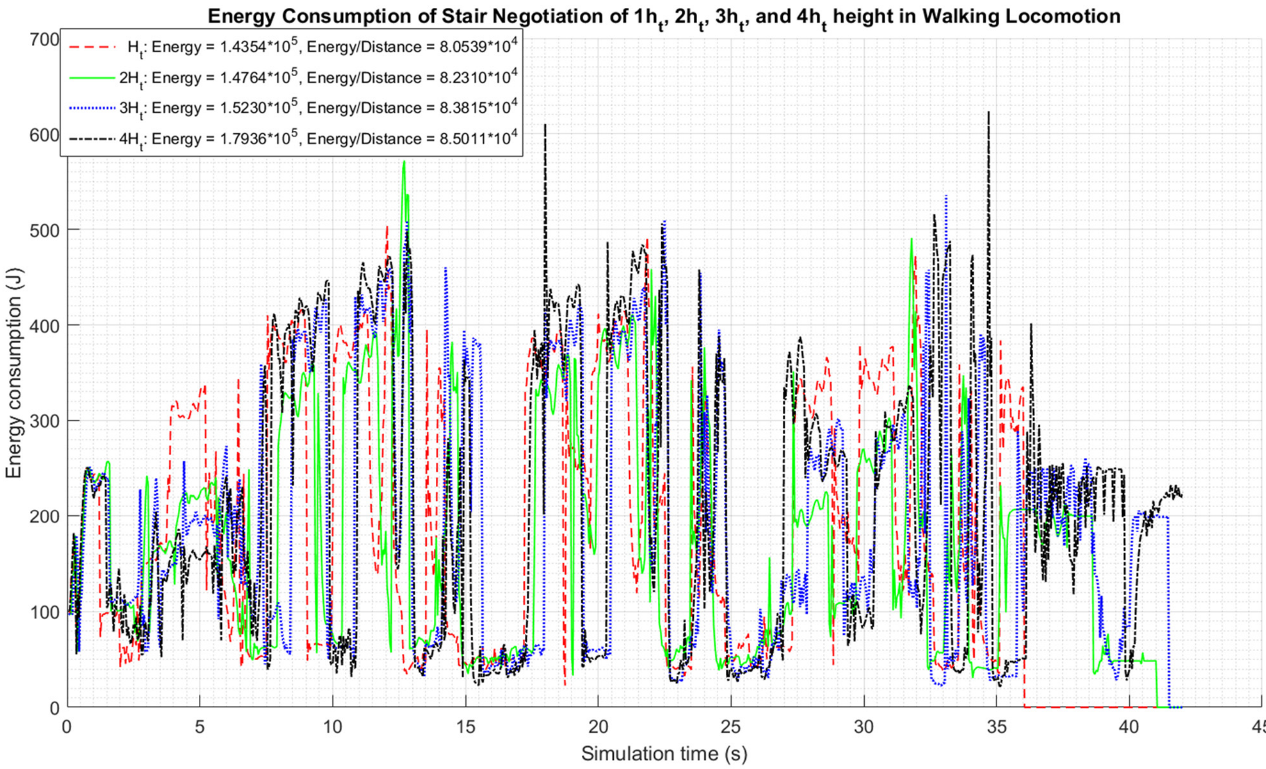


Figure 5. Energy consumption of stairs climbing negotiation

Beside energy, the proposed criterion was proposed based on both internal states of the robot (energy) and the external environmental information (obstacle height). The flowchart illustrating the proposed locomotion mode transition method is shown in Fig. 7.

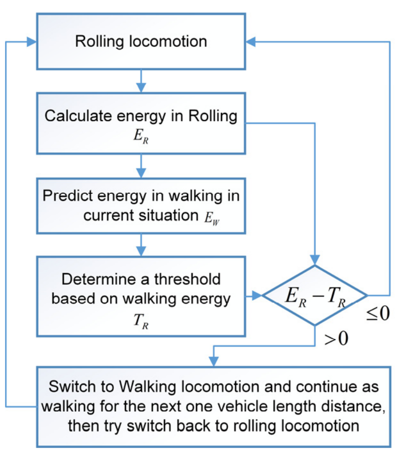


Figure 7. Autonomous Locomotion Mode Transition Flowchart

As shown in Fig. 7, the robot starts to move in rolling locomotion, the robot calculates the energy consumption (E_R) in current situation; At the same time the robot uses the environmental information gathered by sensors to calculate and predict the energy consumption that another alternative locomotion walking (E_W) will consume in the current situation; Subsequently an energy threshold value (T_R) is determined by the predicted energy consumption E_W; A decision-making process is executed in a way 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, then switch back to rolling locomotion; otherwise if $E_R \leq T_R$, the robot keeps rolling.

In above proposed method, the future work includes a method to determine the threshold value T_R for locomotion mode transition based on the predicted E_W; or T_R can directly equals to E_w, in fact the optimization degree of the walking gait affects significantly in determining the threshold value. A time window should also be used to avoid unnecessary locomotion transitions, which means the locomotion transition should not be invoked unless the energy consumption of rolling (E_R) keep over T_R for a certain time period.

V. Conclusion

In this paper, a climbing gait to negotiate stairs of various heights of a hybrid quadruped robot was proposed. The energy consumption of different heights stairs negotiation using the proposed climbing gait was evaluated. The energy consumption knowledge of walking locomotion was applied to propose a locomotion mode transition method of hybrid robots.

The novelty of the proposed method is summarized as: i) The proposed locomotion mode transition criterion was developed with both the internal states of the robot and the external environmental information; ii) Energy consumption was utilized to reflect the vehicle-terrain interaction parameters instead of directly evaluating these parameters using terramechanics models, which can be achieved by the real-time running of the vehicle in the rolling locomotion mode; iii) The threshold value of the proposed criterion is determined by the energy consumption predictive evaluation of the alternative locomotion in current situation, thus make this method generalizable to current existing various hybrid robots.

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