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Research paper

Design and analysis of a novel walking vehicle based on leg mechanism with variable topologies

Jianxu Wu[a], Yan-an Yao[a,*]

[a] School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing, 100044, PR China

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ABSTRACT

In order to improve the adaptability of one-degree-of-freedom leg mechanism to unknown terrains while maintaining its control simplicity, energy efficiency and integral rigidity, a novel close-chain mechanism with variable topological structures is proposed to act as a single leg to generate different gaits. The design process of the closed kinematic chain is completed by integrating two types of mechanical joints. Besides, the kinematics of the single leg under two modes is analyzed using vector loop method, and the particular structure of the leg mechanism is designed with optimized parameters. The topological states are represented with graphs and a matrix. Moreover, the whole close-chain legged unit and the walking vehicle are developed and constructed. In particular, to evaluate the crossing ability, this paper proposes the obstacle-surmounting probability. A series of dynamic walking simulations is conducted and analyzed to support the obstacle-surmounting capability and mobility comparison. Legged units are fabricated to verify the theoretical analysis, and walking experiments with a multi-legged vehicle are performed to testify the prototype performance.

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1. Introduction

At present, legged vehicles are widely needed in applications. On rough terrains and in unstructured environments, the legged machines [1,2] have an advantage over the tracked and the wheeled machines in terms of locomotion capability. Therefore, the maneuverability [3], the energy efficiency [4] and the payload capability [5] of the legged vehicles have been studied by many researchers. With different performance characteristics, the legged machines have been tasked in diversiform occasions: BigDog [6] and AlphaDog [7] which can carry 154 kg and 181 kg of payloads respectively have been used as delivery vehicles in military tasks; Octopus robot [8], with a payload of more than 500 kg, can perform disaster rescuing and safety guarding; ASV [9] and DANTE II [10] are used for supervision mission and volcano exploration; Walking Harvester [11] can complete tasks in forestry and agriculture; ASIMO [12] has been used as the receptionist. Accordingly, in consideration of application fields and mission sections, the selection and the design of the leg mechanism should satisfy various functional requirements.

To simplify control and drive system in a multi-legged arrangement, the close-chain leg mechanism (CCLM) with comparatively fewer degrees of freedom (DoFs) is a preferable choice. Especially, the planar CCLM generally driven by a single motor has shown great potential in various types, such as Rygg [13], Chebyshev mechanism [14], Walking Vehicle [15], Theo Jansen mechanism [16], Klann mechanism [17] and also, the reconstruction study for ancient machinery by Chiu, Hwang

* Corresponding author.
E-mail address: yayao@bjtu.edu.cn (Y.-a. Yao).

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Nomenclatures

CCLM	close-chain leg mechanism
CoG	center of gravity
DoF	degree of freedom
LMVT	leg mechanism with variable topologies
WCCLM	whole close-chain leg mechanism
c	category of kinematic pair
C	crank link
D	separated pair
f	foot point
F	shank link
G	ground link
h	obstacle height
H	stride height
j	number of joints
l	stride length
lo	number of loops
L	thigh link
M	motion restrictor
n	number of links
o	orientation of the kinematic pair
p	supporting point
P	prismatic pair
r	link length
R	revolute pair
S	sliding link
T	ternary link
v	arbitrary orientation
x_{pi}	x-coordinate of point f in type-P
x_{ri}	x-coordinate of point f in type-R
x_{si}	x-coordinate of pre-assigned point
X	fixed pair
y_{pi}	y-coordinate of point f in type-P
y_{ri}	y-coordinate of point f in type-R
y_{si}	y-coordinate of pre-assigned point
β	angle between shank link and ground at demarcation point
ΔV	supporting fluctuation along Y-axis
ΔX_i	movement distance of swing foot point along X axis in bench trajectory
$\Delta X_i{}'$	movement distance of supporting foot point along X axis in bench trajectory
ΔY_i	movement distance of swing foot point along Y axis in bench trajectory
$\Delta Y_i{}'$	movement distance of supporting foot point along Y axis in bench trajectory
θ	rotational angle of link

and Chen, et al [18–20]. With respect to steering capability, LARM biped mechanism [21] realizes turning locomotion by adding actuators, and DQV [22] with multi-legged structure adopts the skid-steering pattern. Furthermore, these studies have demonstrated that the crank-driven leg mechanisms with one-DoF perform better at high stride frequency [23]. Besides, the close-chain series structure possesses the integral rigidity, more suitable for missions under a high load [24].

To sum up, the assembled mechanical components in most studies on CCLM have constant physical shapes and connections. Thus, this invariant legged hardware morphology can only generate a single gait curve. Nevertheless, the legged platform is required to control and regenerate gaits along with the change of environment [25,26]. In other words, the energy consumption needs to be reduced on the smooth ground, and the obstacle-crossing efficiency needs to be enhanced when the legged platform moves through irregular terrains. Therefore, this problem becomes the main challenge in practical applications where versatility and terrain adaptability are needed [27,28]. The reconfigurable Theo Jansen linkage [29,30] and Klann mechanism [31] have effectively improved the trajectory flexibility. With five-DoFs and seven-DoFs, they can realize the valid gait reconfiguration via parametric changes. Similarly, a hexapod robot [32] with the hybrid-driven mechanism performs the turning gait by adjusting the link lengths. A legged walking robot with two adjustable parameters could climb stairs [33]. In brief, these approaches of parametric variation are mainly concerned with the quantitative properties.

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