THE BIONIC STRUCTURE AND MOTION BEHAVIOR OF UNMANNED GROUND VEHICLE

Bo Su [(1)], Xingjie Liu [(1)], Lindong Mu [(1)] , Zuming Kang [(1)] , Sergei Matrossov [(2)], Vladimir Koutcherenko [(2)]

[(1)]China North Vehicle Research Institute, Beijing, China, Email address：feist201@qq.com
[(2)]Science & Technology Rover Company Ltd, St.Petersburg, Russian, Email address：simrcl@mail.ru

ABSTRACT

Unmanned ground vehicle (UGV) is a special automotive ground vehicle with its own power, and completes prescribed missions automatically by prior deployment or remote control, rather than through manual control on the platform. The mission objects and working environment determines the special feature and performance of UGV which mainly works in the dangerous, polluted and monotonous situation. Considering that UGV works in both flat ground and complex unstructured terrain, this paper raises a novel motion behavior combining bionic and vehicular structure to improve its motion and adaption ability in the complex terrain. The research work is based on the study on the motion laws and inner structure of ground wheeled vehicle and legged animal.

1. INTRODUCTION

The development of special operating unmanned ground vehicle is promoted by the endless exploration spirit to the unknown environment of human beings and the practical problems faced when working in disaster, pollution and other special circumstances. The unmanned ground vehicle used in special circumstances needs to have a strong ability to adapt to the unknown environment, as well as its stability and mobility while the traditional vehicle performance is hard to meet the requirement of mobility. Based on the biological characteristics, the new walking mechanism and behavioral research can get better effect when adopting or melding bionic technology. Currently, there are many scholars have carried out related research work on the fusion technology of vehicle and bio-robot. Jinliang Luo worked on kinematic analysis, which is based on wheel-legged metamorphic engineering machinery walking mechanism [1]. Lijie Zhang did research on bionic composite wheel-legged joint structure and carried out analysis of kinematic and kinetics [2]. Zerun Ma et al. proposed a serial-parallel hybrid wheel-legged structure that could adapt to the complex terrain, and analyzed and established the mathematical relationship between the height of the obstacle and width of the cross channel the robot could achieve and the mechanism dimension [3]. Yan Xu et al. studied the stability control technology of wheel-legged robot, and put the stability criterion of wheel legged bionic unmanned vehicle forward [4]. In this paper, the wheeled vehicle will be the basis, into which bionic leg, foot and trunk structure characteristics will be incorporated. It will improve the mobility in complex environment of unmanned ground vehicle without changing its basic structure and characteristics.

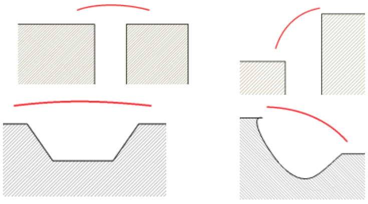
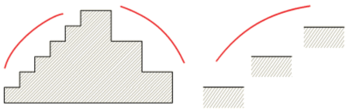
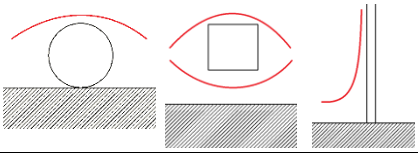
2. THE APPLICATION ENVIRONMENT OF UNMANNED GROUND VEHICLE

Unmanned ground vehicle is needed not only to reach the high-speed motor performance in off-road of manned vehicle to implement collaborative work with manned vehicle, but also to have stable walking ability in extremely complex rough terrain to meet the requirements of working environment which is “dangerous, boring, corrosion, dynamic, bad” that manned vehicle is difficult to reach. Although there are complex and changeful terrain, the landform and billions of growing plants, and the man-made construction nearly every corner on the earth, analyzing ground environment from the perspective of walking, it could be attributed to geometric features and support features preliminarily.

2.1 The geometric features of terrain

The geometric structure parameter of unmanned ground vehicle walking system is closely related to the geometrical characteristic of terrain. The influence factors of terrain geometry characteristics that cause the loss of working ability of unmanned ground vehicle mainly include: collision and bellying of unmanned ground vehicle caused by terrain with local convexity will lead to walking ability lost; bellying and getting stuck after sinking of unmanned ground vehicle caused by terrain with local subsidence will lead to walking ability lost; the transverse and longitudinal slope of large angle formed by the global fluctuation will lead the overturn of unmanned ground vehicle. The following table (Tab. 1) shows typical geometric features of the terrain [5].

Table 1. The typical geometric features of the terrain

The specific urban environment	Definition	Sketch of terrain	Define parameters
Gully	Discontinuous physics surface appears in the horizontal plane, there might be vertical height difference		Width Depth Height difference
Slope	The continuous physical surface has a certain slope		Gradient
Step	The continuous physical surface has a vertical height difference		Gradient Height Width
Barrier	The object which directly influence the process of moving vehicle		Length Width Height Diameter

2.2 The geometric features of terrain

The traction-driving performance, stability etc. of unmanned ground vehicle is closely related to the support characteristics of terrain. The factors of terrain support characteristics that cause the loss of working ability of unmanned ground vehicle mainly include: when passing through soft terrain with low bearing capacity, unmanned vehicle will subside; when passing through hard or soft terrain with low friction, skid will occur to unmanned vehicle, and then overturn or direction deviation will appear; when passing through loose slope, unmanned vehicle will slip down [6]..

Support characteristics of terrain could be described with the mechanical properties of soil. The soil is multiphase system composed of a number of fine particles. There are interactions between those particles, and they are affected by the external condition. Fig. 1 below presents the model of interaction between rigid wheel of walking system and soft soil [7].

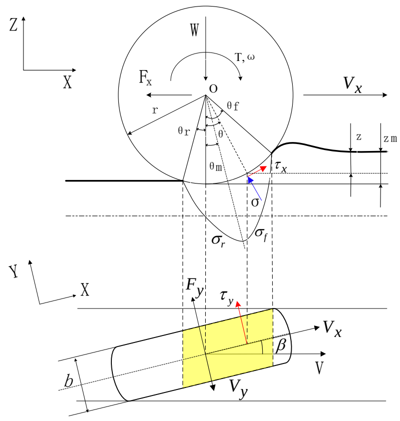


Figure 1. Interaction model of wheel-soil

In Fig. 1, W is the vertical load applied on the wheel; F_x is the longitudinal drawbar pull on the wheel; F_y is the lateral force on the wheel; T is the driving torque applied on the rotation shaft of the wheel by the drive; θ_f is the approach angle; θ_r is the departure angle; θ_m is the corresponding angle of the wheel center from the vertical position to the point where has the maximum normal force on the wheel; τ_f, τ_r is the tangential stress of an arbitrary point in the front and back zone of action; σ_f, σ_r is the normal stress of an arbitrary point in the front and back zone of action; Z is the wheel sinkage.

3. WALKING MISSION REQUIREMENTS OF THE UNMANNED GROUND PLATFORMS

The Examples of the unmanned ground platforms and prospects of military equipment or in civilian applications, you can get more than 100 kinds of mission requirements, and is increasing rapidly. According to the idea of the fourth literature, from the functional class of the unmanned ground platform, you can obtain the following four categories of preliminary functional requirements[8].: monotone, continuing mission requirements; existing platform was coordinated combat mission requirements; combat support mission requirements; high-risk complex tasks demand environment job.

Use demand - functional cluster analysis method, unmanned ground platform mission requirements of the four induction walking function, as shown in Tab. 2. Through the analysis of the four classes(16 items),unmanned ground platform typical application requirements and functional cluster analysis showed that under the complex environment of high demand for the adaptation of walking function is 11.5 items, about 72% of demand, for the known passable road walking function ,the demand for the 3 items , about 19% of demand (including repeated demand), for the do not need to walk or need simply walking function is 3.5 items, approximately 22% of demand (including demand repeat).

Table 2. Typical UGV mission requirements and functional analysis of walking

task		Walking functional requirements	Clustering walking function		
			It does not have the flat terrain or slow moving function	Known passable road walking function	Unknown complex environment with high fitness walking function
Monotonous continuing task	cruising	1. certain mobility, speed 7-12km / h (instead of people), 45-60km / h (instead of patrol cars) 2. The provisions of the road traffic environment independent autonomous road conditions and traffic regulations patrols and patrols 3. cruising capability (6-9 hours)	+	+	–
	Duty	1.Simple ability to move or static work	+	–	–
	monitor	1. The ability to move certain to monitor the transfer point 2. Static work	+	+	–
	reconnaissance	1. The ability to walk the complex environment, with high adaptability and high stability of the terrain; 2. With stealth, mute function 3. have strong battery life	–	–	+
	View detection front	1. With the manned platforms battlefield mobility; 2. The ability to walk the complex environment, with	–	–	+

And cooperative combat missions manned platforms		high adaptability and high stability of the terrain; 3. With stealth, mute function 4. have strong battery life			
	Fire guided	1. With the manned platforms battlefield mobility; 2. The ability to walk the complex environment, with high adaptability and high stability of the terrain; 3. With stealth, mute function 4. have strong battery life	—	—	+
	Trick target	1. Quick high mobility, high capacity to adapt to the terrain 2. certain battlefield protection capability	—	—	+
	Fire attacks	1. With the manned platforms battlefield mobility; 2. The ability to walk the complex environment, with high adaptability and high stability of the terrain; 3. battlefield protection capability	—	—	+
	Single Soldier combat support	1. Portable features (weight 2-15kg); 2. The ability to move (buildings, culverts, ruins)	—	—/+	+/—
	Support team	1. travel with complex terrain features (mountains, city 7-12km / h); 2. strong load capacity；	—	—	+
	Battlefield transport security	1. The high mobility off-road capability (follow someone	—	—/+	+

Combat support mission		team along the planned route transportation security)； 2. The high-mobility off-road capability (to perform the specified path alone injured man and recharge)			
	HIGH ALTITUDE supply	1.Walking ability to adapt to the complex environment 2. strong load capacity 3. have strong battery life	－	－	＋
High-risk job tasks in complex environments	Exclude explosives	1. The low ability to walk (with stability) 2. strong load capacity	＋	－	－
	Disaster assistance	1. complex terrain high adaptation ability to walk (the ruins)； 2. have strong battery life	－	－	＋
	Pollution of the environment job	1. Complex terrain high adaptation ability to walk (when the fire occurred after the explosion)； 2. strong load capacity	－/＋	－	＋
	Terrorism stability maintenance	1. Complex dynamic environment the ability to walk 2. rapid mobility capability 3. certain battlefield protection capability	－	－	＋

4. MOTION CHARACTERISTICS ANALYSIS BASED ON TASK AND TERRAIN

The structure principle of the system originates from the expected functions, states and behaviors, whose abstract understructure is the application environment and missions of the system. For example, the motion behaviors and characteristics of field transport unmanned platform was presented based on the above analysis of the environment and missions, as shown in Tab. 3.

Tab. 3 showed the corresponding motion characteristics of the mission functions and environment terrain of a field transport unmanned platform. Several conclusions were drawn as follows according to the cross statistics of functions and environment.

(1) The basic functional characteristics: the function which is required to be satisfied in any environment. It means the basic conditions of the platform design, which are carrying goods or other task load, light-weighting (transportability), Small-sized (transportability), Simple structure (economical, reliable, maintenance) and controlling easily.

Table 3. The motion behaviors and characteristics based on task functions and environment terrain.

No.	Terrain environment \ Task function	Relative importance	1 Horizontal rigid pavement/Asphalt or Cement	2 Horizontal rigid pavement/Ice road	3 Horizontal soft pavement/Desert	4 Horizontal soft pavement/Swamp	5 Horizontal soft pavement/Snow	6 Gentle slope rigid pavement/Asphalt or Cement	7 Gentle slope rigid pavement/Ice road	8 Gentle slope soft pavement/Desert	9 Gentle slope soft pavement/Swamp	10 Gentle slope soft pavement/Snow	11 Steep slope rigid pavement/Asphalt or Cement	12 Steep slope rigid pavement/Ice road	13 Steep slope soft pavement/Desert	14 Steep slope soft pavement/Swamp	15 Steep slope soft pavement/Snow	16 Rigid convex obstacle pavement	17 Rigid depressed obstacle pavement	18 Soft convex obstacle pavement	19 Soft depressed obstacle pavement	20 Rigid step pavement	21 Soft step pavement	22 Continuous random rolling pavement	Weight
1	High speed travel in straight line（60-80km/h）	1	■					■																	2
2	Low speed travel in straight line（10-30km/h)	1		■	■	■	■		■	■	■	■												■	9
3	Steering in motion	1	■	■	■	■	■	■	■	■	■	■													10
4	Steering in situ	2	■					■																	2
5	Emergency braking	1	■	■	■	■	■	■	■	■	■	■													10
6	Parking in situ	2	■	■	■	■	■		■	■	■	■	■												10
7	Carrying goods or other task load	1	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	21
8	Self stabilization in motion	1						■					■		■	■	■	■	■	■	■	■	■	■	12
9	Trafficability of the terrain and obstacles	1																■	■	■	■	■	■	■	6
10	Autostability after crashing barriers	2																■	■	■	■	■	■	■	6
11	Efficient driving and endurance（5h）	3	■																						1
12	Lightweighting（transportability）	4	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	22
13	Small-sized（transportability）	4	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	22
14	Simple structure（economical, reliable, maintenance）	3	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	22
15	Easy to control	4	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	22
	Weight		11	9	9	9	9	10	8	8	8	8	8	4	6	6	6	8	8	8	8	8	8	9	

(2) The basic characteristics of the environment: the environment which is required to be satisfied in any function, none. It means no unmanned platform is able to realize all functions in a single environment.

(3) The standard environmental characteristics: horizontal rigid pavement. It is the environment that achieves the maximum functions and met the maximum probability of application in the life-cycle.

(4) The little environmental characteristics: steep slope rigid ice pavement and Steep slope soft pavement. They are the environment that achieve the minimum functions and met the minimum probability of application in the life-cycle.

Functions and environment were merged, which were the same motion functions and unattainable functions, and environment of the basic functional characteristics. Then terms were collected and 15 corresponding mission functions and environment terrain of the unmanned ground platform was listed in Tab. 4 as follows.

Table 4. Corresponding mission functions and environment terrain

No.	Movement behavior and State analysis	Whether the traditional vehicle behavior or not
1	High speed / High power electric wheel driving	y
2	Low speed high torque electric wheel driving	y
3	Dynamic adjustable attitude /Multi wheel uniform ground pressure/Dynamic moving centroid transfer walking	n
4	Dynamic ground pressure	n
5	Independent suspension / balanced suspension	y
6	Differential steering /	y

	independent steering	
7	Transverse step steering	n
8	Differential steering in situ/Angle wheel steering/All wheel steering	y
9	Electronic brake	y
10	Mechanical brake	y
11	Special grounding mode - fixing	n
12	Discrete touchdown(stepping) walking mode	n
13	The energy absorption / buffer mechanism	n
14	Efficient driving/Motor coordination/Energy efficiency	y
15	Miniaturization/Light weight/Modularization	y

5. VEHICLE BEHAVIOR AND BEHAVIOR FUSION BIONIC CONFIGURATION

Take six wheels drive unmanned platform as an example to explore the behavior of the vehicle integration and biomimetic behaviour [9].Vehicle technology and bionic technology process integration iterate to avoid using bionic behavior and reduce the intrinsic behavior of the vehicle features and basic behavioral characteristics, as shown in Tab. 5:

Table 5. Fusion of bionic behavioral techniques six wheels drive unmanned platform driver

Serial number	Locomotor activity / state analysis	Bionic behavior / institutional structure
1.	Dynamically adjustable posture / multi-round uniform ground pressure / dynamic migration centroid shift (eg stepped) type walking, discrete touchdown (stepped) way of walking	Four-legged animals (horses, dogs, camels, etc.) stride walking / legs and torso structure
2.	Dynamically changing ground pressure	The foot end structure of foot type animal
3.	Lateral steering stride	Laterally stride myriapoda(Spiders) leg structure
4.	Special grounding - sand-fixing	Camel palm structure
5.	Energy absorber / buffer mechanism	Bounce animal body

5.1 Wheel Step walking mode

Wheel Step walking mode use a certain number of wheeled walking mechanism, as shown in Fig. 2.Wheel according to a certain order or along the surface of the support to move forward a step away from the distance (mobile phase), or the wheels on the supporting surface stop moving, walking through the mechanism of the body moves forward a step from distance (support phase).

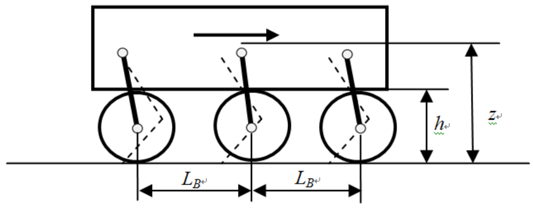


Figure 2. Wheel Step walking mode diagram

5.2 Bionic leg mechanism

Wheel type step way of walking can solve the low bearing capacity of pavement through the issues and have high speed rolling movement and walking step of fast switching capability, but for complex disorders or ups and downs Road, due to wheel type walking wheel not separated from the ground, does not have step or discrete touchdown, and in order to ensure the wheel rolling movement speed, wheel diameter is larger, the spring under load, so the ability of overcome obstacles is lower than legged walking way. In order to improve round step type walking mechanism across the stage to achieve climb the steps in the process of minimal energy consumption and minimal impact, minimum trajectory scheme selection, legged animals bionic leg structure is adopted [10], when encounter obstacles step, the front wheel by means of self-driving force along the walls will raise the wheel and drive platform barriers. As shown as Fig. 3, the design is as follows:

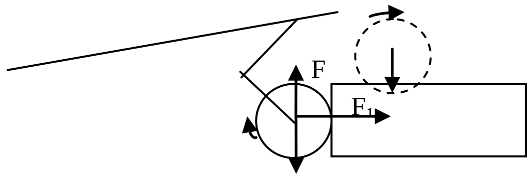


Figure 3. Bionic leg structure over step obstacle

5.3 Bionic foot and wheel structure

Adopting wheel-step type walking wheel, the contact form with the ground and work mode keep changing, and the wheel can host the function of bearing, rolling and driving, buffering, sand-fixation at the same time in the process of walking, meanwhile, the wheels of using traditional rubber pneumatic tire don't have the ability above. Based on the mechanism structures of animal foot end or sole in special environment, such as the research on bionic ostrich legs [11], we can explore a new wheel structure, see Fig. 4.

Figure 4. Drum surface of bionic sand wheel imitate from ostrich foot 3D surface

5.4 Articulated body structure

In spite of the wheel-step type walking style, and equipped with bionic legs of multiple degrees of freedom, it's still difficult to safeguard six wheels even ground and get better traction performance on the road of continuous ups and downs,. Animal has experienced a long evolution and natural selection, the ability of adapting to the natural environment of terrain far exceeds the ordinary wheeled vehicles. Especially the kind of cats like cheetah, because of its multiple degrees of freedom movement structure, the leg is redundant and remains the ability of multiple freedom adjusting and keeps balance. From imitating the physiological structure of cheetah, we can change the rigid body to the flexible hinged body, and increase hinge joints on car body to increase the redundancy and stability of the car body. The figure of car body of increasing the hinge points is shown in Fig. 5.

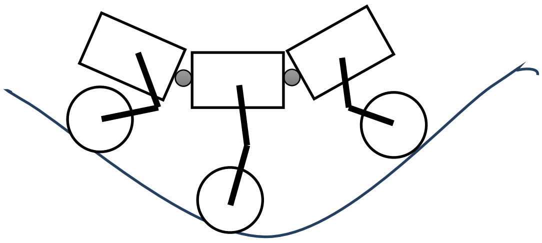


Figure 5. Ground adaptability of bionic articulated body

5.5 Buffer mechanism

When the unmanned platform drives from a high platform, it needs buffer mechanism to absorb energy to slow down the impact. The bionic wheel described earlier has a certain buffering capacity. In the legs we can design a buffering mechanism, to simulate the biological muscle to buffer. The buffering mechanism just likes the buffering mechanism of general legged robot. Articulated point, in fact, not only can be designed into mechanical articulate, also can increase the buffering mechanism. The hinge points of bionic articulated body imitate from a cat's spine, and the spine have the function of bearing, protection, absorbing shock, in addition the vertebrate spinal structure are no different.

6. CONCLUSIONS

The requirements of future work under special environment lead the technical development of unmanned ground vehicle for special operation, to the direction of fusion with vehicle and bionic features. The practical application of wheel-foot unmanned ground vehicle is the exploration of the fusion with both vehicle engineering theory and bionic structure theory. Through the analysis and experiment, it is clearly that wheel-foot unmanned ground vehicle has stronger stability and better performance of passing the complex terrain, than the traditional wheel type, and it has higher walking efficiency than legged robot on flat terrain. However, the wheel-foot robot still faces a lot of problems, such as complex structure, too many drive units, less walking efficiency than legged animal. For the better application in engineering, the dynamic and kinematic of bionic step structure still needs to be optimized. Also, smaller moment of inertia, lighter bionic material, and multi freedom deformable structure should be explored. Then the combination of vehicle and legged animal will be perfect.

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