A Cable-Driven and Rigid-Flexible Structures Coupled Landing Gear System for Spacecraft Soft Landing on Asteroids

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Abstract—Soft landing on weightless asteroids is challenging in space exploration missions. This paper proposes a cable-driven landing gear system (LGS) with rigid-flexible coupled structures (RFCSs) for the soft landing of a spacecraft on asteroids. The cable-driven mechanism improves the compliance of the spacecraft's landing legs and has the merits of being lightweight and compact. The RFCS minimizes the impact force of the landing legs when crashing the asteroid's surface. We designed a three-legged LGS and formulated its kinematics and dynamics. We conducted simulations and experiments of a simplified spacecraft prototype. The results showed that the spacecraft can safely land on rough slopes, with the legs contacting the ground at different sequences. The collision speeds of 10-50 cm/s are verified. This study provides a new idea for the landing and operation of these cable-driven RFCS probes in a weightless environment. The results are valuable for the design of asteroid landers and their stabilizing control.

I. INTRODUCTION

Asteroid exploration has significant scientific, economic, and social value [1] for studying the origin of life in the solar system [2], mining rare metals and other resources [3], and protecting human civilization [4]. However, there are only three successful asteroid sample return missions, i.e., the Hayabusa 1 [5], Hayabusa 2 [6], and OSIRIS-Rex [7]. Several missions are during preparation, such as the Calathus mission [8] and the ZhengHe mission [9].

Asteroid exploration is challenging due to the tiny surface gravity, unknown surface material mechanical properties, and large self-rotation speed of asteroids [10]. These factors make the landing extremely dangerous. No successful soft landing has been achieved so far. Soft landing on outer planets is an open challenge in deep space explorations. The landing gear system (LGS) is the key mechanism of the spacecraft.

Researchers designed many LGSs in Mars and Moon exploration missions. For example, NASA's first Mars landing spacecraft in the Viking 1/2 mission was equipped with three scalable landing legs, consisting of a main pillar and two auxiliary pillars, filled with honeycomb aluminum material and plastic bending rods, respectively, for buffering [11]. Similarly, the Phoenix Mars probe had landing legs, with an aluminum honeycomb as the main buffer and a bent rod as



Fig. 1. Conceptual design of the spacecraft during landing.

the auxiliary buffer [12]. Curiosity used an aerial crane landing method [13]. In addition, Mars Pathfinder, Spirit, and Opportunity all applied airbags for buffering during landing [14]. The LGS of the ExoMars probe has two layers of compressible cushioning material at the bottom, which deforms and absorbs impact energy during landing [15]. Moreover, the four legs of the Tianwen-1 Mars probe had an inverted tripod configuration with two multi-functional main buffers. The buffers made of TWIP steel rods absorbed impact loads in the relative sliding movement during landing [16].

The LGS designed for lunar probes also achieved great success. For instance, the Surveyor-X lunar probes had three foldable landing legs. For impact load buffering, hydraulic dampers were installed inside the main pillar, and honeycomb aluminum blocks were added to the landing legs [17]. The Apollo-11 lunar probe had four landing legs, with cylindrical aluminum honeycomb material inside the main and auxiliary legs for landing cushioning [18]. The Luna-16 probe also had four landing legs. The legs' metal pull rods and hydraulic buffering devices absorbed the energy during the landing [19]. The ChangE-3 to -5 probes used four foldable landing legs, with honeycomb aluminum material embedded in the pillars of each leg for soft landing [21]. In addition, Wang et al. designed a lunar probe with four landing legs, adopting magnetorheological fluid dampers to absorb impact energy [22]. Moreover, the bottom of the Venus probes was equipped with a rigid metal hole ring, which was crushed during the ground contact to withstand most of the impact energy [20].

Soft landing on small bodies is more difficult than landing on Mars and the Moon due to three factors. The LGS should absorb the enormous impact energy and adapt to ground materials. For instance, in the comet exploration mission [23], the lander had three landing legs, each consisting of a shock absorber tripod containing honeycomb aluminum material to

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absorb impact energy during landing. Zhao et al. developed an LGS that converts the relative motion between the body and legs into motor rotation, generating damping torque for the damping motor to dissipate the impact energy during probe landing [24]. Yan et al. proposed a flexible asteroid lander that dissipated energy through collision and deformation [25]. The legged buffering mechanisms are mainly used for Mars and Moon exploration probes. However, landing on Mars and the Moon does not require consideration of microgravity environments, and the buffer design for asteroids has unique characteristics.

With skeletal muscles, animals like blue sheep can run and jump dynamically on uneven mountain areas and safely land on the ground, even from a ten-meter-high location. The hoofs and legs of the blue sheep are rigid-flexible coupled structures (RFCSs) that can absorb the impact energy during landing. Crab legs are also RFCSs that enable them to walk safely on the terrain with sharp stones. Cable-driven mechanisms [26], [27], [28], [29], [30] and RFCSs [31], [32], [33] mimicking the skeletal muscle of animals have been widely used in robot design. This paper proposes an animal body structure-inspired LGS design idea for soft landing. The LGS is a cable-driven and flexible-rigid structure coupling mechanism. The spacecraft can safely land in highly challenging situations using the LGS.

The contributions of this work are as follows. (1) We propose a cable-driven landing gear mechanism design method for spacecraft landing safely in a microgravity environment. The mechanism has the merits of being lightweight and compact. (2) Inspired by the animals' legs in nature, we investigate the RFCS modeling, simulation, and experiments for LGS design of spacecraft landing in harsh surface conditions.

II. LANDING GEAR SYSTEM DESIGN

Fig. 1 illustrates the spacecraft during the landing process in an asteroid sample return mission. The LGS consists of three rigid-flexible coupled landing legs. The legs are symmetrically installed on the three sides of the body of the descent stage. Fig. 2(a) shows the mechanism of the landing leg, comprising a rigid multi-link mechanism, a passive flexible mechanism, and an active flexible mechanism. The rigid multi-link mechanism comprises a top fixture, a bottom fixture, six linkages, a sliding sleeve, and a linear bearing. The fixtures are attached to the side of the body. Linkage 1 connects the bottom fixture with a rotational joint. Linkages 1, 2, and 3 connect one by one in series with rotational joints. Similarly, linkage 4 connects the top fixture, and linkages 4, 5, and 6 connect one another. The front end of linkage 6 connects linkage 3 with a rotational joint. The sliding sleeve is installed on linkage 1 with a rotational joint. The linear bearing is fixed in the sliding sleeve. There is a slide joint between linkage 4 and the sliding sleeve.

The passive flexible mechanism includes torsion springs, a chamber, a tube, a universal joint ankle, a force sensor, and a landing foot. The torsion springs are set at the joints between linkage 1, 2, 3, 4, and 5. The chamber is fixed at the end of linkage 3. The chamber and tube comprise a buffer with an



Fig. 2. (a) CAD model of the cable-driven and rigid-flexible structures combined landing leg in unfolding state. (b) Landing leg in folding state.

aluminum honeycomb inside the chamber. The flexible universal joint ankle connects the landing feet to the end of the tube, adapting the landing legs to uneven ground. A biomimetic thorn structure is designed at the bottom of the foot pad to prevent its slipping on the ground. The force sensor between the tube and the ankle detects the collision force on the foot pad.

The active flexible mechanism contains a cable and a driving motor. The front end of the cable is fixed on linkage 6. The rear end of the cable is attached to a winch driven by the motor. When the motor drives the winch to rotate and wrap the cable, the landing legs retract. The folding state of the leg is shown in Fig. 2(b). Hence, the landing leg only has one active degree of freedom (DoF) and belongs to an under-actuated mechanism. Through passive flexibility adaptation and active variable stiffness control, our LGS buffers the ground collision force, absorbs impact energy, and improves the success rate of landing. This article focuses on designing, modeling, and testing the LGS.

III. MODELING AND SIMULATION

A. Modeling

1) Kinematics and Dynamics of the Landing Leg

The model of one landing leg is shown in Fig. 3. L_i , m_i , I_i , and r_i represent the six linkages, their masses, inertia, and lengths, respectively. J_1 to J_7 are the rotational joints between the linkages. θ_i are the rotational angles of the joints. l_i is the distance from the center of mass (COM) to the rotational joints. Here $i = 1, 2, 3, \dots, 6. a, b$, and c represent the distance from the connection point of L₁ and L₄ (y_3 , z_3) to J₁, the distance from the front end of the cable (y_4, z_4) to J_6 , and the distance between J_3 and J_7 , respectively. The height and radius of the foot pad are d and R, respectively. The angle of the cable from the horizontal axis is β . (y_{b1}, z_{b1}) , (y_{b2}, z_{b2}) and (y_{b3}, z_{b3}) are the coordinates of the J₁, J₄, and rear end of the cable, respectively. The foot pad and universal joint coordinates are (y_0, z_0) and (y_1, z_0) z_1), respectively. Then, the coordinates of the COMs of the linkages (v_{ci}, z_{ci}) and (v_0, z_0) can be calculated using relationships between the linkage lengths and angles. Li forms a closed chain. The motions of L_4 , L_5 , and L_6 have relationships with L₁, L₂, and L₃. Therefore, θ_4 , θ_5 , and θ_6 can be represented using θ_1 , θ_2 , and θ_3 . Assuming the coordinates of J₅ are (y_{J5}, z_{J5}) , then θ_4 , θ_5 , and θ_6 are:



Fig. 3. Model of one landing leg.

$$\begin{cases} \theta_4 = \arctan[(z_{b2} - z_3) / (y_3 - y_{b2})] \\ \theta_5 = \pi - \arccos[(r_4^2 + A^2 - B^2) / 2r_4 A] \\ -\arccos[(r_5^2 + A^2 - r_6^2) / 2r_5 A] \\ \theta_6 = \pi - \arccos[(r_5^2 + r_6^2 - A^2) / 2r_5 r_6] \end{cases}$$
(1)

where $A = [(y_2 - y_{J5})^2 + (z_2 - z_{J5})^2]^{0.5}$ and $B = [(y_2 - y_{b2})^2 + (z_2 - z_{b2})^2]^{0.5}$. (y₂, z₂), (y₃, z₃), and (y_{J5}, z_{J5}) are:

$$\begin{cases} y_2 = y_{b1} + r_1 c_1 + r_2 c_{1-2} + c c_{2+3-1} \\ z_2 = z_{b1} + r_1 s_1 + r_2 s_{1-2} - c s_{2+3-1} \\ y_3 = y_{b1} + a c_1 & z_3 = z_{b1} + a s_1 \\ y_{J5} = y_{b2} + r_4 c_4 & z_{J5} = z_{b2} - r_4 s_4 \end{cases}$$
(2)

where $s_{i\pm j} = \sin(\theta_i \pm \theta_j)$, $c_{i\pm j} = \cos(\theta_i \pm \theta_j)$. The positions of the linkages and joints of the leg can be entirely determined by the variables θ_1 , θ_2 , and θ_3 .

The leg motion dynamics was modeled to determine the effect of the cable's tension. For simplicity, the model does not consider the friction and damping of the joints and torsion springs. The dynamics is expressed by a Lagrange equation:

$$\frac{d}{dt}\left(\frac{\partial L_l}{\partial \dot{q}_{i1}}\right) - \left(\frac{\partial L_l}{\partial q_{i1}}\right) = Q_{i1} - J_r^T F_T \qquad L_l = T_l - V_l \qquad (3)$$

where L_l is the Lagrange function, $q_{i1}=[\theta_1, \theta_2, \theta_3]$ is the generalized coordinates, and $Q_{i1}=[M_1, M_2, M_3]=[0, 0, 0]$ is the generalized force. J_r is the velocity Jacobian matrix of the point (y_4, z_4) . F_T is the tension provided by the cable. T_l is kinetic energy, including the linkages' translational and rotational kinetic energy E_{kl} and E_{tl} . V_l is the potential energy, including the linkages' translational energy, including the linkages' gravitational potential energy E_{gl} and the elastic potential energy E_{el} of the torsion springs. The free position of the three torsion springs is $2\pi/3$. The compression angles of the springs are $\pi - \theta_2$, $\pi - \theta_3$, and $\pi - \theta_5$, respectively. Then, E_{el} is:

$$E_{el} = \frac{1}{2}K_1(\theta_2 - \frac{\pi}{3})^2 + \frac{1}{2}K_2(\theta_3 - \frac{\pi}{3})^2 + \frac{1}{2}K_3(\theta_5 - \frac{\pi}{3})^2 \quad (4)$$

where K_1 , K_2 , and K_3 are the stiffness coefficient of the springs. According to (1)-(4), the dynamics of the leg is



Fig. 4. Model of the spacecraft.

governed by three second-order nonlinear differential equations:

$$\boldsymbol{M}(\boldsymbol{\Theta})_{3\times 3} \, \boldsymbol{\ddot{\Theta}}_{3\times 1} + \boldsymbol{C}(\boldsymbol{\Theta}, \boldsymbol{\dot{\Theta}})_{3\times 1} = -J_r^T F_T \tag{5}$$

where $M_{3\times 3}$ is the mass matrix, $C_{3\times 1}$ is the centrifugal force, Coriolis force, and the gravity force vector.

2) Kinematics and Dynamics of the Spacecraft

The simplified model of the spacecraft is shown in Fig. 4. m_0 and v_b are the mass and speed of the body, respectively. Assuming leg 1 is on the plane yoz, y_b -o- z_b is the body coordinate system, and the center of the body is (y_f, z_f) , then (y_{b1}, z_{b1}) and (y_{b2}, z_{b2}) are:

$$\begin{cases} y_{b1} = y_f + \Delta y_1 & z_{b1} = z_f - \Delta z_1 \\ y_{b2} = y_f + \Delta y_2 & z_{b2} = z_f + \Delta z_2 \end{cases}$$
(6)

Then, we can obtain the coordinates of the centroids of each linkage of leg 1. Rotating leg 1 counterclockwise and clockwise by 120° around axis z_b obtains leg 2 and leg 3.

The probe's body has 6 DoFs in total. Being an underactuated structure, each landing leg has redundant DoFs. Hence, the dynamics of the spacecraft is exceedingly complex. To streamline the analysis, we only consider the scenario when all legs land simultaneously. The pose changes of the three legs are assumed identical, and the spacecraft undergoes no horizontal movement or flipping. Based on the single-leg model, the dynamic model incorporates only one generalized coordinate z_f , representing the spacecraft's height. The dynamic model of the spacecraft is:

$$\begin{cases} \frac{d}{dt} \left(\frac{\partial L_2}{\partial \dot{q}_{i2}} \right) - \left(\frac{\partial L_2}{\partial q_{i2}} \right) = Q_{i2} - J_1^T F_{N1} - J_2^T F_{N2} - J_3^T F_{N3} \\ L_s = T_s - V_s \end{cases}$$
(7)

where L_s is the Lagrange function of the spacecraft. $q_{is}=[\theta_1, \theta_2, \theta_3, z_f]$. J_1 , J_2 , and J_3 are the velocity Jacobian matrices corresponding to the contact points between the foot pads and the ground. F_{N1} , F_{N2} , and F_{N3} represent the contact forces (CFs) experienced by the foot pads. T_s is the kinetic energy:

$$T_{s} = E_{ks} + E_{ts} = (m_{0}v_{b}^{2} / 2 + 3E_{kl}) + 3E_{tl}$$
(8)

where E_{ks} is the translational kinetic energy of the body and the three landing legs. E_{ts} is the rotational kinetic energy of the connecting rods on the legs. V_s is the potential energy:



Fig. 5. Simulation results of three-legged simultaneous landing (3-mode). (a) Foot-ground contact force. (b) Joint angles of one leg. (c) Body centroid height. (d) Distribution of the maximum foot contact force. (e) Distribution of the maximum change of centroid height.

$$V_s = E_{gs} + E_{es} = (m_0 g z_f + 3 E_{gl}) + 3 E_{el}$$
(9)

where E_{gs} is the gravitational potential energy of the body and the three landing legs, and E_{es} is the elastic potential energy of the springs. Q_{i2} is the generalized force. The resistance forces of the leg joints J_1 , J_2 , and J_3 are considered because they impact the spacecraft landing process. Assuming that the damping coefficients of the three joints are the same and denoted as ρ , the resistance torque M_{ri} at the three joints is:

$$M_{ri} = -\rho \dot{\theta}_i \quad (i = 1, 2, 3) \tag{10}$$

Substituting (8)-(10) into (7), we obtain four second-order nonlinear differential equations:

$$\boldsymbol{M}(\boldsymbol{\Theta}, \boldsymbol{z}_{f})_{4\times 4} (\boldsymbol{\Theta}, \boldsymbol{\ddot{z}}_{f})_{4\times 1} + \boldsymbol{C}(\boldsymbol{\Theta}, \boldsymbol{\Theta}, \boldsymbol{z}_{f}, \boldsymbol{\dot{z}}_{f})_{4\times 1}$$

= -[\(\rho\bar{\theta}_{1} \) \(\rho\bar{\theta}_{2} \) \(\rho\bar{\theta}_{3} \) \(0]^{T} - J_{1}^{T} F_{N1} - J_{2}^{T} F_{N2} - J_{3}^{T} F_{N3} \) (11)

where $M_{4\times4}$ is the mass matrix, and $C_{4\times1}$ contains the centrifugal force, Coriolis force, and gravity vector. Solving (11) will yield the motion of the spacecraft and the changes in the joint angles. Finally, the foot-ground interaction is modeled as a spring-mass-damper system, and the CF F_{Ni} acting on the foot is:

$$F_{Ni} = k_i \Delta z_{ni} + c_i v_i \quad (i = 1, 2, 3)$$
(12)

where k_i and c_i represent the elastic and damping coefficients of the foot-ground interaction, respectively, Δz_{pi} is the distance from each foot pad to the ground, and v_i is the landing velocity of each leg. i = 1, 2, 3.

B. Simulation

The simulation parameters were: $m_0 = 12 \text{ kg}$, $m_1 = 0.2 \text{ kg}$, $m_2 = 0.12 \text{ kg}$, $m_3 = 0.6 \text{ kg}$, $m_4 = 0.07 \text{ kg}$, $m_5 = 0.03 \text{ kg}$, $m_6 = 0.045 \text{ kg}$, $r_1 = 0.22 \text{ m}$, $r_2 = 0.09 \text{ m}$, $r_3 = 0.5 \text{ m}$, $r_4 = 0.19 \text{ m}$, $r_5 = 0.05 \text{ m}$, $r_6 = 0.19 \text{ m}$, $l_1 = 0.11 \text{ m}$, $l_2 = 0.045 \text{ m}$, $l_3 = 0.25 \text{ m}$, $l_4 = 0.095 \text{ m}$, $l_5 = 0.025 \text{ m}$, $l_6 = 0.095 \text{ m}$, $l_1 = 0.0032 \text{ kg} \text{ m}^2$, $l_2 = 3.24 \times 10^{-4} \text{ kg} \text{ m}^2$, $l_5 = 0.05 \text{ kg} \text{ m}^2$, $l_4 = 8.42 \times 10^{-4} \text{ kg} \text{ m}^2$, $l_5 = 2.50 \times 10^{-5} \text{ kg} \text{ m}^2$, $l_6 = 5.42 \times 10^{-4} \text{ kg} \text{ m}^2$, a = 0.06 m, b = 0.105 m, c = 0.05 m, d = 0.04 m, R = 0.05 m, $K_1 = K_2 = 3.8296 \text{ N·m/rad}$, $K_3 = 0.3240 \text{ N·m/rad}$, $F_T = 10 \text{ N}$, $\rho = 0.02 \text{ N·m·s/rad}$, $g = 0.0057 \text{ m/s}^2$ (asteroid Phobos), $(y_{b2}, z_{b2}) = (0 \text{ m}, 0 \text{ m})$, $(y_{b1}, z_{b1}) = (0.02375 \text{ m}, -0.102 \text{ m})$, $(y_{b3}, z_{b3}) = (-0.067 \text{ m}, 0.045 \text{ m})$, $v_{b0} = 0.1 \text{ m/s}$, and h = 0.1 m (landing height), $\theta_{10} = 65.07^{\circ}$, $\theta_{20} = 60^{\circ}$, and $\theta_{30} = 60^{\circ}$. The initial angular velocities were zero.

The landing attitudes were classified into four modes according to the foot-ground contact sequence. In the 3-mode, all legs contacted the ground simultaneously. In the 1-2 mode, the ground surface under leg 1 was elevated by 10 cm



Fig. 6. Influence of foot-ground contact parameters in simulation. (a) The maximum contact force. (b) The change of centroid height.

compared to legs 2 and 3. In the 2-1 mode, the ground beneath legs 1 and 2 was elevated by 10 cm. In the 1-1-1 mode, the ground under leg 1 was raised by 10 cm, and the ground under leg 3 was lowered by 10 cm. The last three modes are notified as asymmetrical landing attitudes.

1) Three Legs Contact Ground Simultaneously

First, we conducted the 3-mode landing using MATLAB 'ode45' function. Additional parameters were: $y_f = 0$ m, $\Delta y_1 = 0.197$ m, $\Delta z_1 = 0.116$ m, $\Delta y_2 = 0.173$ m, $\Delta z_2 = -0.014$ m, $k_i = 50$ N/m, $c_i = 80$ N·s /m, and $z_{f0} = 0.4578$ m. The posture changes and CFs were the same among the three legs.

Fig. 5(a)(b)(c) depict the variations in foot CFs, joint angles, and body height (z_f) , respectively. The spacecraft reaches the lowest point of 0.32 m upon the initial ground impact at 1 s, experiencing significant fluctuations in CFs and joint angles. Then, the spacecraft rebounds, resulting in zero CFs and damped oscillations in joint angles. The second ground contact occurs at 17.6 s, leading to minor fluctuations. The body centroid height stabilizes at 0.36 m by 24 s. The CFs converge to zero due to the weightless condition.

The simulations were repeated to investigate the effect of joint stiffness on the landing process. Specifically, K_1 and K_2 increased from 2 to 5 N·m/rad at the step of 0.2 N·m/rad, while K_3 increased from 0.2 to 0.5 N·m/rad at the step of 0.02 N·m/rad. Fig. 5(d) illustrates the maximum CF, revealing a consistent pattern of increased force with decreasing joint spring stiffness. However, the overall change is only 0.013 N, suggesting that alterations in joint stiffness have a negligible impact on the maximum CF. Fig. 5(e) displays the body height change from the first ground contact. The body height change increases when K_1 decreases. However, the influence of K_2 and K_3 is more intricate and reliant on K_1 . Notably, the body height change peaks at 22.34 cm when $(K_1, K_2, K_3) = (2.0, 5.0, 0.2)$ N·m/rad.



Fig. 7. Simulation results when the probe lands with different foot contact sequences. (a) 1-2 mode. (b) 2-1 mode. (c) 1-1-1 mode.

We also explored the influence of foot-ground contact's elastic and damping coefficients. Simulations were performed with k_i ranging from 10 to 600 N/m at the step of 10 N/m and c_i ranging from 10 to 130 N·s/m at the step of 2 N·s/m. As shown in Fig. 6(a), the maximum CF increases with the ground damping coefficient. The effect of ground elasticity on the maximum CF is negligible. Fig. 6(b) shows the body height change, which derives the minimum of 4.83 cm at $k_i = 10$ N/m, $c_i = 20$ N·s/m, and the maximum of 69.12 cm at $k_i = 390$ N/m, $c_i = 10$ N·s/m. The surface plot looks like a wrinkled cloth, indicating a subtle influence of ground properties on body height. It can be concluded that the body height change tends to decrease when $c_i < k_i$ or $c_i \approx k_i / 8$.

2) Asymmetrical Feet Contact Sequences

The 1-2 mode, 2-1 mode, and 1-1-1 mode were simulated in ADAMS software. The parameters were $k_i = 400$ N/m, $c_i = 80$ N·s/m. The friction coefficient was 2.0. The simulation results of the asymmetrical modes are shown in Fig. 7.

The foot-ground CFs are shown in the first row of Fig. 7. In the 1-2 mode, leg 1 softly contacts the ground at 1 s, followed by the other two legs at 1.7 s. The pulses of the CFs reach around 7.5 N. Soon after, the spacecraft rebounds. The second touchdown occurs at 10.5 s by leg 1 and 13.6 s by legs 2 and 3. In the 2-1 mode, legs 1 and 2 touch down at 1.2 s with a force of 1.52 N, while the third leg hits the ground at 1.65 s with 6.48 N. The rebound phase ensues, with leg 3 hitting the ground again at 10.6 s. Leg 3 experiences greater CFs and a prolonged airborne period after rebound due to the lower ground surface beneath it. In the 1-1-1 mode, legs 1, 2, and 3 contact the ground one by one. The CFs are 2.3 N, 8.8 N, and 21.1 N. Then, the spacecraft rebounds, with legs 2 and 3 making contact again at 8.25 s, followed by leg 1 at 14.2 s.

We employ the stability margin (SM) concept in legged robots to assess the spacecraft's stability. SM is defined as the



Fig. 8. The spacecraft prototype and experiment platform.

shortest distance from the centroid to the supporting polygon of the legs on the horizontal projection plane. The second row of Fig. 7 shows the variation of SM and body tilt angle. In the 1-2 mode, the SM is initially 0.35 m when the tilt angle is zero. It bottoms at 0.28 m upon the first impact. The SM remains at 0.29 m when the spacecraft reaches stability. In the 2-1 mode, the SM hits a minimum of 0.31 m during the initial impact and stabilizes at 0.32 m. In the 1-1-1 mode, the SM hits a local minimum of 0.27 m at 2.32 s during the initial touchdown. During the airborne phase, the margin continuously diminishes to 0.2 m and gradually rises to 0.27 m. The 1-1-1 mode has minimal stability at the tile angle of 13.8°. This means asymmetrical terrain surface mostly affects the stability of the spacecraft.

The third row of Fig. 7 presents the trajectories of the body centroid and the feet in a top view. In the 1-2 mode, the spacecraft slides towards the higher side of the ground because the horizontal resilience forces from legs 2 and 3 propel the spacecraft toward leg 1. In the 2-1 mode, the spacecraft shifts toward leg 3 (the lower ground surface) due to the horizontal forces exerted by legs 1 and 2. In the 1-1-1 mode, the trajectories have notable bends during the initial ground contact, implicating that the probe experiences self-rotations on the ground. The spacecraft deviates to the side of legs 2 and 3 because leg 1 receives a large ground reaction force.

In summary, the spacecraft successfully achieves stable landings across diverse postures. The minimum SM is greater than 0.2 m despite the uneven ground. The thorn structure of the foot pads suppresses sliding on the terrain. The landing legs with RFCSs adapt to varying terrain conditions, effectively mitigating the impact during spacecraft touchdowns.

IV. PROTOTYPE AND EXPERIMENTS

A. Prototype and Landing Test Platform

The spacecraft prototype and test platform are shown in Fig. 8. The pulley is affixed atop the frame, guiding the rope through. The counterweight hangs the spacecraft through the

 TABLE I

 Landing Performance at Different Landing Speeds

Landin g speed	Maximum contact force (N)			Max. body	Stabilizing time	
(cm/s)	Leg1	Leg2	Leg3	(m/s ²)	Leg	Body
10	11.3	10.8	11.8	1.49	1.8	1.4
30	13.8	13	13.8	1.83	2.3	1.5
50	18.3	17.6	19	1.94	2.6	1.6

 TABLE II

 Landing Performance at Different Feet Contact Sequences

Landing mode	3	1-2	2-1	1-1-1
Max. contact force(N)	13.8	15.4	15.6	18.2
Max. body acceleration(m/s ²)	1.83	2.26	1.55	1.15
Max. body tilt angle(°)	0	6.5	5.7	6.6

rope. The slider is outfitted with a motor and an electromagnet, while the control box manipulates the motor and electromagnet. Varied landing speeds were realized by modifying the mass of the counterweight. Before each test, the slider lifts the spacecraft at a constant height. Upon disengaging the electromagnet, the spacecraft descends freely onto the sample surface.

B. Landing Experiments in Multiple Conditions

1) Different Landing Speeds

The spacecraft always lands in the 3-mode in this experiment. The experiment was conducted at landing speeds of 10, 30, and 50 cm/s. The performance indices for various landing speeds are summarized in Table I. The results reveal that the spacecraft can safely land at multiple speeds. The maximum CFs increase with the rise in landing speed, as do the peak body acceleration and leg stabilizing time. In addition, the body's stabilizing time is significantly shorter than the legs', and the impact of landing speed on the body's stabilization time is relatively minor. This shows the excellent cushioning ability of the rigid-flexible coupled landing legs, protecting components inside the body.

2) Different Feet Contact Sequences

In this test, the spacecraft lands on the sandy terrain at 30 cm/s. The experiments include all four landing modes. The 3-mode has already been carried out in trials with varying landing speeds. In the asymmetrical landing modes, the sand surface was piled according to the methods in Section III. B.

Fig. 9 depicts the variations of the CFs and body roll/pitch angles in the asymmetrical landing experiments. In the 1-2 mode (see Fig. 9(a)), leg 1 makes the initial soft contact at 2.8 s. Then, the major impact occurs at 3.2 s, with the CFs of all legs peaking around 14 N. The CF of leg 1 keeps vibrating until 6.5 s, while the body's roll angle stabilizes at 4.4 s. This indicates the legs reduce the body's vibrating time. In the 2-1 mode (see Fig. 9(b)), the landing begins with legs 1 and 2 contacting the ground at 2.8 s. Once leg 3 lands, the first two legs endure a rebound. The system enters the steady state from 4.5 s. In the 1-1-1 mode (see Fig. 9(c)), the plots of CFs are similar to that of the 2-1 mode, except that leg 1 endures



Fig. 9. Experiment result of different foot-ground contact sequences. (a) 1-2 mode. (b) 2-1 mode. (c) 1-1-1 mode.

more force than leg 2. The tilt angles stabilize at 4.3 s, while the forces stabilize at 5 s.

Table II lists the performance indexes when landing in different modes. It is shown that the peak CF is the minimum in the 3-mode landing and the maximum in the 1-1-1 mode landing. Therefore, flat terrain benefits the even distribution of foot-ground impact forces. Furthermore, the 1-1-1 mode has minimal body acceleration, where sequential leg impacts grant the spacecraft optimal flexibility against the ground. The 2-1 mode has the minimal body tilt angle and angular velocity because the stability margin is the maximum in this case. Conclusively, the spacecraft demonstrates reliable landing capabilities on unstructured terrains. The legs help to reduce the body's vibration time in all conditions.

3) Discussion on the Sim-to-Real Gap

The spacecraft's landing performances in simulation and experiment are compared. The first rows of Fig. 7 and Fig. 9 show the difference in CFs. In the simulation, the first landing legs endure the least force during the impact, while they endure the most force in the experiment. Digging into the reason, the counterweights reduce the tilt angle of the body, thus imposing more weight on the first landing legs. Furthermore, the simulated CFs converge to zero, but the experimented CFs stabilize at positive values. Although the counterweight offsets a part of the spacecraft's weight, the remaining weight is still much larger than that in the microgravity environment, which explains the non-zero CFs.

The body tilt angle is compared in the second rows of Fig. 7 and Fig. 9. In the 1-2 mode and 2-1 mode, the roll angle's amplitude is consistent in sim-to-real conversion. In the 1-1-1 mode, the simulated roll angle of 13.4° is prominently larger than the experiment value of 6.6°. The explanation is that unstructured terrain induces the rebound phase in the weightless environment, reducing the probe's stability. Finally, due to the gravity difference, the response time is much longer in the simulation than in the experiment. Therefore, the spacecraft's landing performance has a noticeable sim-to-real gap. The microgravity condition on the

asteroid's surface poses a challenge when conducting experiments on Earth.

V. CONCLUSION

This paper introduces an LGS featuring cable-driven mechanisms with RFCSs designed to address challenges in soft landings on asteroid surfaces. The landing legs adopt an underactuated structure with a single active DoF. Kinematic simulations validate the folding and extending motions of the single leg through the rotation of the rope winch. Dynamic models are presented for the single-leg and the simplified three-legged spacecraft. The landing attitudes of four different modes are simulated and experimented with the spacecraft prototype and the test platform. The results affirm the effectiveness of the landing legs in buffering impacts and safeguarding the spacecraft body. Future improvements will try to reduce the sim-to-real gap. The spacecraft's rebound will be eliminated by optimizing the stiffness/damping of the leg joints and equipping the spacecraft with thrusters. The results will pave the way for successful asteroid exploration missions.

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