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Evaluation of Landing Stability of Two-step Landing Method for Small Lunar-planetary Lander

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This paper discusses landing stability of a novel landing method called “Two-step Landing Method” which is applicable to small lunar-planetary lander. Especially influence of lateral residual velocity on the landing is discussed, because the situation is often caused by a guidance error and may give a serious risk of lander overturning. The method enforces intentional body tumbling at the contact of primary legs. Landing stability of the method was evaluated by three- dimensional simulations. Numerical simulation models have been constructed on Mechanical Dynamics Software ADAMS, and refer to “SLIM” which is small lander proposed by ISAS/JAXA. I performed landing simulations of monopod and biped type as the proposed method and four-leg type as a conventional method. Simulations results showed the proposed method has higher landing stability than the conventional method.

Key Words: Space Exploration, Landing Dynamics, Lunar-planetary Exploration Lander, SLIM

1. Introduction

Small experimental spacecraft named as “SLIM” (Smart Lander for Investigating Moon) is proposed by ISAS/JAXA.[1)] SLIM will demonstrate “pinpoint landing” which means landing on the Moon with 100m order accuracy using novel technologies such as a guidance navigation control[2)] and an image-based autonomous navigation method[3)]. In addition, ISAS/JAXA make SLIM compact and lightweight because these are necessary for high frequently future explorations.[4)]

The configuration of SLIM have been studied four-leg type which is a conventional type. [5),6)] However, the conventional type may give a risk of the lander’s overturning if SLIM lands on a rough site of the moon. Because SLIM is planned to be launched by Epsilon rocket, the lander is needed to be designed considering the rocket’s envelope area for satellites. Thereby, the landing legs cannot spread widely without expanding gears of the landing legs. Consequently, center of mass of the lander is high. It affects landing stability of the lander. This constrain is considered to be a trouble for future small lunar and planetary landers.

There are various studies to enhance lander’s landing stability of a lander. Maeda *et al*. have studied that adjusting appropriate damper’s characteristics of active landing legs toward landing site enable lander’s stability higher.[7)] Watanabe *et al*. have studied that exchanging momentum from landing impact for another mass’s momentum makes lander’s overturning risk lower. [8)]

However, another novel landing method is needed for small and lightweight lunar and planetary landers. This is because that if we apply above overturning protection gears to the landers, we cannot avoid increasing the lander’s size and weight. This is wrong for small lunar and planetary landers which have constrains concerning lander’s size and weight.

In this paper, the author proposes a novel landing method called “Two-step landing method” for stable landing of small landers, and examines the method’s characteristics by numerical simulations. “Two-step landing method” can be applicable to small and lightweight landers such as SLIM, and can give better landing stability. We have studied the proposed method’s characteristics in the case of free fall landing. [9)] The results of the previous research are described in section 2. So, in this paper landing dynamics with lateral residual velocity is discussed. Such landing situation is often caused by a guidance error and may give a serious risk of lander overturning. In the numerical simulations, parameters including lander’s initial velocity, the number of primary legs and slope angle of landing site are considered, and landing success or failure is examined for each case. From the results, landing stability of the method is evaluated. Furthermore, comparing the method with four-leg type as a conventional landing method, the effectiveness of the proposed method for small lunar and planetary landers is investigated.

2. Two-step Landing Method

Two-step landing method enforces intentional body tumbling. The proposed landing method’s sequence is shown in Fig. 1.

1) The lander falls with body attitude tilted, and primary legs contact with a planetary surface.
2-a) The lander tumbles, and the landing leg located on lander’s deck and called lower assisting leg contacts on the surface.
2-b) Two landing legs located on upper part of the lander and called upper assisting legs contact on surface.

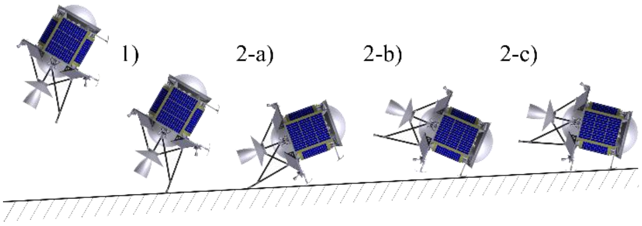


Fig.1. Landing sequence of Two-step Landing Method.

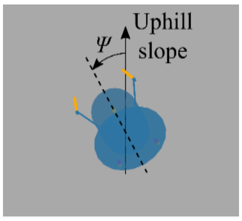


Fig.2. Upper view of Two-step Landing Method

2-c) Eventually, the lower and the upper assisting legs bear the lander's weight.

There are skids on tip of the upper assisting legs.

We have studied the proposed method's characteristics in the case of free fall landing. The simulation results show that the proposed landing method can have landed on steep slope. Especially the method landed easily on uphill site. However, if a projection line of lander's axis toward landing sites and inclination direction of landing sites were different as shown in Fig. 2, the lander overturned easily. Thus, the method was needed to tilt body attitude toward inclination direction of landing sites. The tendency of overturning easily was clearer in lander with two primary legs called biped type. The reason was that the contact with landing site of one of two primary generated torque in the direction of body's rolling.

Two-step landing method is also effective for exploration after landing. For Small and light landers, exploration regions will be restricted because the landers cannot carry a large rover. The lander of Two-step landing method can travel on a planetary surface using skids and rest propellant.$^{10)}$

3. Numerical simulation model

In this study, three-dimensional simulations were performed using Mechanical Dynamics Software ADAMS (product by MSC Software Corporation). ADAMS was used on landing analysis of skycrane of Curiosity in NASA$^{11)}$.

3.1. Lander models

Lander models constructed on ADAMS are shown in Figs.3. and 4. The lander model with a primary leg is called monopod type and that with two primary legs is called biped type. The model parameters are shown in Table.1. The models are based on SLIM and consist of one or two primary legs, two upper assisting legs, a lower assisting leg, skids, a tank and a deck. The skids and primary legs which will experience large impacts are constructed as elastic parts and made in CFRP. I designed elastic parts using BEAM that is one of functions of ADAMS.

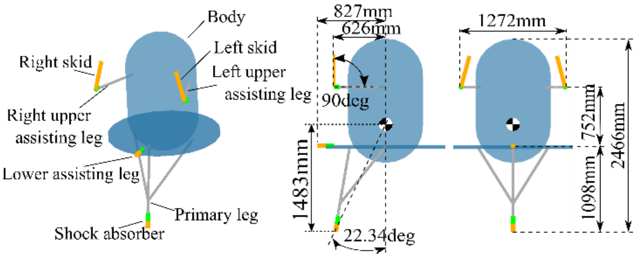


Fig.3. Lander model of monopod type

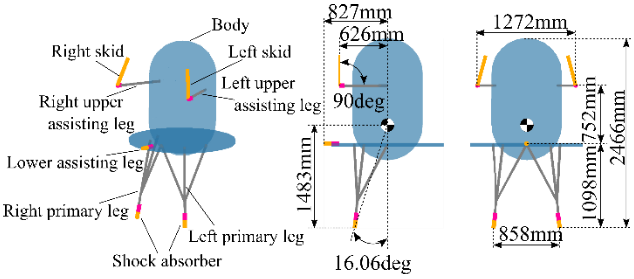


Fig.4. Lander model of biped type

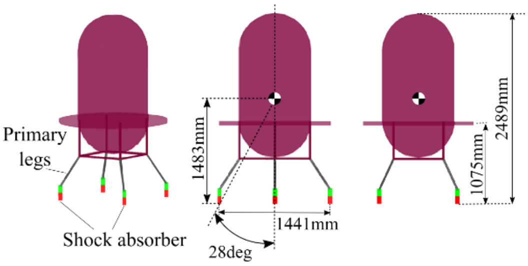


Fig.5. Lander model of four-leg type

SLIM has porous aluminums on tip of primary legs as shock absorbers. $^{12)}$ The models have shock absorber models that have the property of crushing itself if landing impact load is larger than a certain value called compression force f_c. $^{5)}$ The compression force is 15000[N], of which the value is calculated from impact energy if one primary leg contact with a planetary site and the constrain of compression stroke. $^{12)}$

In addition, four-leg type model is also constructed as a conventional method in order to discuss the effectiveness of Two-step landing method as a landing method for small lunar and planetary landers. The four-leg type model is also based on SLIM. The model on ADAMS is shown in Fig.5. The model parameters are shown in Table.2. The location of the four-leg model's center of gravity is same as that of Two-step landing method.

3.2. Contact model between lander and regolith

The vertical force F_1 with respect to landing site is defined as spring-damper system by the following equation. $^{5)}$

$$F_1 = K\delta + C\frac{d\delta}{dt} \tag{1}$$

Here, K denotes spring coefficient, C denotes damping coefficient and δ denotes penetration depth. The horizontal force F_2 with respect to landing site is defined as coulomb friction system by the following equation.

$$F_2 = \mu F_1 \tag{2}$$

Table 1. Lander model parameters of Two-step Landing Method

Symbol	Parameter	Value	Unit
M_1, M_2	Mass of body	170	kg
J_1, J_2	Moment of inertia of body [x, y, z]	[59.0,39.6,47.0]	kgm^2
w_s	Width of skids	50	mm
t_s	Thickness of skids	20	mm
l_s	Length of skids	400	mm
E_m, E_s	Young's modulus of main leg or skids	1.09×10^5	N/mm^2
ν_m, ν_s	Poisson's ratio of main leg or skids	0.3	-
ζ_m, ζ_s	Damping ratio of main leg or skids	0.05	-
N_m, N_s	Number of segments of main leg or skids	8	-
f_{c1}, f_{c2}	Compression force of shock absorber	15000	N

Table 2. Lander model parameters of Two-step Landing Method

Symbol	Parameter	Value	Unit
M_3	Mass of body	150	kg
J_3	Moment of inertia of body [x, y, z]	[54.5,37.6,44.5]	kgm^2
f_{c3}	Compression force of shock absorber	15000	N

Table 3. Contact parameters between landers and regolith

Symbol	Parameter	Value	Unit
K	Stiffness coefficient of soil	10	N/mm
C	Damping coefficient of soil	20	Ns/mm
μ_s, μ_d	Static and Dynamic friction coefficient	0.8	-

The values of the contact parameters are shown in Table.3. The values are decided on the basis of an experimental analysis in SELENE-B project.$^{6)}$ The experiments have been performed vertical drop test and food-pad drag test in order to examine contact dynamics. The worst value of friction coefficient μ is used in SELENE-B because the larger friction coefficient was, the more inferior landing stability was. $^{13)}$

3.3. Definition of lander's attitude and Terrain slope angle

Lander's attitude is expressed in Euler's angles. The definition of coordinate system is shown in Fig.6.Initial lander attitude turns on lander's center of gravity in the order of initial roll angle φ, yaw angle ψ and pitch angle θ.

3.4. Judging of landing success or failure

Judging of landing success or failure is determined from lander's angular velocity and reaction force at end time of a numerical simulation (after 30[s] from start time of lander's falling). Simulation results are defined as landing success, which is called "Stable" if there are three of six or seven contact points including one or two primary legs, two upper assisting legs, a lower assisting les and tips of skids, and lander's angular velocity is lower than 0.1[deg/s]. The reason is that as discussed in section 2, three parts of a lander including left and right skids and a lower assisting leg bear lander's weight.

Moreover, if tank or deck of the landers contact with landing site, simulation results are defined as landing failure, called, which is called "Unstable". In addition, slipping of landers after 30[s] was not considered. The flowchart of judging of landing success or failure is shown in Fig.7.

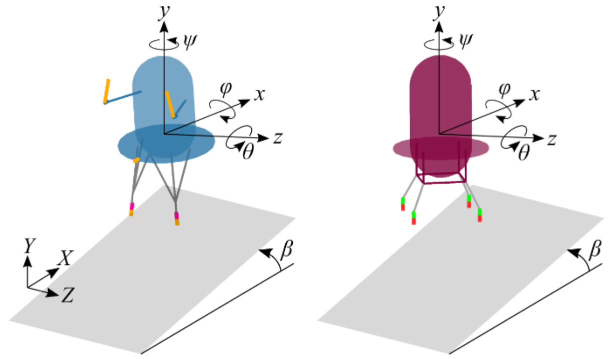


Fig.6. Coordinate system

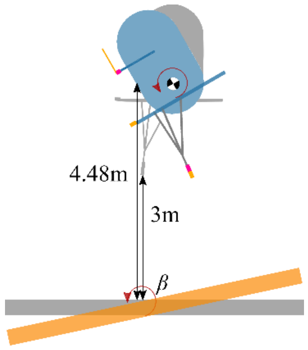


Fig.8. Drop height

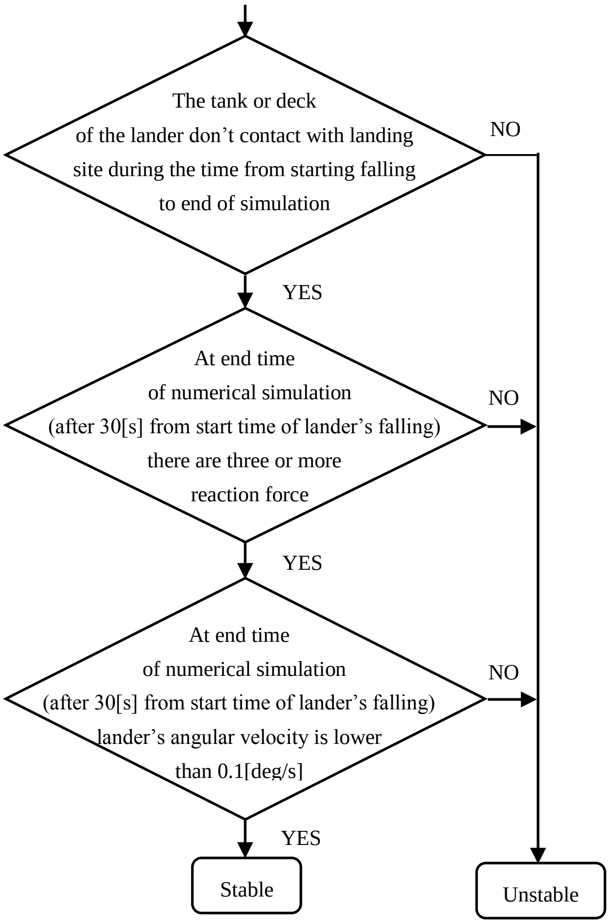


Fig.7. Flowchart of judging of landing success or failure

Table 4. Simulation parameters of Two-step Landing Method

Symbol	Parameter	Value	Unit
φ	Initial roll angle	0	deg
ψ	Initial yaw angle	0	deg
θ	Initial pitch angle	30	deg
β	Terrain slope angle	0, -10, -20	deg
v_x	Lateral velocity toward *x*-axis	-1.0 ~ 1.0	m/s
v_y	Lateral velocity toward *y*-axis	-0.6 ~ 0.6	m/s

Table 5. Simulation parameters of four-leg type

Symbol	Parameter	Value	Unit
φ	Initial roll angle	0	deg
ψ	Initial yaw angle	0	deg
θ	Initial pitch angle	25	deg
β	Terrain slope angle	0, 10, 20	deg
v_x	Lateral velocity toward *x*-axis	-1.0 ~ 1.0	m/s
v_y	Lateral velocity toward *y*-axis	-0.6 ~ 0.6	m/s

In the case of four-legs type, if the tank or deck of the lander contacts with landing site during the time from start of falling to end of simulation, the simulation result are defined as landing failure, which is called "Unstable".

4. Condition and results of numerical simulations of landing with lateral velocity

4.1. Conditions of simulations

In this study, landing simulations with lateral velocity are performed. Landers may have the situation that landing with lateral residual velocity due to errors of guidance and sensors. So, landing stability with lateral velocity (toward lander's *x* and *z*-axis) has to be examined considering four simulation parameters including lander's initial velocity, the number of primary legs and slope angle of a landing site.

Landing stability was evaluated from the simulation results in various values of above parameters. In this study, the results are called Landing success/failure map. The parameter values are shown in Table.4. The value of slope angle is 0, -10 and -20[deg]. The reason is that the simulation results in the case of free fall landing showed that Two-step landing method land easily on landing site if the slope angle of the site is negative value. The value of four-leg type shown in Table.5 are determined by the lander's configuration and a previous research.$^{14)}$

Drop height, which is defined as the distance between primary legs and landing site, is 3[m] if lander's attitude is not change (initial roll φ, yaw ψ and pitch θ angle is 0[deg]). Thus, if lander's attitude is change, the distance between center of mass of landers and landing site is always 4.48[m] as shown Fig.8. Gravity in the simulations is one sixth of earth's gravity.

4.2. Results of simulations

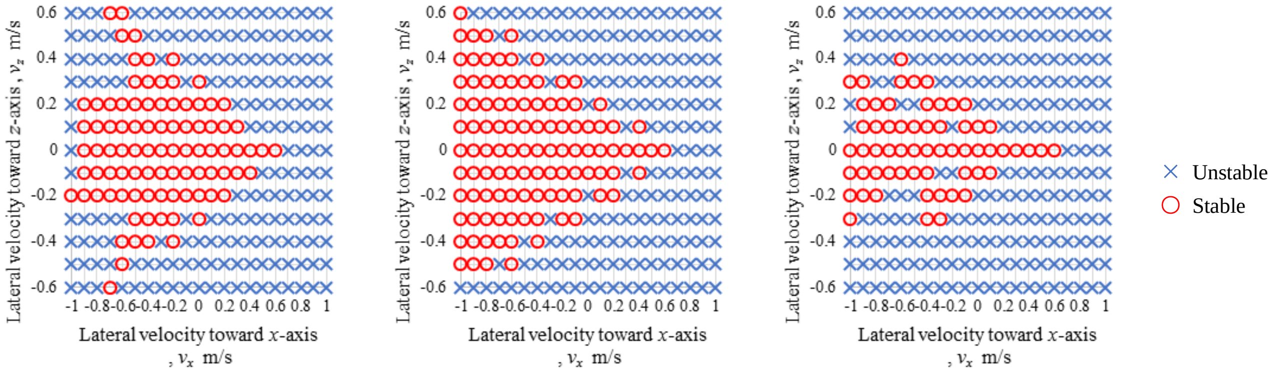
Landing success/failure maps are shown in Figs.9, 10 and 11. The maps show simulation results of monopod type in Fig.9, biped type in Fig.10, and four-leg type in Fig.11. The map's vertical axis is lateral velocity toward lander's *z*-axis and horizontal axis is lateral velocity toward lander's *x*-axis. The simulation results show the following things.

- Two-step landing method including monopod and biped type land easily on steep slope if the landers have negative values of lateral velocity toward lander's *x*-axis.
- Landing stability of Two-step landing method varied from the number of primary legs. Monopod type overturns easily if the lander has a large value of lateral velocity toward *z*-axis. On the other hand, biped type almost lands successfully with the lateral velocity with which monopod type cannot land.
- Two-step landing method has higher landing stability than four-leg type.

Firstly, Two-step landing method landed easily on steep slope. Especially the landers with negative lateral velocity toward *x*-axis (in other words, landing with lateral velocity toward uphill direction) hardly overturned.

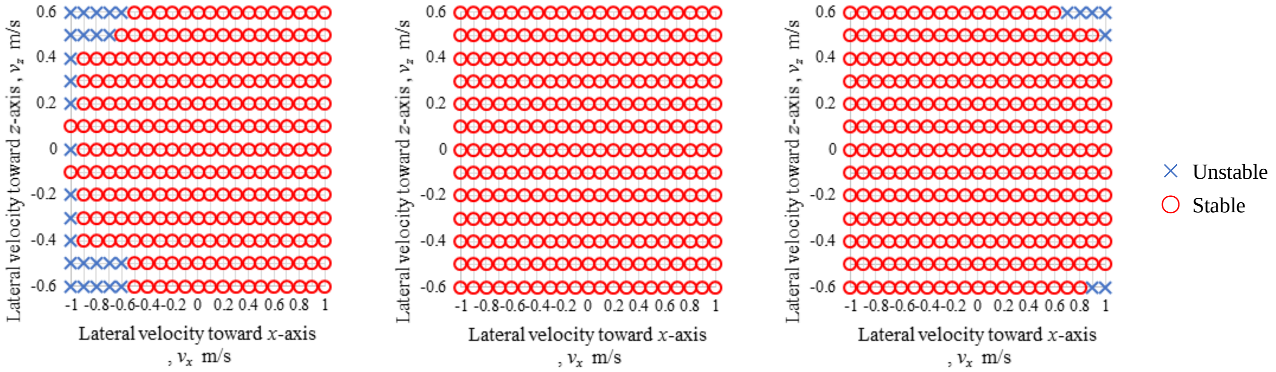
Secondly, landing stability of Two-step landing method varied from the number of primary legs. Biped type was more difficult to overturn with lateral velocity toward *z*-axis. Dynamics simulation examples are shown in Figs.12 and 13. If the lander lands with the large velocity, three parts of the lander including left or right skids and primary legs and a lower assisting legs bear lander's weight. But, the lander will not roll and can land successfully. On the other hand, as discussed in section 2, in the case of free fall landing monopod type was more difficult to overturn than biped type. The summary of these results is as follows.

- monopod type: A margin of lander's attitude toward inclination direction of landing sites is allowed. The lander is needed to make lateral residual velocity smaller.
- biped type: The lander is needed to tilt body attitude toward inclination direction of landing sites. A margin of lateral residual velocity is allowed to land on steep slope.



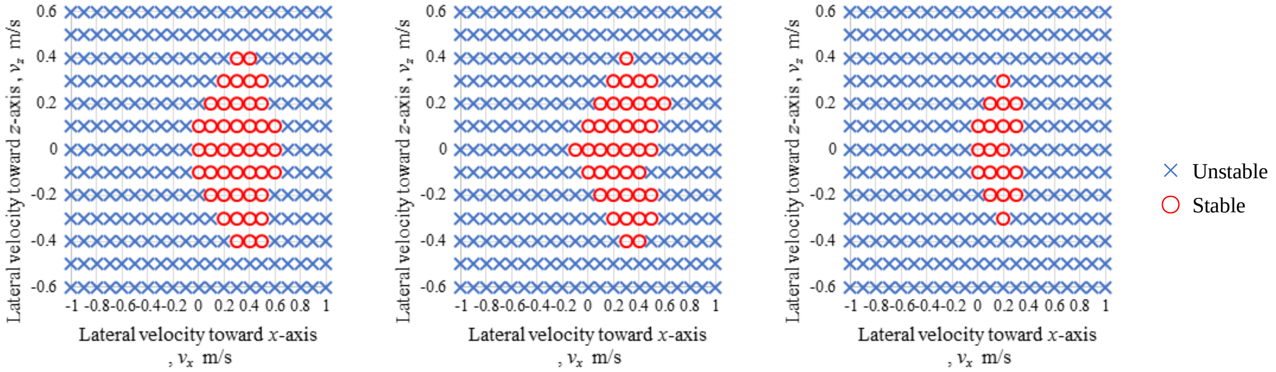
(a) β=0[deg] (b) β=-10[deg] (c) β=-20[deg]

Fig.9. Landing success/failure map of monopod type (θ=30[deg])



(a) β=0[deg] (b) β=-10[deg] (c) β=-20[deg]

Fig.10. Landing success/ failure map of biped type (θ=30[deg])



(a) β=0[deg] (b) β=10[deg] (c) β=20[deg]

Fig.11. Landing success/ failure map of four-leg type (θ=25[deg])

Finally, Two-step landing method had higher landing stability than four-leg type. Four-leg type overturned if the lander has negative lateral velocity toward *x*-axis. When initial pitch angle is large, a reaction force vector passes close to center of mass of the lander. As a result, the landers have landed easily on steep slope in free fall landing. However, in landing with lateral velocity if initial pitch angle is too large, the lander overturned because of inertial force due to lateral velocity. On the other hand, Two-step landing method particularly in biped type hardly overturned when the lander had lateral velocity toward *x*-axis is negative. In addition, Two-step landing method did not roll and land successfully with lateral velocity toward *z*-axis with which four-legs types could not land.

5. Conclusion

In this paper, a novel landing method called “Two-step landing method” was proposed, and the characteristics of the method were examined by numerical simulations. Especially the situations of landing with lateral residual velocity were discussed. Three-dimensional simulations using Mechanical Dynamics Software ADAMS (product by MSC Software Corporation) were performed. The landers are constructed in the basis of SLIM on ADAMS. Four parameters including lander’s initial velocity, the number of primary legs and slope angle of landing site were considered in the simulations. The lading stability of the proposed method was discussed through examining landing success or failure in various parameters. Furthermore, comparing the method with four-leg type as a conventional landing method, the effectiveness of the proposed method was evaluated for small lunar and planetary landers. The landing simulations showed the following findings concerning landing with lateral residual velocity.

- Two-step landing method lands easily on uphill and steep slope if the lander has lateral velocity toward the landing site. The landing site is that four-leg type cannot land on.
- Landing stability of Two-step landing method varied from the number of primary legs. Biped type has higher landing stability than monopod type.
- Two-step landing method has higher landing stability than a conventional method.

These results and our previous research show Two-step landing method is more effective than a conventional method in not only free fall landing but also landing with lateral velocity for small lunar-planetary landers such as SLIM.

Further evaluating landing stability of the proposed method by experiments is needed. The experiments using modules concerning lunar environment contribute to discuss the effectiveness of the method for small lunar-planetary lander.

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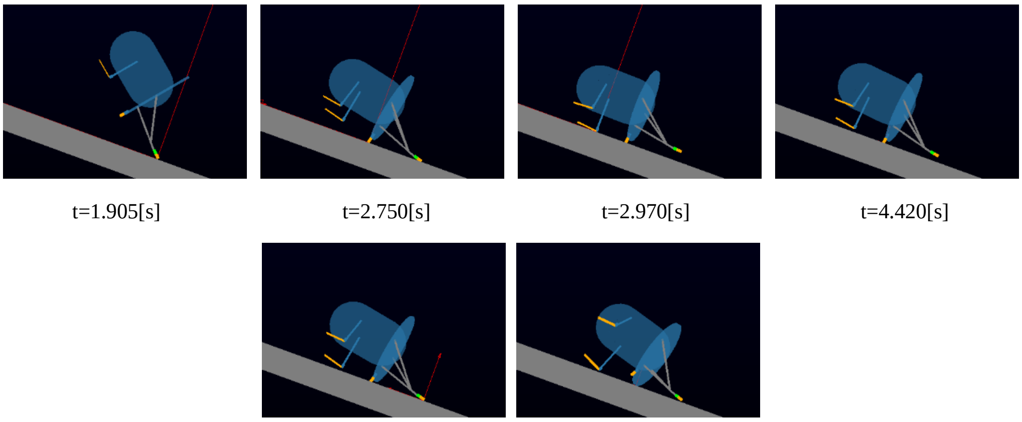
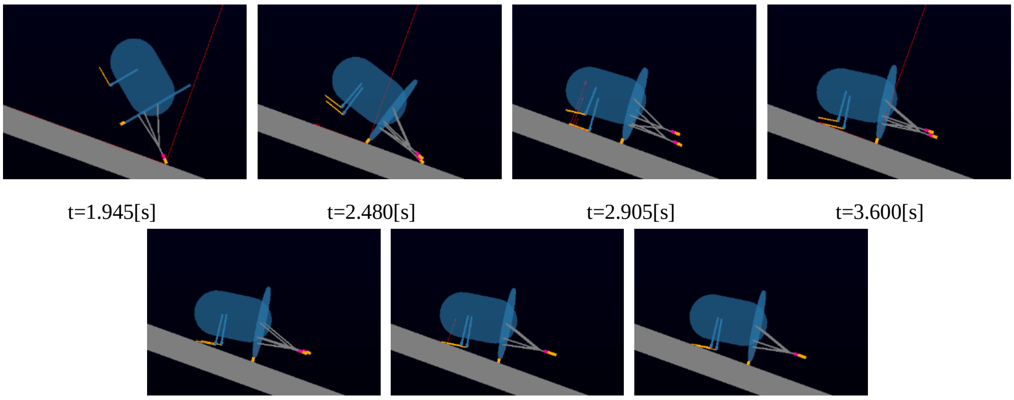


t=1.905[s] t=2.750[s] t=2.970[s] t=4.420[s]

t=4.770[s] t=5.800[s]

Fig.12. Landing dynamics of monopod type on ADAMS（θ=30[deg], β=-20[deg], v_x=-0.3[m/s], v_z=-0.4[m/s]）



t=1.945[s] t=2.480[s] t=2.905[s] t=3.600[s]

t=4.365[s] t=5.930[s] t=10.00[a]

Fig.13. Landing dynamics of biped type on ADAMS（θ=30[deg], β=-20[deg], v_x=-0.3[m/s], v_z=-0.4[m/s]）

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