Analysis of Open-Loop Tail Control On Quadruped Locomotion in Contact Critical Terrains

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***Abstract*—The robotics field has seen a recent surge in usage of quadruped for various tasks ranging from planning, navigation, and even dexterous manipulations. In fact, recent research has shown quadruped capable of traversing through uneven terrains. But despite the fact that quadrupeds are becoming more standard and robust within the field, traversal over extreme terrain is still a challenge. This is due to inaccurate mapping of the environment, leading to clipping, slippage, and incorrect foothold planning. Furthermore, proprioceptive sensing capabilities require enough prodding of the environment to have good estimation of the terrain. For more contact critical environment, where a slight misstep is potentially fatal to the quadruped, the legged robot needs to be capable of performing dynamic movements. Since the control system of a quadruped is underactuated, it is more difficult to perform such tasks. Tails are seen as a natural extension of increasing the number of actuations. In this work, we analyze on how a time-based switched open-loop tail control system can help a quadruped re-stabilize in contact critical terrain conditions. We showcase these results in a physics simulator called Gazebo.**

***Index Terms*—quadruped, contact critical terrain, extreme terrain, multi-link tail, simulation, gazebo**

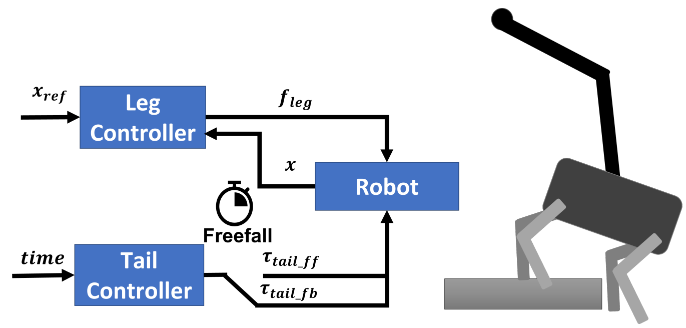


Fig. 1: Control architecture of quadruped traversing contact critical terrains. Quadruped follows a reference state trajectory with a switch controller where an open-loop controller executing when quadruped walks over terrains such as cliffs, holes, etc.

I. Introduction

The field of legged robotics have seen great success in research and industrial applications in the past few years [1]. This can be attributed to the advances in the hardware, to enable higher computational performances, and the control design, with researchers finding ways to handle the hybrid dynamics with optimization based schemes. This in general can be seen as both Spot from Boston Dynamics and ANYmal X from ANYbotics are industry certified. Furthermore, quadrupeds are becoming more and more accessible, evident of research relating to quadrupeds [2]–[6]. As a whole, quadruped being accessible to everyone showcases how advance the 4-legged locomotion problem has come.

More recently, there have been a number of works that present the locomotion problem on off-road terrain environments, such as [5], [6]. The first work uses reinforcement learning to directly transform depth image data (in the form of scandots) to corresponding joint angles. This shows promising result in the capability to walk through stairs, gaps, and platforms as well as the robustness of using neural networks to directly map from image data to commanded joint angles in the quadrupedal frameworks. The latter work focuses on a more structured problem formulation. It uses a student-teacher policy where the teacher has privileged information and the student uses a belief encoder-decoder to decompose the proper sensory information. This is then mapped to an action space where the corresponding action is then compared with the teacher's. The work shows outstanding results, and they display the quadruped capabilities by taking it through a trail.

However, despite the current research work showing great robustness in off-road structured terrain, a large contribution to these results are due to the capability of obtaining accurate mapping of the environment. For more extreme environments, these are not so trivial to obtain. The computer science community has seen its fair bit of struggle with segmenting the environment under extreme weather and off-road conditions [7], [8].

With less accurate mapping, more unexpected events such as slipping and clipping will occur. Proprioceptive sensings are considered where base off knowledge of the positions of the contacts, an estimation of the terrain parameters can be deduced. Work in this area has been done where given the ability to prod the environment, a quadruped was able to blindly estimate the slope of a staircase and walk up the staircase [9].

However, these conditions are considered only when there exists enough proprioceptive information to get a good estimation of the environment. When one misinformation of proprioceptive sensing is critical, such as a quadruped mistepping and falling off a cliff, the underactuated control of a quadruped limits the ability of a quadruped to stabilize.

To address the issue of quadrupeds in contact critical environments, a natural extensions to unexpected events is to introduce a tail controller into the legged locomotion problem. Tails, inspired from animal designs, are known to be capable of uprighting the body and aid in rejection of impulsive disturbances [10]–[12]. The former analyzes the effects of a squirrel tail to upright itself in mid-air while the latter two showcase tails control for disturbance rejection. However, these work do not showcase the affects of tail control for quadupeds in more contact critical environments.

In this work, we analyze the affects of how time based switch control, feedback tail control as the initial system and open-loop control as the second, can help stabilize the legged locomotion problem over contact-critical terrain. This is simulated in a quadruped software development kit known as Quad-SDK [13]. More explicitly, we analyze, in an environment where foot planning is crucial, how different schemes of control may be beneficial or disruptive to the stabilization problem to the overall legged system summarized in schematic diagram in Figure 1.

II. Preliminaries

The following are preliminary details on representing the dynamic model of a quadruped with a tail, and how the effects of the tail actuation propagates the dynamics of the quadruped forward.

From the Euler Lagrange formulation, the generalized coordinates for the quadruped are notated as $\mathbf{q_r} := [p_r, \theta_r, q]^T \in \mathbb{R}^n$ where p_r, θ_r, and q are the inertial position, euler angles, and joint positions respectively, $n = 18$ is the number of states, and subscript "r" stands for robot. Additionally, subscript "c" and "t" stands for contact and tail respectively. Then, the following dynamics of the quadruped is as follows:

$$\mathbf{M}_r(\mathbf{q}_r)\ddot{\mathbf{q}}_r + \mathbf{C}_r(\mathbf{q}_r, \dot{\mathbf{q}})_r + \mathbf{J}_c^T(\mathbf{q}_r)\lambda_c + \mathbf{J}_{br}^T(\mathbf{q}_r)\lambda_t = \tau \quad (1)$$

where $\mathbf{M(q_r)} \in \mathbb{R}^{nxn}$ is the mass-inertial matrix, $\mathbf{C_r(q_r, \dot{q}_r)} \in \mathbb{R}^n$ is the gyroscopic terms and potential terms, $\tau \in \mathbb{R}^{12}$ is the torque of joints, and $\mathbf{J}$ are the jacobian of the lagrange multiplier, where "br" stands for base of robot inertial frame.

Composing the tail formulation, the corresponding dynamics is as follows

$$\mathbf{M}_t(\mathbf{q}_t)\ddot{\mathbf{q}}_t + \mathbf{C}_t(\mathbf{q}_t, \dot{\mathbf{q}}_t) + \mathbf{J}_{bt}^T(\mathbf{q}_r)\lambda_t = \tau_t \quad (2)$$

where $\mathbf{q_t} \in \mathbb{R}^{n_t}$ is the generalized coordinates of the tail. Note, $\mathbf{M_t(q_t)}, \mathbf{C_t(q_t, \dot{q}_t)}$, and $\mathbf{J}_{bt}^T(\mathbf{q_r})$ are the corresponding tail mass-inertial, gyroscopic, and jacobian of the lagrange multiplier matrices.

Furthermore, the holonomic constraints of the position and orientation of the base and the the tail, expressed as $\mathbf{p}_{br}(\mathbf{q}_r) = \mathbf{p}_{bt}(\mathbf{q}_t)$, can be differentiated twice to form the following expression

$$\mathbf{J}_{br}(\mathbf{q}_r) + \dot{\mathbf{J}}_r(\mathbf{q}_r, \dot{\mathbf{q}}_r) = \mathbf{J}_{bt}(\mathbf{q}_t) + \dot{\mathbf{J}}_{bt}(\mathbf{q}_t, \dot{\mathbf{q}}_t) \quad (3)$$

Combining (1)-(3), the following decoupled system yields the following

$$\begin{bmatrix} \mathbf{M}_r & \mathbf{0} & \mathbf{J}_{br}^T \\ \mathbf{0} & \mathbf{M}_t & \mathbf{J}_{bt}^T \\ \mathbf{J}_{br} & -\mathbf{J}_{bt} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}_r \\ \ddot{\mathbf{q}}_t \\ \lambda_t \end{bmatrix} = \begin{bmatrix} \tau - \mathbf{C}_r + \mathbf{J}_c^T\lambda_c \\ \tau_t - \mathbf{C}_t \\ \dot{\mathbf{J}}_{bt} - \dot{\mathbf{J}}_{br} \end{bmatrix} \quad (4)$$

Note, (4) has an equality relationship between difference of the base-robot and the base-tail jacobians with their respective states and the time derivatives of the difference of the jacobians. These coupling terms are the key components in this paper to analyze how well a tail controller will help stabilize quadruped locomotion under extreme terrain conditions.

III. Simulation Setup

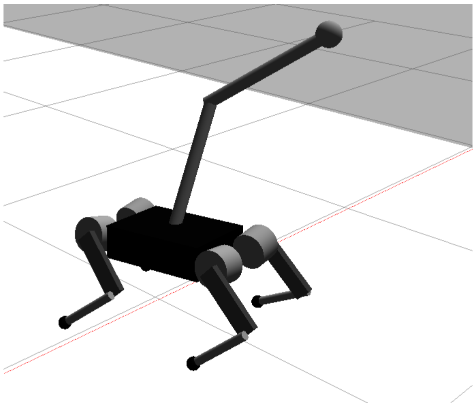
An experimental setup was created to do analysis on the effects of open-loop tail control on quadruped locomotion. The next few subsections covers details regarding the model of the quadruped and the environmental setup.

A. Model

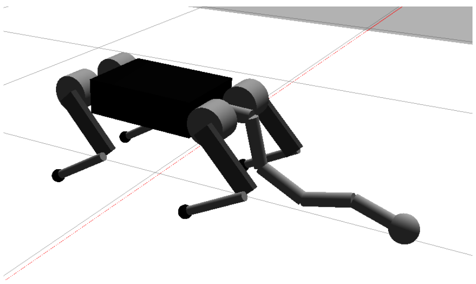
TABLE I: Quadruped BOM

Link	# Components	Parent	Joint Type
Base	1	-	-
Hip	4	Base	Revolute
Upper Leg	4	Hip	Revolute
Lower Leg	4	Upper Leg	Revolute
Toe	4	Lower Leg	Fixed
Tail Link	1-6, 10	Base	Revolute
Tail Mass	1	Tail Link	Fixed

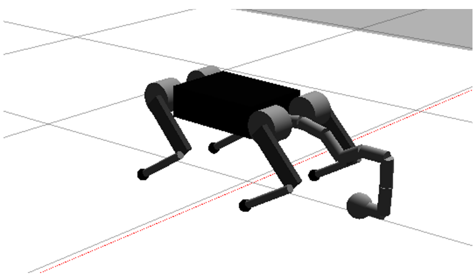
Modeling the quadruped in the simulation environment Gazebo requires a Unified Robot Description File (URDF). A "bill of material" is shown in Table I as the necessary components to generate the kinematic chains to the simplified model of a quadruped. The kinematic chains of the robot can be described as a tree-like structure starting from the base as the root link. Then, for each corresponding leg component, the chain is linked from base to hip, hip to upper leg, upper leg to lower leg, and lower leg to toe. Correspondingly, additions of tails were linked to the center of the base of the body for symmetry. A state estimator and controller plugin was modified for the tail such that the joint angles of the tail and torque control could be executed in the simulation environment. Note, the model incorporates dynamic properties and can be seen in the URDF in the github repository [1]. Figure 2 shows different tails with quadrupeds that can be simulated on this platform.



(a) 2 Link Tail Model



(b) 6 Link Tail Model



(c) 10 Link Tail Model

Fig. 2: Robot model with multi-link tails. Tail is capable of either rotating in both the saggital or frontal plane (2-tail) or just the front plane (3+ tail)

B. Environmental Setup

The experiment is inspired from this work that uses sequential MPC for tail stabilization [14]. In this work, the experiment consists of ten simulations per scene batch in Gazebo where each scene has different initial position, tail numbers, feed forward torques, and execution time of feed forward torques, but with a fixed elevation change (80cm cliff) as shown in Figure 3.

The simulations is decomposed into three components, the prefall stage, the freefall stage, and the postfall stage. The prefall stage starts by having the quadruped walk laterally at a speed of 1m/s off a cliff while executing a feedback tail control of up to two degree of freedom (if tail exists). As the legged robot walks towards the edge of the cliff, a leg will attempt to land on air, causing the quadruped to rotate. The other three legs will follow where there is no legs in contact, defined as the freefall stage. The legged robot attempts to stabilize during the free fall event by executing a time-based switched system that runs an open-loop torque tail controller (if no open-loop control, tail will use a feedback controller). During the impact of landing, the postfall stage, the footstep planner continues to trot in the horizontal direction all while attempting to stabilize from landing. Experimental data is collected during the entire event using PlotJuggler [15], where a successful land is defined when the quadruped lands upright and an unsuccessful land is if the quadruped lands on its side. Joint states were collected by a state estimator plugin that collects state from the controller and contact plugin that interfaces with the Gazebo simulator.

Furthermore, details about the different batch simulation parameters is seen in Section IV-A Table II.

[1]Github Link: Multi-Link Tail Controller Repository

IV. Results

Eight of the simulated batches of a quadruped walking off within different simulation parameters can be seen in Table II. The subsections will discuss based off the results seen in Table II on how different factors such as tail controllers can be beneficial or detrimental to the stabilization problem for quadruped walking in extreme terrain conditions. More specifically, the subsections will discuss the difference in performance for quadruped with and without a tail controller, euler angles during freefall, and how the open-loop tail control during freefall can affect the stability problem. Note, the author does remark the low sample size. However, the author believes that despite the low sample size, these results are still reliable.

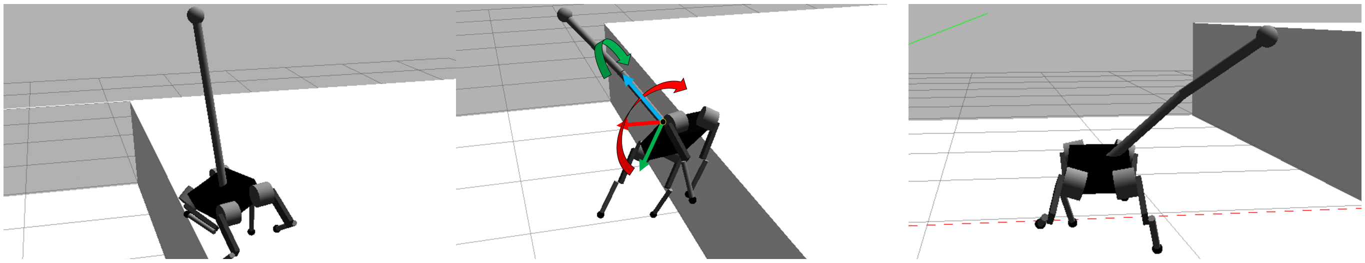
TABLE II: Setup for Quadruped in 80cm Dropoff

	Tail Number							
	0	1					2	
Initial Pos.	4.6	4.6		4.76			4.71	
Scene	1	2	3	4	5	6	7	8
Freefall[s]	4.95-5.08			4.73-4.86			4.91-5.06	
Torque 1[N]	-	-	20	-	20	30	-	45
Time 1[s]	-	-	4.5	-	4.75	4.75	-	4.75
Torque 2[N]	-	-	-	-	-	-	-	-45
Time 2[s]	-	-	-	-	-	-	-	5
Land Rate	0%	0%	50%	40%	0%	0%	30%	90%

A. Effects of No Tail vs. Tail

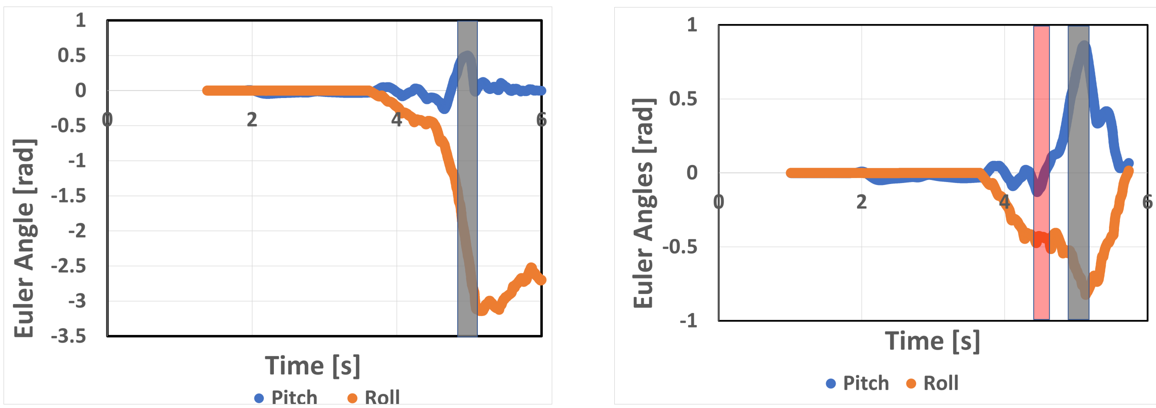
The performance of a successful landing rate with and without a tail is easily seen in Table II. Without a tail control, scene 1, there is no actuation within the system to re-orient the base of the quadruped while the leg control prepares for stance. This is reflected by the zero percent land rate for a quadruped with no tail.

With a tail, the land rates have found an increase of success, although not as strong of an indication as expected. Scenes 2-3 and 7-8 showcase a clear increase in landing rate with a properly timed open-loop feed-forward tail control. Moreso, an increase in the number of fully actuated open-loop tail controller (scene 8) shows increases the successful landing

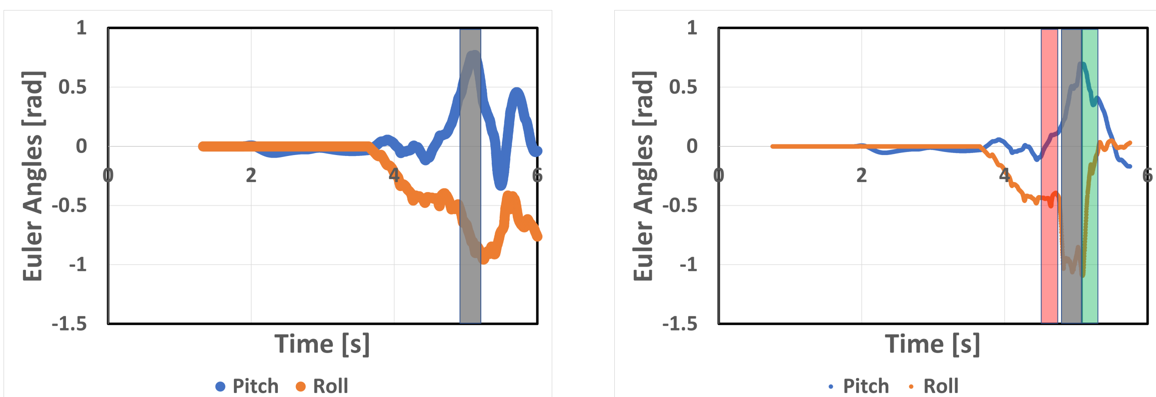


(a) Prefall (b) Freefall and Open-Loop Control (c) Postfall

Fig. 3: Quadruped traversing over cliff. Quadruped undergoes three stages: prefall, freefall, and postfall. Quadruped in freefall executes open-loop tail controls (80cm drop off). Tail torque control is executed in the roll and pitch axes of the tail frames. (Axes: Red -X, Green - Y, Blue - Z)



(a) Unsuccessful Scene 1 (b) Successful Scene 3



(c) Unsuccessful Scene 7 (d) Successful Scene 8

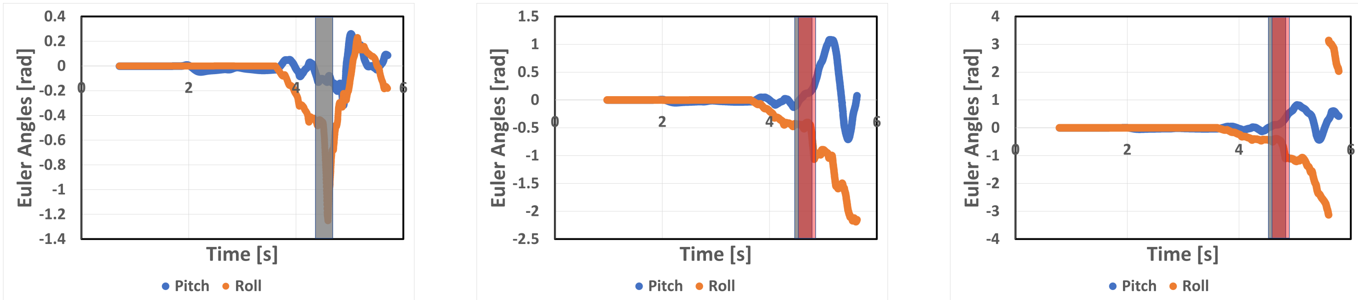
Fig. 4: Euler Angles for stabilizing torque control for quadruped freefalling. Grey bar is the duration of freefall, the red bar is the duration of the open-loop torque in the tail roll axis, and the green bar is the duration of the open-loop torque in tail pitch axis.

rates from 50% in scene 3 to 90% in Scene 5. However, the stability problem is not determined solely by the number of actuated tails as demonstrated in Scenes 4-6, where there is an opposite relationship in successful landing rates of applying an open-loop tail control.

As there is more to the stability problem than the relation of having no tail or having a tail, one framework to view these opposing results to the stability problem is through the lens of the euler angles during freefall as discussed in Section IV-B.

B. Euler Angles During Freefall

As the quadruped walks off the cliff and steps onto air, the quadruped tilts due to an unexpected event. The legged robot's additional legs will also leave contact, beginning the freefall



(a) Successful Scene 4 (b) Unsuccessful Scene 5 (c) Unsuccessful Scene 6

Fig. 5: Euler Angles for non-stabilizing torque control for quadruped freefalling. Grey bars is the duration of the quadruped during freefall and red bar is the duration of the open-loop feedforward torque in the tail roll axis.

event. One question to frame during this freefall is does the euler angle of the base of the quadruped during the freefall timespan affect having a successful landing. Figure 4 and 5 graphs the trajectory of either the successful or unsuccessful euler angles of each scene mentioned in Table II.

Figure 4a implies that a successful landing is impacted by the initial angle as scene 1's initial roll angle during freefall is at 90°. Therefore, the orientation is much harder to stabilize with the footstep planner with the following initial condition and final conditions. This is reflected by Figure 4b. Logically, these results are sound as if the initial orientation is in a nominal position as the legged robot falls, then the landing position will be close to the nominal position. This conclusion is reflected in the success rate found in Scene 3, 4, and 7 in Table II. However, this conclusion is not entirely reflected in Figure 4d, 5b, and 5c where the initial roll angle is relatively similar to Scene 3,4 and 7. It is important then to conclude that initial conditions during freefall does have a role in the success rate of landing, but other factors from a controls perspective should be taken as a method of analyzing stability and therefore successful landing rates.

C. Beneficial and Detrimental Torque Control

Due to the nature of the control problem open-loop during the switch), it is natural to consider whether the open-loop torque successfully aids the stabilization process, helps but the control is not enough to stabilize the quadruped, or is too disruptive and is detrimental to the stability problem.

Figure 5 is the case where open-loop tail control does not at least successfully aid in the stability problem. In Figure 5a, the max angle during freefall nearly reaches a lateral orientation, but despite that and with no open-loop feedforward torque, the quadruped is able to have some success rate of re-orienting itself to a nominal orientation due to the feedback control of the tail and the footstep planner. However, Figure 5b and 5c shows where a open-loop tail control shortly after freefall event is detrimental to the landing problem. This is highlighted in Figure 4 where the open-loop tail control is beneficial when executed prior to freefall. However, the open control is also beneficial during the freefall event as shown in 4d. Given sufficient enough control input to properly re-orient before freefall and enough degree of control, the stability problem is almost guaranteed as shown in Table II. This concludes that a tail controller, given sufficient admissibility and controllability of the system, is capable of stabilizing the locomotion task for contact critical environments.

V. Conclusion

The impact of a tail as a time-base switched control system for the stability and landing problem under contact critical terrain condition is prevalent in the analysis of this work. It is shown that a tail control can stabilize the quadruped better compared to a quadruped without a tail over extreme terrain conditions. It is also shown that under properly curated open-loop control, quadrupeds are capable of reliably landing and stabilizing under contact critical environments. Furthermore, it is analyzed that the initial conditions during freefall is a factor to the stability and landing problem. Future works will integrate proper proprioceptive state estimation techniques to recognize critical contact conditions and use optimal control laws to best execute a stabilization and landing policy.

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