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Correspondence to:
Weizhong Guo
wzguo@sjtu.edu.cn

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Novel design of a family of legged mobile landers based on decoupled landing and walking functions

Rongfu Lin and Weizhong Guo

State Key Laboratory of Mechanical Systems and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

Abstract The lander has made a significant contribution to soft landings and exploration of an extraterrestrial surface. To further expand its detection range and meet the needs of base construction in the future, it is necessary to design a legged mobile lander (LML) that lets the fixed lander walk. In this paper, a decoupled functions synthesis method (DFSM), which means the decoupled landing and walking functions for LMLs, is proposed: it uses separate structures of landing leg (LL) and walking leg (WL) to perform landing and walking functions. The structure of the Chang'e lander's leg is selected and designed as the LL. The structures of WLs are determined and presented by the Lie group type synthesis method. In accordance with the combination principle, the landing-walking leg (LWL) for LMLs is designed by combining the structures of a LL and a WL. The structures of a family of LMLs are achieved by assembling the same or different structures of legs. Furthermore, the actuated joints are assigned according to the principle for selecting the actuated joint and one case of LWL is selected as an optimized type by the qualitative evaluation. Finally, one leg of LMLs is taken as an example to analyze the properties and abilities during different stages.

1. Introduction

The exploration mission of extraterrestrial bodies, such as the Moon, Mars and other asteroids, is an important strategy for deep space exploration. In the current space exploration mission, the combination of a legged stationary lander (LSL) and a rover is mainly used for landing and exploring the extraterrestrial surface [1]. Up to now, the “circling” and “landing” missions of the Moon have been based on this combination of a fixed landing and rover. Furthermore, in this mode, the lander has two important tasks: to help the rover to soft land on the extraterrestrial bodies' surface, and to perform on-site exploration at the landing site. Meanwhile, the rover mainly executes major exploration and investigation around the landing site. This exploration mode is suitable for many requirements of the exploration task. The design of landers has drawn extensive interest in many nations, such as Surveyor 1 [2], Luna 16 [3], Apollo [4], EuroMoon 2000 [5], ELENE-B [6], Altair lunar lander [7], Chang'e 3 [8] and so on.

However, with the development of the extraterrestrial body's exploration task, the existing mode with LSL reveals some limitations, such as it leads to limit the exploration range of the rover because it has to receive energy or other aids from the lander after extravehicular activity; the body of the lander has no ability to adjust its pose, which is not beneficial to provide the condition for the ascent and base construction in the future. Certainly, the proposal of LMLs can meet the needs of large area exploration, “return” mission, and base construction in the future. Thus, it is urgent and of realistic significance to study the research on LMLs. Some novel exploration mode is necessary to deal with the previously mentioned limitations.

To date, there have been few studies discussing some novel methods or exploration strategy for exploring extraterrestrial bodies. Zhang et al. [9] proposed a conceptual design of a manned lunar lander with wheel-legged mobile system, which enhances the capability of lunar exploration.

Our previous work [10] put forward a novel exploration mode for the task. The lander has the multi-abilities of fixed lander and rover with landing and walking functions. Furthermore, our group also designed this kind of LML with a passive limb [11]. In addition, some special legged mobile landers were obtained containing a rhombus joint by the method Lie group and differential manifolds [12]. Owing to the main backbone needs to bear most of the impact force during landing, one actuated limb (also called transmission limb) is taken to protect the actuated joint against the impact force. Although some structures of the LMLs were proposed, there is work we also need to do, such as it is necessary and meaningful to put forward some mechanisms of LMLs with decoupled landing and walking functions, which means it uses different structures to realize the landing and walking functions.

This paper aims at a novel design of LMLs with decoupled landing and walking functions by designing and combining the structures of the existing landing legs of the LSL [2-8] and the type synthesis experience of walking robot in our lab [10-13]. The paper is detailed in seven sections. The overall concept and design procedure of LMLs is outlined in Sec. 2. The structure design of LLs based on Chang'e leg is presented, which has the functions of deployable and landing buffer in Sec. 3. The structural design of WLs, which has the functions of deployability, orientation, terrain adaptability is presented in Sec. 4. In Sec. 5, the structures of LWLs and LMLs are designed and presented by combining the structures of LLs and WLs based on the combination principle. In Sec. 6, one case of LMLs is selected as an optimization one after putting forward the actuated joint selection approach and type evaluation. Finally, Sec. 7 contains the conclusions.

2. Design concept and procedure for LMLs based on decoupled landing and walking functions

2.1 Overview of the design concept of DFSM method

A design concept for achieving novel LMLs is necessary. As mentioned, the exploratory mission can be separated into three stages: launching & ascent stage, descent & landing stage and walking & exploring stage. The lander performs a deployable function during first stage, landing buffer function during second stage, and walking, orientation and terrain adaptability function during third stage. Furthermore, the key issue of the type synthesis of LMLs is to deal with the landing function and walking function since in the landing function the lander has no mobility, which is a truss while the walking function needs the lander to have flexible mobility. According to the phenomenon, one can use separate structures to operate the different functions during the second and third stages, and both of the structures have the deployable function in the first stage. In view of the function, a leg whose structure performs the landing and deployable functions is called the landing leg (LL), while a leg whose structure performs walking, orientation, terrain adaptability and deployable functions is called the walking leg (WL). Furthermore, the leg of an LML whose structure has LL and WL is called the landing-walking leg (LWL), which realizes the decoupled landing and walking functions.

Thus, a design concept for designing LMLs, called the decoupled functions synthesis method (DFSM), is put forward: designing separate structure to realize different functions (in this paper it mainly refers to the landing function and walking function), and combining them under some combination principles.

Taking inspiration from the structure of the Chang'e [8] lander and DFSM, an LML is mainly composed of a body and four LWLs. The structure of each LWLs mainly consists of one LL and one WL, both of them can be decomposed into two parts, the upper part and the lower part. The upper of LL is called upper part I, and the upper part of WL is called upper part II. The lower part connects with a foot pad by a passive sphere joint to have the terrain adaptability. The lower part is also the common part of LL and WL, as shown in Fig. 1.

2.2 Design procedure for LMLs based on DFSM

Accordingly, DFSM for designing structures of LMLs is presented in four phases. Phase 1, the structure design of an LL. Phase 2, the structure design of a WL. Phase 3, structure design of LWL by combining an LL and a WL under certain combination principle. Phase 4, qualitative evaluation and actuated joints selection for an LWL. Finally, the structures of LMLs are obtained and listed by assembling the structures of legs. Note that the process for design of LL or WL by using the lie group type synthesis method [14, 15] mainly includes determining the motion characteristic of the mechanism, each limb and design of the structures of each joint corresponding to the motion characteristics of joints.

3. Structure design of LLs based on Chang'e lander

Before designing the structure of LLs, the structure of Chang'e LL is analyzed. LL is made up of a main backbone, a single function auxiliary backbone, a multi-function auxiliary backbone and a foot pad which will avoid excessive sink into regolith, as shown in Fig. 2. The structure is decomposed into the upper part I and the lower part. The structure of the upper part I is regarded as a parallel mechanism and the lower part connects with a foot pad by a passive sphere joint to have terrain adaptability. Three backbones connect with the body by U joints while the auxiliary backbones connect with the main backbone by S joints.

To absorb the impact shock, energy absorbers are installed into the three backbones. During landing, the main bumper backbone absorbs the vertical impact force and the auxiliary bumper backbones the horizontal impact force. During launching & ascent stage, the length of the multi-function auxiliary

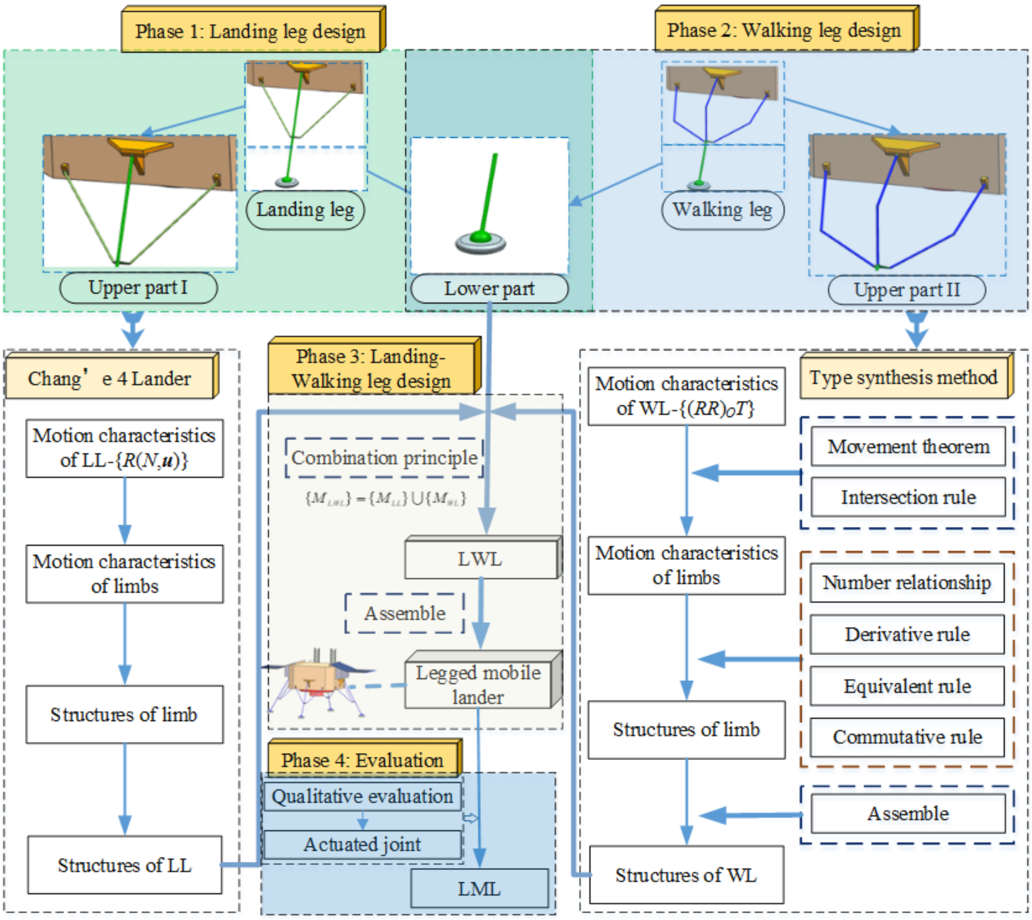
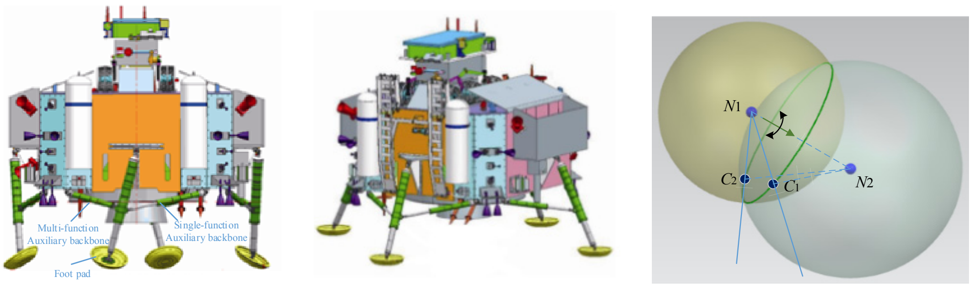


Fig. 1. Synthesis procedure of DFSM for designing LMLs.



(a) (b) (c)

Fig. 2. Structure of the landing leg: (a) stowed position; (b) deployed position; (c) rotation axis.

backbone is short and locked to achieve the stowed position, as shown in Fig. 3(a). During the descent stage, the length of the multi-function auxiliary backbone will be long and locked to achieve the deployed position, as shown in Fig. 2(b). For facilitating describing the information of the rotation axis, the corresponding diagram is presented in Fig. 2(c). Point N_1 and point N_2 depict the center of the U joint connecting the body and main backbone, single function auxiliary backbone, respectively. N_1C_1 and N_2C_1 denote the position of the main backbone and the auxiliary backbone in deployed position, while N_1C_2 and N_2C_2 denote the position in stowed position, respectively. The main backbone rotates around line N_1N_2. After landing, three backbones in upper part I of the landing leg are discarded through the approach of pyrotechnic separation devices. So, some aerospace pyrotechnic devices are installed in the joints located at the end of backbones.

Based on the above statement, the motion characteristics, LL is presented as {$R(N,\boldsymbol{u})$} for the ability to operate the deployed and landing buffer functions during launching & ascent and descent & landing phases. One can design a family of

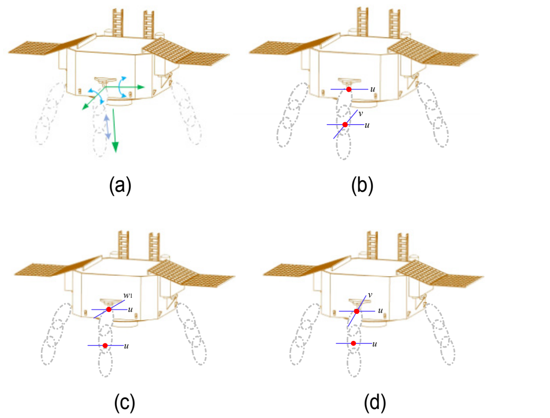


Fig. 3. Motion requirements of the legged mobile lander: (a) $(RR)_O T$; (b) $R(RR)_O$; (c) $R(RR)_O$; (d) $(RR)_O R$.

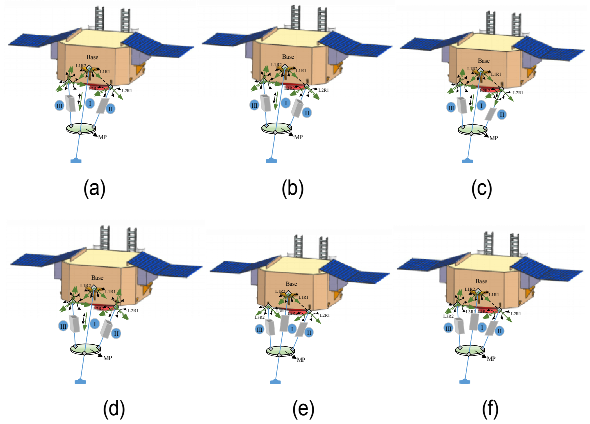


Fig. 4. Arrangement of motion characteristics of limbs: (a) case I: $\{M_1\}$; (b) case II: $\{M_2\}$; (c) case III: $\{M_3\}$; (d) case IV: $\{M_4\}$; (e) case V: $\{M_5\}$; (f) case VI: $\{M_6\}$.

novel LL based on the existing leg of the LSL. Fortunately, the existing leg structures of Chang'e 4 LSL belong to that of LL. Based on the successful experience of Chang'e 4 LSL, its structure can be used as LL in this paper. Some other LLs with $\{R(N,\boldsymbol{u})\}$ will be reported in another paper by the type synthesis method.

4. Structure design of WLs for LMLs

The structure of WLs consists of the upper part II and the lower part. The lower part of WL is the same as that of LLs, whose motion characteristic is 3D R-characteristics, realized by a spherical joint. The upper part II of walking legs is a parallel mechanism, which is made up of an end-effector, a basement (the body of LMLs), linked by three limbs (one main backbone and two auxiliary backbone). In this section, the novel design of the upper part II of WLs will be presented in detail.

4.1 Motion characteristics of WLs

The motion characteristics of WLs need to be presented corresponding to their functions, which need the ability to operate the four functions among the five ones apart from the landing function.

According to displacement subgroup method [14] and the extraction rules [15-17], the corresponding motion characteristics can be achieved after analyzing the multi-functions. The motion characteristic of WLs is $\{D\}$. The subgroup $\{D\}$ is a resultant of the implementation of the product of two subgroups, $\{T\}$ and $\{S(M)\}$, i.e., $\{D\} = \{T\}\{S(M)\}$, which consists of two parts, upper part II and lower part $\{S(M)\}$. The subgroup of the point of the upper part (or the center of the footpad) is $\{T\}$, whose point of the moving platform (also called as mid-platform) allows for 3-D translations-$\{T\}$. The motions of the point attached on the platform can be realized by other distributions of motions. To realize the center of the footpad's 3-D translations, the mid-platform's motion of the upper part could be $(RR)_O R$, $R(RR)_O$, $R(RR)_O$, and $(RR)_O T$, as shown in Fig. 3.

In what follows, LMLs with the first kind (shown in Fig. 3(a) of motion characteristic $(RR)_O T$) is taken as an example to illustrate the design method. Noted that LMLs with other type of motion characteristics are designed and obtained by the same method.

4.2 Motion characteristics of limbs for WLs

Based on the motion characteristic movement theorem [14] and intersection rules [16], six cases combinations of motion characteristics of limbs are obtained and listed in Table 2 according to the mid-platform's motion, which is $(RR)_O T$. Furthermore, the six layouts of the motion characteristics of the limbs for the walking legs are

$$\{M_1\}=(RR)_O T \cap RTT\tilde{R} \cap TTT\tilde{R}\tilde{R}\tilde{R},$$
$$\{M_2\}=(RR)_O T \cap TTT\tilde{R}\tilde{R} \cap TTT\tilde{R}\tilde{R}\tilde{R},$$
$$\{M_3\}=(RR)_O T \cap (RR)_O TT\tilde{R} \cap TTT\tilde{R}\tilde{R}\tilde{R},$$
$$\{M_4\}=(RR)_O T \cap TTT\tilde{R}\tilde{R}\tilde{R} \cap TTT\tilde{R}\tilde{R}\tilde{R},$$
$$\{M_5\}=RTT\tilde{R} \cap RTT\tilde{R} \cap RTT\tilde{R}, \text{ and}$$
$$\{M_6\}=RTT\tilde{R} \cap RTT\tilde{R} \cap (RR)_O TT\tilde{R},$$

as shown in Fig. 4, respectively.

$(RR)_O T$ means that there are three motion characteristics including 1-D T-characteristic and two R-characteristics whose axes intersect at a point O; $RTT\tilde{R}$ denotes that there are four motion characteristics including a nonmovable R-characteristic, a movable R-characteristic (represented by $\tilde{R}$) and 2D T-characteristics whose directions are perpendicular to the axis of the movable R-characteristic.

In addition, according to the GF theory [16], the geometric condition of these six cases is concluded as listed in Table 1:

Condition A: The axis of L_1R_1 (which means the first R-characteristic of the first limb) coincides with that of L_2R_1. The axis of L_1R_2 is parallel to that of L_2R_2. The direction of the T-characteristic of the first limb is parallel to the plane of the 2D

Table 1. Six cases of motion characteristic arrangements for limbs.

Cases	Limb 1	Limb 2	Limb 3	Condition
I	$(RR)_OT$	$RTT\tilde{R}$	$TTT\tilde{R}\tilde{R}\tilde{R}$	Condition A
II	$(RR)_OT$	$TTT\tilde{R}\tilde{R}$	$TTT\tilde{R}\tilde{R}\tilde{R}$	Condition B
III	$(RR)_OT$	$(RR)_OTT\tilde{R}$	$TTT\tilde{R}\tilde{R}\tilde{R}$	Condition A
IV	$(RR)_OT$	$TTT\tilde{R}\tilde{R}\tilde{R}$	$TTT\tilde{R}\tilde{R}\tilde{R}$	None
V	$RTT\tilde{R}$	$RTT\tilde{R}$	$RTT\tilde{R}$	Condition C
VI	$RTT\tilde{R}$	$RTT\tilde{R}$	$(RR)_OTT\tilde{R}$	Condition C

Table 2. Configurations of limb with $RTT\tilde{R}$.

Joint	Configuration of limbs			
P R	RRRP	RPRP	RRRR	RPRR
	RRPR	RPPR	RRPP	-
R P Pa	RRPPa	RRRPa	RPPaR	RPRPa
	RRPPa	RPaPR	RPaRR	RPaRP
C R P Pa	CRP	CPR	CRPa	CRPa
	CRR	CPaR		
U P R	UPP	UPR	URP	URR
U P Pa R	UPaP	URPa	UPaR	UPPa
R U* U	RU*R	RRU*		

T-characteristics of the second limb and the third limb is located at any position between base and moving platform.

Condition B: The planes spanned by the two R-characteristics of the first and second limbs are parallel to each other in this case.

Condition C: The axis of L_1R_1 coincides with that of L_2R_1. The axis of L_3R_1 is parallel to that of L_1R_1. The axes of L_3R_2, L_3R_2, L_3R_2 are parallel to each other and the plane spanned by 2D T-characteristics of each limb is be parallel to each other at the same time.

4.3 Structure determination of limbs for WLs

In light of the above discussion, five types of motion characteristics of limbs are presented: $(RR)_OT$, $RTT\tilde{R}$, $TTT\tilde{R}\tilde{R}\tilde{R}$, $TTT\tilde{R}\tilde{R}$ and $(RR)_OTT\tilde{R}$. Furthermore, the corresponding structures of limbs can be obtained. Only some of the practical limbs are given in this section.

As for $(RR)_OT$, the structures are obtained $(RR)_OP$, $(RR)_OR$, UR and UP. This paper uses some simple joints, including the revolute (R), prismatic (P) joints, and some composite joints such as cylinder (C), spherical (S), universal (U) joints, pure translation universal joint (U^*) and the parallelogram joint (Pa).

As for $RTT\tilde{R}$, the motion characteristics include one non-movable R-characteristic, one movable R-characteristic and 2D T-characteristics which are perpendicular to the axis of movable R-characteristic. The limbs with $RTT\tilde{R}$ motion are synthesized and listed in Table 2.

Table 3. Typical structures of legs with $(RR)_OT$.

Case	Configurations of legs	
Case I	UR&URR&URS	UP&URR&PSS
	UP&UPR&UPS	UP&UPR&RSS
	UP&UPR&URS	UP&UPR&RSS
	UP&CRR&UPS	UP&CRR&PSS
Case II	UP&URU&UPS	UP&URU&PSS
	UR&URU&URS	UP&URU&RSS
	UP&UPU&UPS	UP&UPU&PSS
	UP&PUU&UPS	UP&PUU&PSS
Case III	UP&SPR&UPS	UP&SPR&PSS
	UP&SRR&UPS	UR&SRR&PSS
	UR&SRR&URS	UP&SRR&RSS
Case IV	2-UPS&UP	2-URS&UR
	2-PSS&UP	2-RSS&UR
	2-U*PS&UP	2-SRU&UP
Case V	3-URR	3-CRR
	3-UPR	3-CPR
	3-UPaR	3-CPaR
Case VI	2-URR&SRR	2-CRR&SRR
	2-UPR&SPR	2-CPR&SPR
	2-RRRR&SRR	2-RPRR&SRR
	3-UPaR&SPR	2-CPaR&SPR

By the same method, the corresponding structures or configurations of $TTT\tilde{R}\tilde{R}\tilde{R}$, $TTT\tilde{R}\tilde{R}$ and $(RR)_OTT\tilde{R}$ are synthesized and listed.

4.4 Structure determination of WLs

The structures of WLs are obtained by assembling three corresponding limbs under the arrangement conditions (shown in Fig. 6). Some typical structures of these six cases legs are listed in Table 3.

To expand the terrain adaptation function to a greater extent, the experience of existing landers and walking robots in the laboratory [16] are adopted. Using the spherical passive joints with 3-D motion is adopted. Typical structures of legs with the upper part and the lower part are obtained and shown in Fig. 5, which are corresponding to the cases in bold listed in Table 3.

5. Structure design of LMLs based on DFSM method

5.1 Combination principle for LWLs

To design the appropriate leg structures of LWLs which consist of LLs and WLs, the principle for combining the two structures is proposed.

According to the principle of combination mechanism and Lie group theory [14] and intersection of screw manifolds [16], the motion characteristics of LWLs contain that of LLs and WLs,

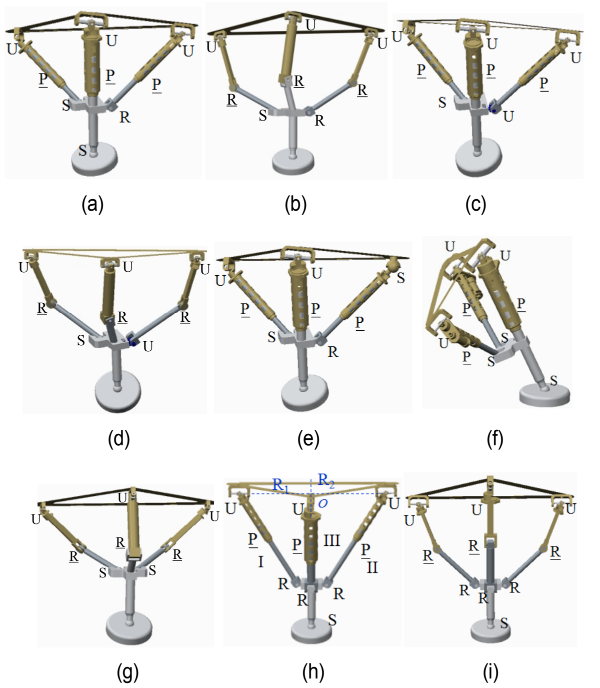


Fig. 5. Some typical configurations of walking legs with $(RR)_O T$: (a) case I: UP&UPR&UPS; (b) case I: UR&URR&URS; (c) case II: UP&UPU&UPS; (d) case II: UR&URU&URS; (e) case III: UP&SPR&UPS; (f) case IV: UP&2-UPS; (g) case IV: 2-URS&UR; (h) case V: 3-UPR; (i) case V: 3-URR.

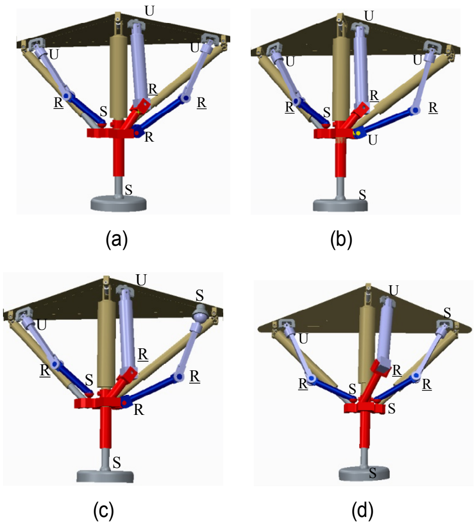


Fig. 6. Some typical legs for LMLs: (a) case I; (b) case II; (c) case III; (d) case IV.

$$\begin{cases} \{M_{LWL}\} = \{M_{LL}\} \cup \{M_{WL}\} \\ Dim\{M_{LWL}\} = Dim\{M_{LL}\} + Dim\{M_{WL}\} \\ \qquad - Dim\{\{M_{LL}\} \cap \{M_{WL}\}\} \end{cases} \tag{1}$$

where $Dim\{M_{LWL}\}$ means the motion dimension of an LWL.

To satisfy the condition of Eq. (1), one principle can be achieved:

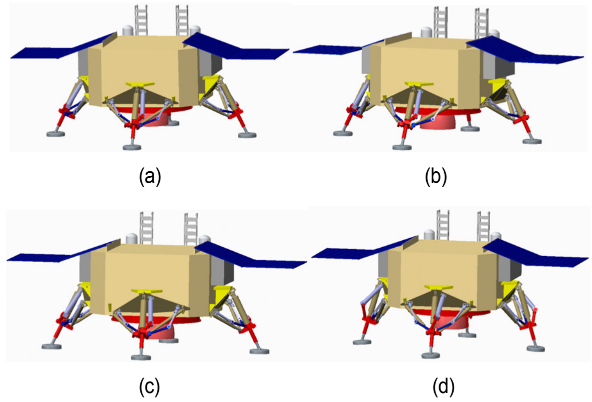


Fig. 7. Typical configurations of symmetrical LMLs: (a) case I; (b) case II; (c) case III; (d) case IV.

$$\{R(N,u)\} \in \{(RR)_O T\}, \tag{2}$$

which means that the R-characteristics of the walking leg are collinear to that of the landing leg to let the LL and WL have the ability to rotate around the same axis, which is collinear to that of the deployable function.

Based on the criterion (Eq. (2)), numerous legs of LMLs are carried out by combining LLs and WLs (detailed in Sec. 5). Some structures of legs by combining the structure of LLs and WLs corresponding to the six cases can be achieved and some of them are shown in Fig. 7.

As an example, Fig. 7(a) depicts the leg structure for LMLs by combining the structure of landing leg and the case I mechanism with the arrangement of motion characteristics $(RR)_O T \cap RTT\tilde{R} \cap TTT\tilde{R}\tilde{R}\tilde{R}$. Note that some other kinds of structures can be obtained by the same approach.

5.2 Selection of explosive separation devices

A separation device is a crucial component for a payload system [18] and there are different kinds of separation devices including explosive separation devices and non-explosive separation devices. One of them (an explosive separation nut) [19] can be chosen as the separation device.

5.3 Determination of LMLs

The structure of an LML is achieved by combining the body with four structures of legs. Two kinds of structures of LMLs are classified and obtained: the structures of four legs are the same for the first kind, and the structures of four legs are different for the second kind. Some configurations of LMLs with symmetrical structures of legs are shown in Fig. 7.

6. Actuated joint selection and type evaluation of LMLs and its analysis

6.1 Actuated joints selection for LMLs

Usually, the actuated joints cannot be selected arbitrarily. The criterion for selecting the actuated joint is detailed below: in

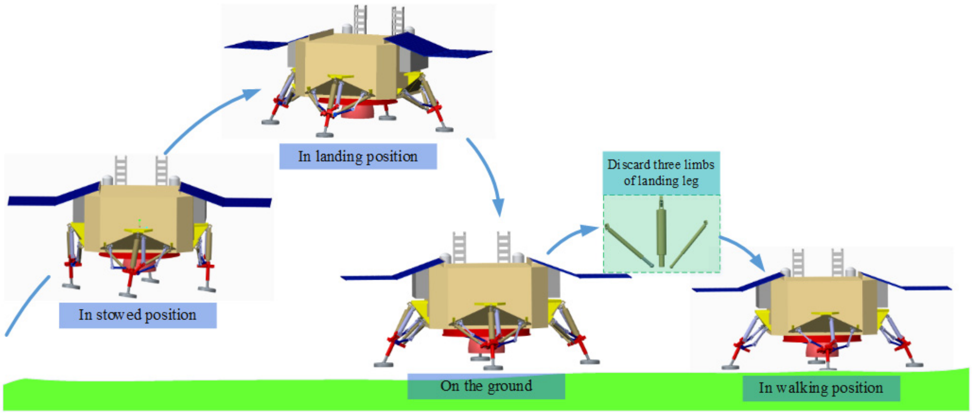


Fig. 8. The lander's positions in different phases.

a general configuration, the DOF of the mechanism with all of the actuated joints blocked is zero.

According to the principle stated above and considering the combination principle, the rule to select actuated joints for LMLs (shown in Figs. 5 and 6) is described as follows: 1) As for WLs, the R joints between the middle platform and body are suggested to act as actuated joints. 2) As for LLs, there are no actuated joints to protect their motors from damage of the impact on the surface during landing. 3) The S joint located in the lower part is designed as a passive one to realize terrain ability. 4) The symbols of actuated joints are represented with an underscore, such as R, shown in Fig. 6.

6.2 Type evaluation of LWLs for LMLs

Evaluation indexes include qualitative and quantitative evaluation indexes. Since this paper mainly focuses on a novel structural design of LMLs without considering the detailed parameters, it focuses only on the qualitative index.

The number of overconstraints is selected as its index, which may form a mechanism more complex than a mechanism without overconstraints and require high manufacturing precision and assembly precision. The number of overconstraints of the mechanism is obtained as follows:

$$\begin{aligned}\Delta &= \sum_{i=1}^{m} c^i - c \\ &= \sum_{i=1}^{m} [6\text{-}D(L_i)] - (6\text{-}D(M_i)) \\ &= 6(m-1) - \sum_{i=1}^{m} D(L_i) + D(M_i)\end{aligned} \tag{3}$$

where Δ is the number of overconstraints if $\Delta > 0$. c is the order of the wrench system of the parallel mechanism's platform, m is the total number of limbs, and c^i is the order of the wrench system of limb i. $D(L_i)$ and $D(M_i)$ are the dimensions of motions of limbs and the moving platform of the mechanism, respectively.

As for LLs, considering the successful experience of Chang'e 4, its leg structure is selected as the LLs.

As for WLs, among the six cases of the motion characteristics arrangement (shown in Fig. 5), their numbers of overconstraints are obtained $\Delta_{\{M1\}}$ = 5-3 = 2, $\Delta_{\{M2\}}$ = 4-3 = 1, $\Delta_{\{M3\}}$ = 4-3 = 1, $\Delta_{\{M4\}}$ = 3-3 = 0, $\Delta_{\{M5\}}$ = 6-3 = 3, $\Delta_{\{M6\}}$ = 5-3 = 2. Since the number of overconstraints equals zero, which is the least one among them, case IV is selected as the proper candidate for LML legs.

Thus, the LWLs with better performance are obtained by combining the structure of one LLs and the case IV WLs, as shown in Fig. 6(d). And the corresponding LML is achieved as shown in Fig. 7(d).

6.3 Analysis of functions of the legged mobile lander

The three positions (Fig. 8) are detailed as below. In the stowed position, four legs of LMLs are stowed. In the landing position (i.e., the deployed position), the landing legs become immovable structures and their main backbones absorb vertical impact force and the auxiliary backbones will absorb horizontal impact force. Furthermore, all the joints of the walking legs are passive in this stage. That is, the walking legs are protected from the impact force since they do not bear any support force and are passive. After landing on the surface, three backbones in upper part I of landing legs are discarded through the approach of pyrotechnic separation devices, and then the walking legs start to work to bear the support force. So, during the walking & exploring stage, only the walking legs are left to work for the exploring mission. Then, the lander can perform the walking function. In the orientation position, its configuration is the same as that in the walking position with four legs standing on the ground. In the walking position, the lander can be regarded as a parallel mechanism and the body is the moving platform whose limbs are its legs in contact with the ground. Since the motion characteristic of the legs is {D}, which has three T-characteristics and three R-characteristics, the body's motion is also {D}. The body can rotate around any axis and translate any direction, which means it has orientation adjustment.

7. Conclusion

To further expand the detection range and meet the needs of base construction in the future, this paper proposes a novel concept for designing LMLs based on decoupled landing and walking functions. LMLs not only perform a soft landing function but also walk to investigate the exploration mission.

In this paper, the DFSM method and its procedure for the novel design of the legged mobile lander are proposed. Then, the structures of LLs and WLs are designed. The combination principle for combining the LLs and WLs is presented. The LWLs for the LMLs are obtained by combining an LL and a WL under the combination principle. Numerous LMLs with the same or different legs are obtained and listed. The number of over-constraints is selected as the quantitative evaluation index and one typical LMLs is chosen as an example to be analyzed. Thus, the DFSM method can also be used for the type synthesis of other mechanisms with multiple functions or motion characteristics. The structures of LMLs provide some technical support and mechanisms for the deep space exploration.

In the future, more evaluation indexes, dimension optimization, the detailed structure, the stiffness, stability and mobility of LMLs will be analyzed and synthesized.

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References

[1] B. B. Donahue, G. Caplin, D. B. Smith, J. W. Behrens and C. Maulsby, Lunar lander concepts for human exploration, *Journal of Spacecraft and Rockets,* 45 (2008) 383-393.
[2] B. Hapke, Surveyor I and Luna IX pictures and the Lunar soil, *Icarus,* 6 (1967) 254-269.
[3] R. J. Williams and E. K. Gibson, The origin and stability of lunar goethite, hematite and magnetite, *Earth and Planetary Science Letters,* 17 (1972) 84-88.
[4] S. P. Weiss, *Apollo Experience Report: Lunar Module Structural Subsystem,* NASA-TN-D-7084, NASA, USA (1973).
[5] R. Parkinson, The use of system models in the EuroMoon spacecraft design, *Acta Astronautica,* 44 (1999) 437-443.
[6] T. Okada et al., Lander and rover exploration on the lunar surface: A study for SELENE-B mission, *Advances in Space Research,* 37 (2006) 88-92.
[7] L. J. Prinzel III et al., Synthetic and enhanced vision system for Altair Lunar lander, *Proc. of the 2009 International Symposium on Aviation Psychology* (2009) 660-665.
[8] W. Wu and D. Yu, Key technologies in the Chang'E-3 soft-landing project, *J. Deep Space Explor.,* 1 (2014) 105-109.
[9] L. Lu, Z. Zhixian, G. Linli, Y. Chen, Z. Yao, L. Min and Y. Peijian, Mobile lunar lander crewed lunar exploration missions, *Manned Spaceflight*, 21 (5) (2015) 472-478.
[10] R. Lin, W. Guo, M. Li, Y. Hu and Y. Han, Novel design of a legged mobile lander for extraterrestrial planet exploration, *International Journal of Advanced Robotic Systems*, 14 (6) (2017) 172988141774612.
[11] R. Lin et al., Type synthesis of legged mobile landers with one passive limb using the singularity property, *Robotica*, 36 (12) (2018) 1836-1856.
[12] R. Lin, W. Guo and M. Li, Novel design of legged mobile landers with decoupled landing and walking functions containing a rhombus joint, *Journal of Mechanisms and Robotics*, 10 (6) (2018) 061017.
[13] Y. Pan and F. Gao, Leg kinematic analysis and prototype experiments of walking-operating multifunctional hexapod robot, *Proceedings of the Institution of Mechanical Engineers, Part C: J. of Mechanical Engineering Science,* 228 (2014) 2217-223.
[14] Q. Li and J. M. Hervé, Type synthesis of 3-DOF RPR-equivalent parallel mechanisms, *IEEE Transactions on Robotics*, 30 (6) (2017) 1333-1343.
[15] R. Lin, W. Guo and F. Gao, Type synthesis of a family of novel 4-, 5- and 6-DOF sea lion ball mechanisms with three limbs, *J. of Mechanisms & Robotics*, 8 (2015).
[16] F. Gao, W. Li, X. Zhao, Z. Jin and H. Zhao, New kinematic structures for 2-, 3-, 4-, and 5-DOF parallel manipulator designs, *Mechanism & Machine Theory*, 37 (2002) 1395-1411.
[17] W. Bu et al., Mobility analysis for parallel manipulators based on intersection of screw manifolds, *Journal of Mechanical Science and Technology,* 30 (9) (2016) 4345-4352.
[18] M. H. Lucy, R. D. Buehrle and J. P. Woolley, *Comparison of Separation Shock for Explosive and Nonexplosive Release Actuators on a Small Spacecraft Panel*, No. NASA-TM-110257, National Aeronautics and Space Administration, Hampton, Virginia, Langley Research Center (1996).
[19] H. Zhao et al., Numerical study on separation shock characteristics of pyrotechnic separation nuts, *Acta Astronautica*, 151 (2018) 893-903.

Rongfu Lin is currently a Post Doctor at State Key Laboratory of Mechanical Systems and Vibration, Shanghai Jiao Tong University, China. His research interests include parallel mechanisms, biomimetic robots.

Weizhong Guo is currently a Professor at State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, China. His research interests include controllable mechanisms, parallel kinematic mechanisms.