Introduction & Literature Review

December 4, 2020

Stability is a significant issue for mobile robot design. Loss of stability can mean the robot is unable to move and must be reorientated or retrieved, which maybe difficult or impossible in some extreme environments, such as in outer space or a nuclear fuel pool. In the worst case it can result in severe damage or destruction of the robot, and any objects it is carrying. This has become more of an issue as mobile robots have become increasingly fast and agile, often running [], jumping [] and hopping [] around less controlled environments.

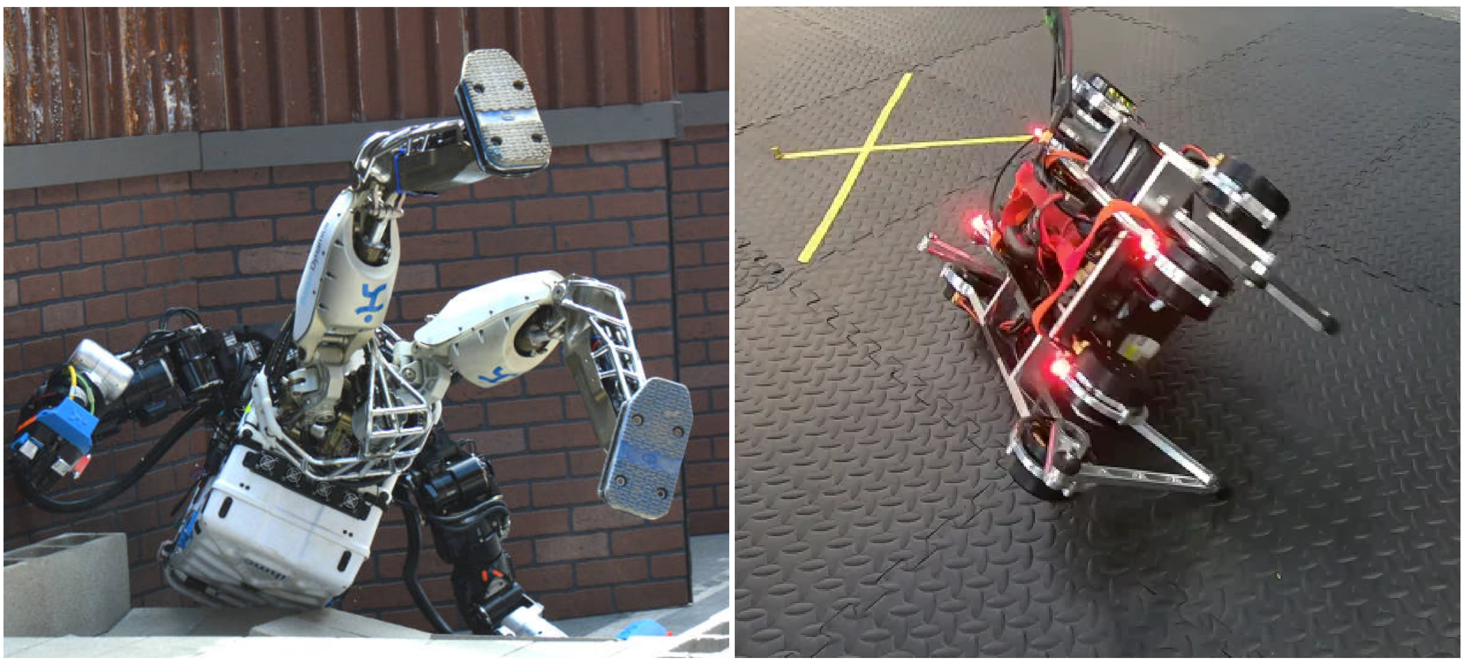

Figure 1: Examples of loss of stability in bipedal and quadrupedal robots.

In many ways the consequences of stability loss in mobile robots are analogous to other situations. A human that falls over has to pick themselves up before continuing on, or if they are infirm they may require assistance. Likewise they could also suffer injury, or if walking along the edge of a long drop, fall to cause severe injury or death. A forklift truck or other piece of heavy plant can topple, injuring the driver and causing the damage or destruction of vehicles and materials.

In general, stability from a biomechanical perspective can be divided into two different types, *static* and *dynamic*. While there are numerous ways to define the difference between the two, such as the maximum lyupanov exponent for dynamic stability [], the following definitions will be used:

- **Static stability** only considers the uniform force of gravity and assumes no other forces are acting on the object.
- **Dynamic stability** considers other forces and torques on the object, both internal and external, as well as gravity.

A stationary object that has no external forces or torques being applied needs to be statically stable, a moving object, or an object that is having a force or torque applied to it other than gravity, needs to be dynamically stable.

Figure 2: Examples of loss of stability (static or dynamic) in a human and forklift truck.

1 Static Stability

To determine if the robot is statically stable, the gravity axis projection of the center of gravity needs to fall within a defined "support polygon" on the plane perpendicular to the gravity axis plane, as in figure 3. If gravity is treated as a constant force along vector g, then the center of mass and center of gravity are equivalent. The center of mass can be calculated for using equation 1 for n bodies of masses $m_{1\ldots n}$ and COM positions $\boldsymbol{p_{1\ldots n}}$. If the gravity vector is parallel to any of the basis vectors, then the perpendicular components of the COM/COG can be used to determine the static stability.

$$\mathrm{COG} = \mathrm{COM} = \frac{\sum_{i=1}^{n} m_i \boldsymbol{p_i}}{\sum_{i=1}^{n} m_i} \tag{1}$$

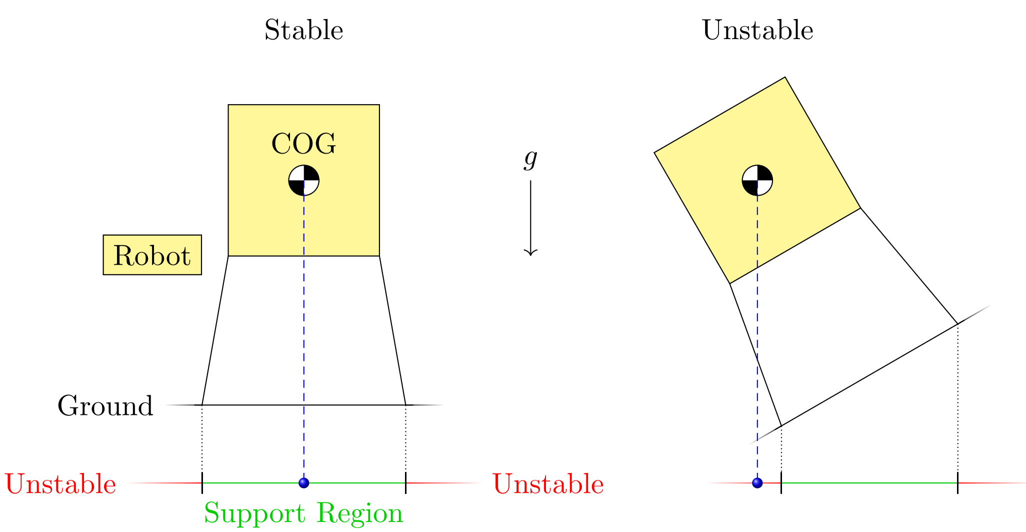

Figure 3: 2D representation of the static stability of a legged robot, with the support region defined by the contact points of the legs with the ground. Notice how the orientation of the robot with respect to the gravity axis can move it in and out of the static stability region.

Fundamentally, there are two different methods to maintain static stability:

- Change the region or shape of the support polygon so the gravity axis projection of the center of gravity remains within the bounds of the support polygon.

- Move the gravity axis projection of the center of gravity so it remains within the bounds of the support polygon.

The former method can be considered equivalent to using a walking pole to steady yourself on uneven ground when hiking, the leg of the pole acts as a new vertex that is used to calculate the support polygon, expanding it sufficiently, or placing your foot in front of you when walking. The latter method can be considered equivalent to leaning back to remain upright when falling forward. Leaning back moves the centre of gravity to keep it within the support polygon.

However, just because the center of gravity falls outside of the support polygon does not mean that loss of stability is inevitable, as long as a force or torque applied to the body counteracts the forces and torques induced by the force of gravity in order to maintain stability. This is similar to applying a torque to your ankle when standing on one leg, or a strong wind keeping you upright when leaning forward. If this is the case, then *dynamic* stability is maintained while *static* stability is lost. If the force or torque is removed, then stability is lost. Conversely, forces and torques can also cause loss of stability even if the center of gravity does not fall outside of the support polygon. This is similar to being pushed over, or stopping too quickly and falling forward. So dynamic stability can maintain stability even if static stability is lost, but static stability cannot maintain stability if dynamic stability is lost.

2 Dynamic Stability

To determine if the robot is dynamically stable,

The concept of the Zero Moment Point, first defined in [], is useful for mobile robots to check if dynamic stability will be maintained. It extends the calculation used for static stability by including inertial forces caused by accelerations of the bodies, as shown in figure 4. Though it has mostly been utilised for bipedal robots to ensure stability while walking, it is also applicable to quadruped robots [], and has even been investigated for the development of a stability warning system in road vehicles [**?**]. The ZMP is formally defined as the point at which the point where the total of horizontal inertia and gravity forces equals zero. It can be thought of as a *dynamically augmented* version of the gravity axis projection of the center of mass.

Equation 2 defines the position of the ZMP for a robot or vehicle with n bodies of masses $m_{1\dots n}$, COM positions $\boldsymbol{p_{1\dots n}}$ and COM accelerations $\ddot{\boldsymbol{p}}_{\boldsymbol{1\dots n}}$, in contact with a planar surface of normal vector $\boldsymbol{n}$ (ZMP cannot be calculated for non-planar surfaces). $\boldsymbol{\tau_{i\dots n}}$ defines the torque acting on each COM, which can be calculated from .

$$\begin{aligned} \boldsymbol{\tau_i} &= \boldsymbol{R_i}\left(\boldsymbol{I_i}\ddot{\theta}_i - \left(\boldsymbol{I_i}\dot{\theta}_i\right) \times \dot{\theta}_i\right) \\ \text{ZMP} &= \frac{\boldsymbol{n} \times \sum_{i=1}^{n} \left(\boldsymbol{p_i} \times m_i \boldsymbol{g} - \boldsymbol{p_i} \times m_i \ddot{\boldsymbol{p}}_{\boldsymbol{i}} - \boldsymbol{\tau_i}\right)}{\boldsymbol{n} \cdot \left(\left(\sum_{i=1}^{n} m_i \boldsymbol{g}\right) - \left(\sum_{i=1}^{n} m_i \ddot{\boldsymbol{p}}_{\boldsymbol{i}}\right)\right)} \end{aligned} \tag{2}$$

3 Payload

When a payload is added to the robot, it is equivalent to instantaneously adding an extra body to the robot of mass m_p and position p_p thus changing the COM. Initially the payload will also create an extra contact point with the ground, changing the support polygon so the robot remains statically stable. However, as soon as contact between the payload and ground is severed, the robot can become statically unstable. This does not mean the robot will immediately lose stability, the dynamic forces created picking up the payload may keep the robot dynamically stable, but once the robot is stationary without other forces acting upon it, it may lose stability. The best way to compensate for this is to change the position of the other bodies so the COM remains within the support polygon. This is akin to leaning back when carrying something heavy. But leaning generally has limited range, so can only compensate for lighter payloads. An alternative is needed for heavy payloads.

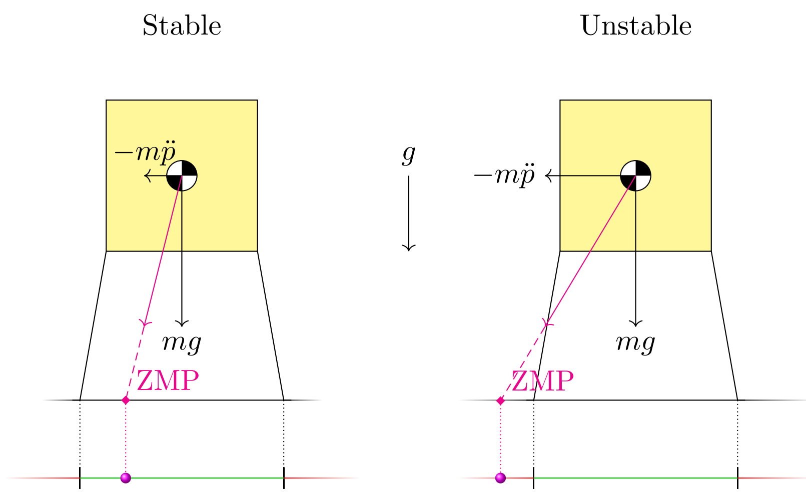

Figure 4: 2D representation of the ZMP of a legged robot under horizontal acceleration, with the support region defined by the contact points of the legs with the ground. Notice how increasing the horizontal acceleration of the robot can make it dynamically unstable.

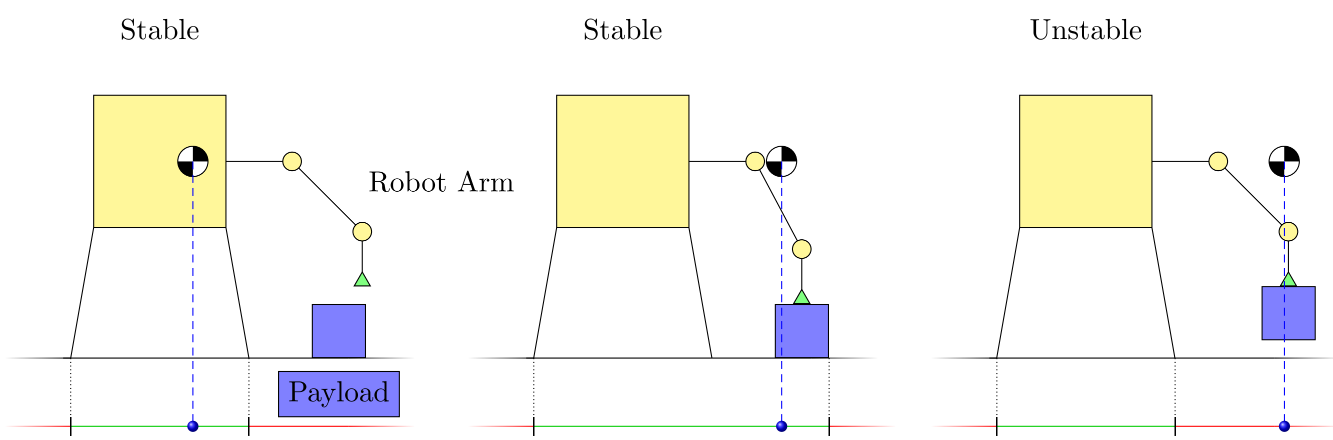

Figure 5: 2D representation of the static stability of a legged robot picking up a payload, with the support region defined by the contact points of the arm and legs with the ground. Notice how the payload acts as a contact point until it is lifted off the ground, preventing loss of stability even as the COM/COG is translated due to the mass of the payload.

4 Tails

4.1 Tails for Stability in the Animal Kingdom

Tails are a common sight in vertebrate animals, a natural extension of the spinal column. While some tails are used purely for grasping, locomotion, communication or decoration, many have some function in maintaining stability.

4.1.1 Case Study 1: Balance

[48] demonstrates how the domestic cat uses its tail for balance when walking along a narrow beam, which was shifted laterally at a certain velocity by 2.5 cm or 5 cm while they are traversing it. Four cats were trained to walk across the beam, before and after a surgical procedure that severed their spinal cord just above their tail, severely affecting its function. As can be seen from figure 6, this procedure caused the cats to fall from the beam far more often than before surgery.

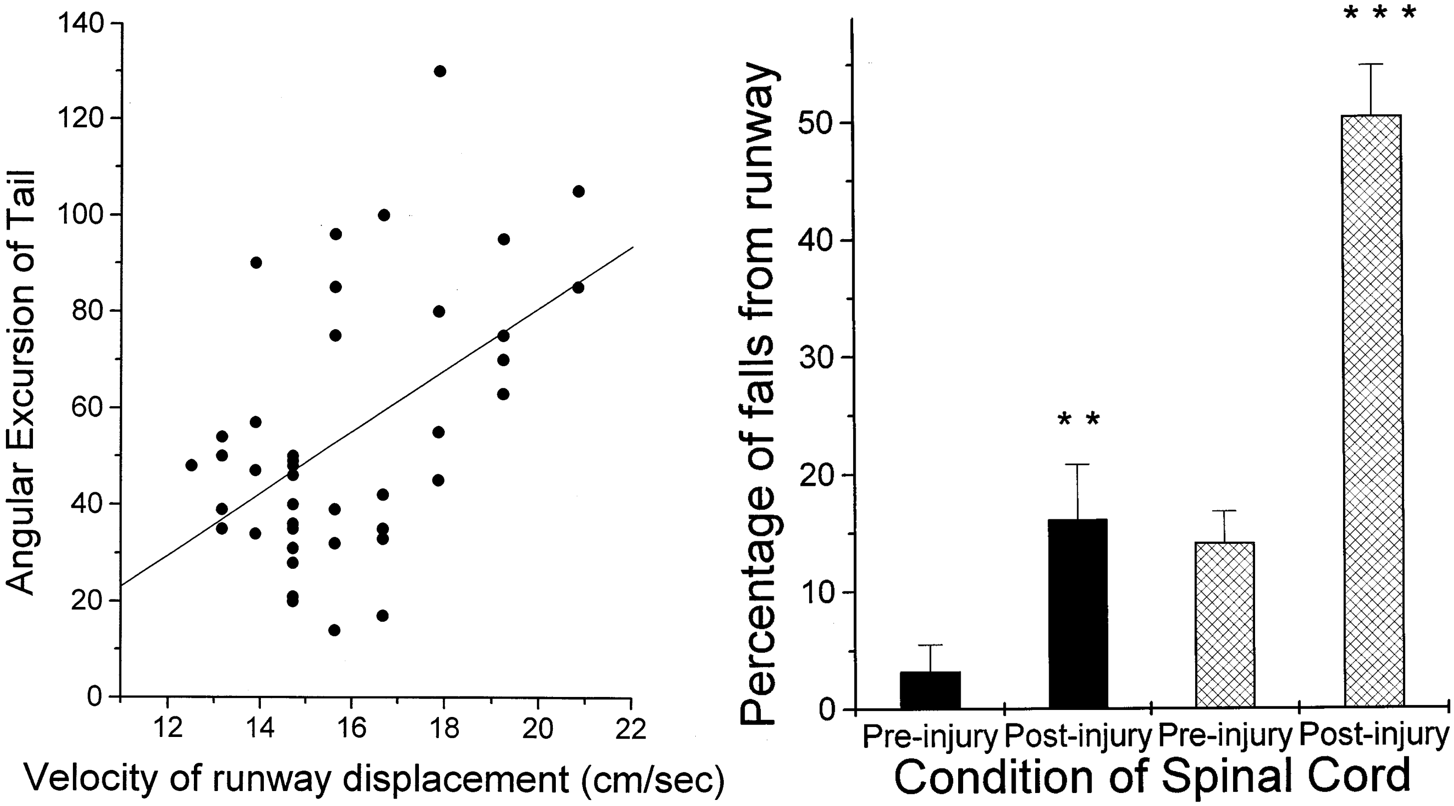

Figure 6: Charts from [48] showing how the cat's tail is used to maintain balance on the beam when it is shifted, and how impairing it causes a major loss of stability. Dark bars are a 2.5 cm displacement, cross-hatched bars are a 5 cm displacement.

4.1.2 Case Study 2: Inertial Force/Torque Compensation

Other animals use a tail to compensate for inertial forces and torques induced during a change in velocity, either in magnitude or direction. [32, 33] examines how the cheetah uses its tail to counteract centrifugal force when turning at high speed, and acceleration and braking forces when speeding up and slowing down. They then applied this to a robotic vehicle, which is discussed in section 4.2.2.

Figure 7: Images from [32, 33] of a cheetah using its tail during a turn and braking while chasing a lure.

4.1.3 Case Study 3: Aerial Reorientation

Finally, some animals use their tail to remain upright while airborne. [12] examines the aerial stability of the arboreal lizard with an intact tail and with their tail removed. Lizards with the tail removed are unable to maintain their body orientation and do not land cleanly, as can bee seen in figure 8. [29] then applies this to a robotic vehicle, discussed in section 4.2.2.

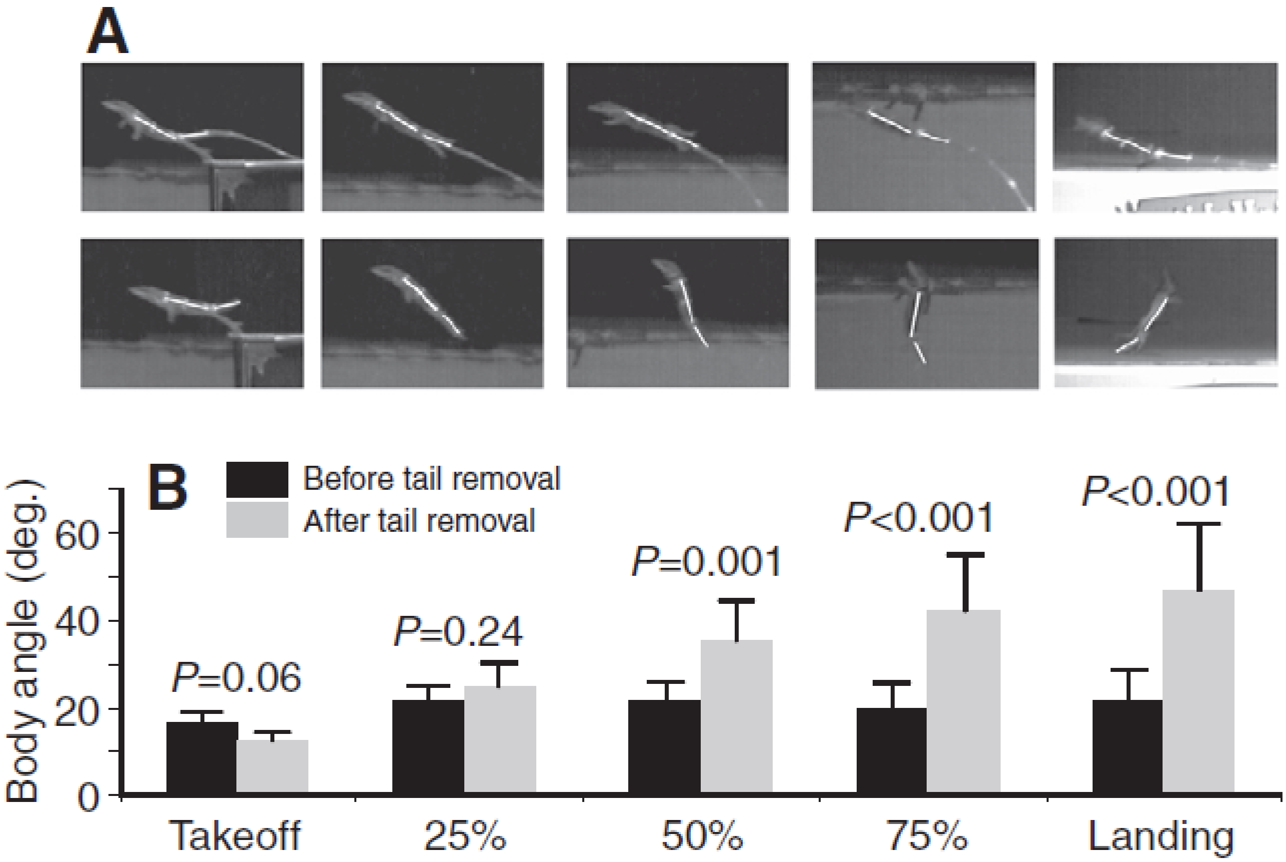

Figure 8: Image from [12], showing the body angle of a lizard during a jump, before and after tail removal.

4.2 State of the Art Mobile Robots

As many mobile robots have looked at animals for inspiration when it comes to solving various problems with dynamics and locomotion, tails have been used in the development of a significant selection of mobile robots, typically for similar functions as seen in the animal kingdom.

4.2.1 Case Study 1: Balance

[3] uses a tail to keep a legged robot, the "MIT Cheetah", from falling over when disturbed, in this case the disturbance being a "wrecking ball", slamming into its side. This can be seen as a similar reaction to the experiments by [48], though it again uses the example of the cheetah in the publication.

4.2.2 Case Study 2: Inertial Force/Torque Compensation

In [32, 33] which also details the functions of the cheetah tail, the robot "Dima" is fitted with a single segment 2-DoF tail which can replicate the motion of the cheetah when this wheeled robot makes a turn at high speed, or accelerates or brakes.

4.2.3 Case Study 3: Inducing Turning Torque

In [34, 26, 25] a roach like robot is fitted with a single-segment yawing tail. By swinging this tail rapidly to one side or the other during locomotion on a low-friction surface, a reaction torque causes the robot body to rotate and the legs to "skid" on the surface.

4.2.4 Case Study 4: Aerial Reorientation

In [9] a tail is used to maintain the pitch orientation of a robot when it is dropped from a height, by inducing torques on the body while airborne. They also consider the effect of tail contact against a surface (such as a wall) to increase the torque on the body. Similar studies in publications such as [28] also examine the same technique when a robot has forward momentum (when it drives off a ledge, for example).

5 Literature Review

5.1 Literature Search

A computerised literature search was undertaken of the electronic databases: **IEEE Xplore**, **Web of Science** and **Scopus** between January 1980 and December 2018, searching for **Tail** or **Appendage** in the document title. Papers were excluded if they concerned water walking, swimming or flying robots, as the use of tails in fluid dynamics was not in the scope of the review. The language was limited to English. To identify relevant studies the titles and abstracts of the literature within the databases were scanned with the search terms:

> (Tail* **or** Appendage) **is contained in** *Document Title* **and** Robot* **not** (Fish **or** Swim) **not** (Surgery **or** Medic* **or** Tumour) **not** (Helicopter **or** Unmanned Aerial Vehicle **or** UAV) **not** Underwater **not** (Chemical **or** Chemistry) **not** Tailor* **is contained in** *Document Title*

The Chemical **OR** Chemistry search terms were included to exclude "tail" in the molecular sense (i.e. the and tail of a polar molecule). The Tailor* negative search term was included to exclude false positives caused by Tail*. An additional search was also conducted using Tail **AND** Tails **AND** Tailed **AND** Tailor* to verify that no relevant records contained both Tail* and Tailor* stems in separate words in the *Document Title*.
To ensure the author identified all relevant literature, that may have been missed by the database search, the authors screened the reference list of the identified papers and cross referenced with the database results.

5.2 Selection and Exclusion Criteria

The following selection and exclusion criteria were utilised to identify literature to meet the aim of the review:

1. Concerning the use of robotic tails with mobile land-based robots to aid locomotion including static and dynamic stability while rolling (i.e. wheeled), walking, hopping/jumping and in free fall.

2. Excluding robotic tails for aquatic locomotion (including water walking), or to aid aerial robotic flight.

5.3 Study Selection Process

An initial database search was conducted, screening all the titles and abstracts. Duplicate records were removed using MATLAB code, which compared the identified paper titles from each database search result, followed by manual inspection of the results. The full-text of the selected studies were then independently screened against the selection and exclusion criteria.

5.4 Results

Figure 14 illustrates the flowchart of the study selection process and the papers identified. In total **185** studies were identified after duplicates were removed, this reduced to **101** papers after the titles and abstracts had been screened. Out of the **101** papers **33** were excluded because:

- The paper was a short abstract for a conference (**5**).

- The paper was a magazine article (**1**).

- The paper included the **Appendage** keyword in the *Document Title* but was not about tails (**20**).

- The paper was the review paper [39] (**1**).

- The paper concerned robots walking on water, like a pond skater (**6**).

This process led to the remaining **68** studies being analysed with data extracted, as detailed in Table **??**. **33** unique physical robots have been identified from the records (that were physically experimented on in an **Experimental** paper), as detailed in Table 1. Since there were some robots which had multiple records associated with them, some of the records had some duplicate data, which was merged together for each individual physical robot. The data is displayed in Table **??**. Papers which did not have a physical robot have this data displayed separately in Table **??**.

5.4.1 Chronology

Figure 15 is a histogram of robotic tail papers published as a function of year, the first paper was published in 2002 and approximately 71% (42 papers) of the papers have been published in the last five years since 2013.

5.4.2 Paper Structure

Out of the 68 studies identified, 44 were **Experimental** papers, 16 were **Abstract Model** papers, and 8 were **Simulation** papers. **Experimental** papers typically develop a control system which is first verified on a simulated model (either an **Abstract Model** or a more complex **Simulation**) then build a prototype or use an existing robot to experimentally verify the control system.

5.4.3 Physical Robots

Table 1 lists the physical robots by name, with the papers they were referenced in and the year the first paper mentioning the robot was published. Table **??** lists the physical robots by their properties. Table **??** lists all the papers that do not have physical robots connected with them.

5.4.4 Research Objectives

5.4.5 Robot Physical Properties

5.4.6 Tail Physical Properties

5.4.7 Tail Actuation

5.4.8 Control System

5.4.9 Locomotion

5.4.10 Tail Dimension Class

5.5 Discussion

5.5.1 Future Research

5.5.2 Actuator Technologies

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Table 1: Table of all the physical robots, the year it was first seen in a selected paper and the selected papers it was found in.

References	**Robot Name**	**First Published**
[22]	3DoF No Catch	2017
[15]	Cheetah-Cub	2016
[38]	DMST	2018
[50]	Dcat	2016
[33, 32]	Dima	2013
[31]	Dima II	2015
[14]	Helios VIII	2009
[35, 36]	IMPASS	2009
[7]	LoadRoACH	2018
[3]	MIT Cheetah	2012
[16, 18, 17]	MSU Tailbot	2013
[30]	MuddyBot	2016
[34]	OctoRoACH	2012
[11, 43, 49, 10, 4]	Penn Jerboa	2015
[40]	R3-RT	2018
[27]	RoMiRAMT	2015
[26, 25]	TAYLRoACH	2012
[29, 9]	Tailbot	2011
[47, 46, 45]	Titrus III	2002
[37]	USRT	2018
[6]	VelociRoACH	2017
[28, 19]	XRL/RHex	2012
[2]	Zappa	2008
[44]	-	2018
[5]	-	2013
[8]	-	2013
[21]	-	2010
[13]	-	2014
[1]	-	2013
[42]	-	2016
[41]	-	2016
[24, 23]	-	2017
[20]	-	2018

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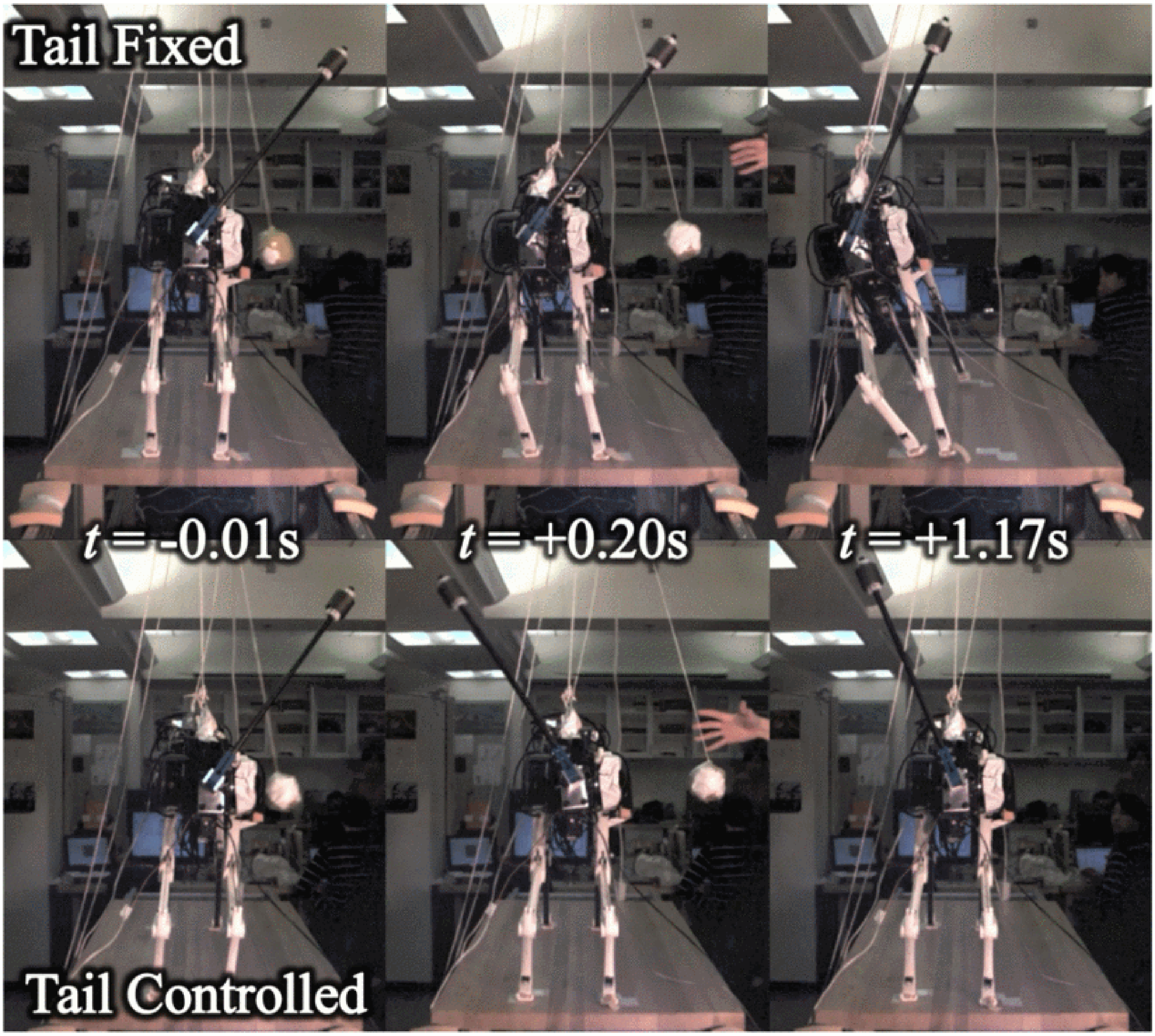

Figure 9: Image from [3] showing the difference in body compensation required with and without a moving tail when impacted by a "wrecking ball".

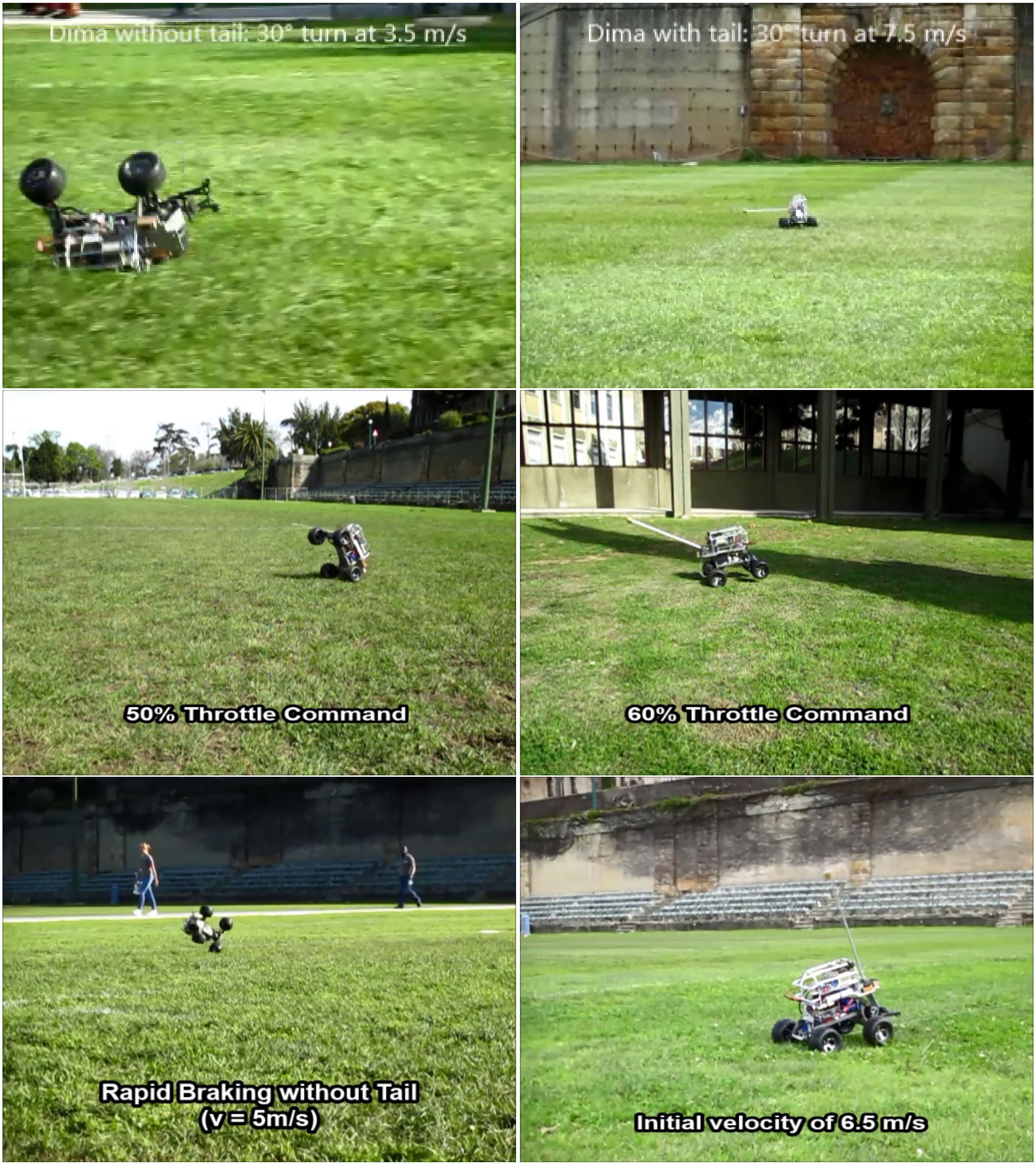

Figure 10: Video stills from [32, 33] of the "Dima" robot performing steering, acceleration and braking manoeuvres with and without a tail.

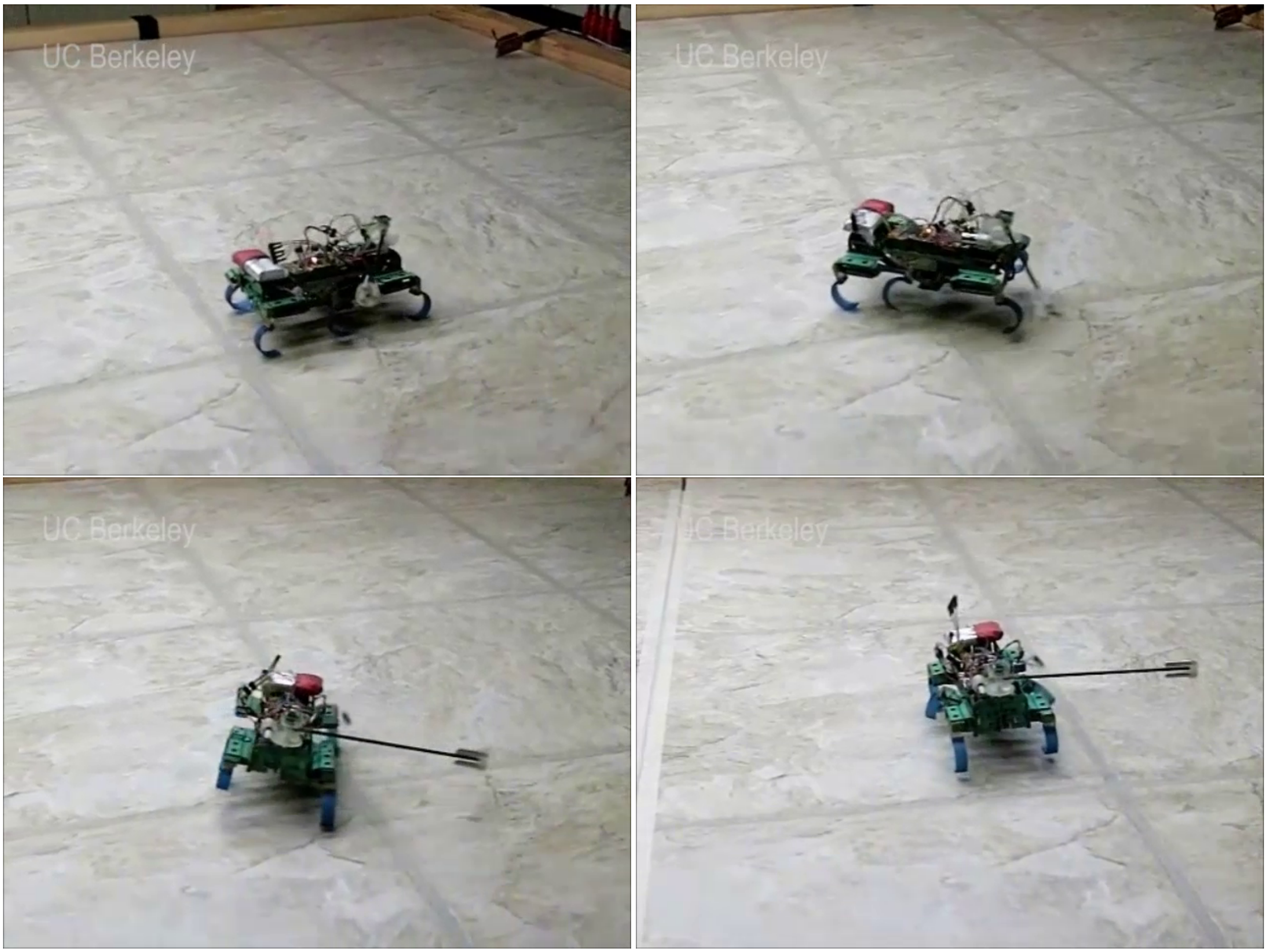

Figure 11: Video stills from [26] of the TalyRoACH robot using its tail to change its direction of motion.

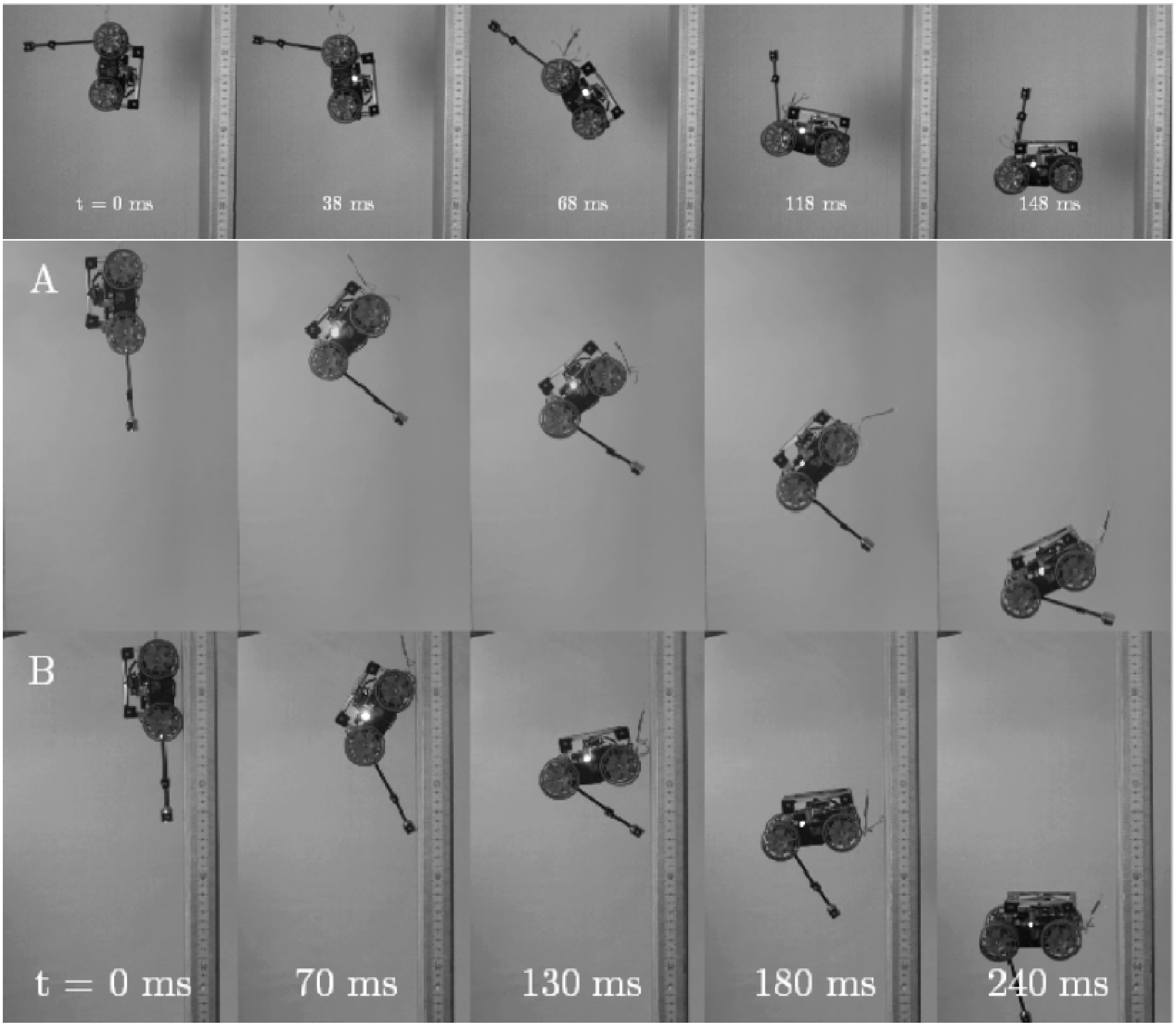

Figure 12: Images from [9] of the MSU Tailbot orienting itself after being dropped from a height, and how the tail contacting a wall can improve the orientation range.

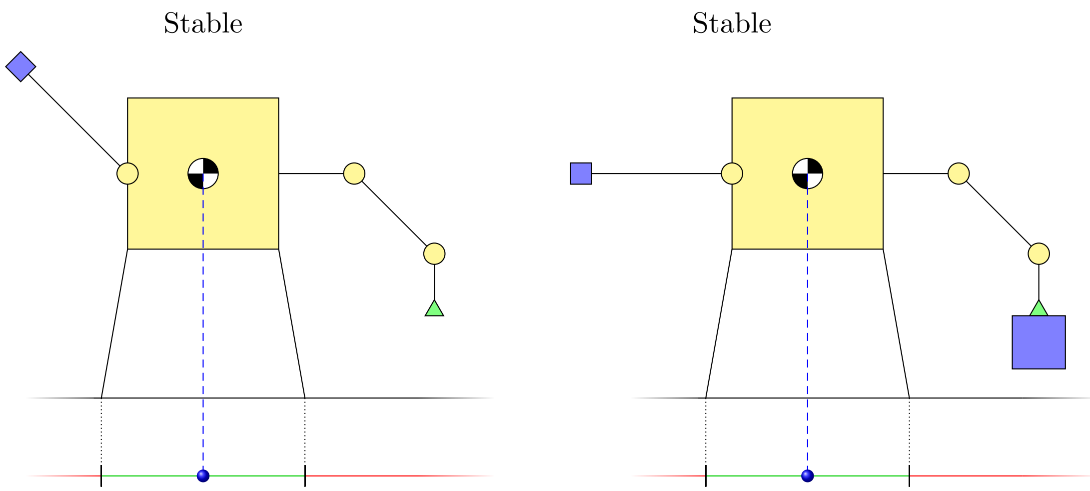

Figure 13: 2D representation of the static stability of a legged robot with a weighted tail picking up a payload. By changing the angle of the tail, the postion of its COG can be adjusted in order to compensate for the payload.

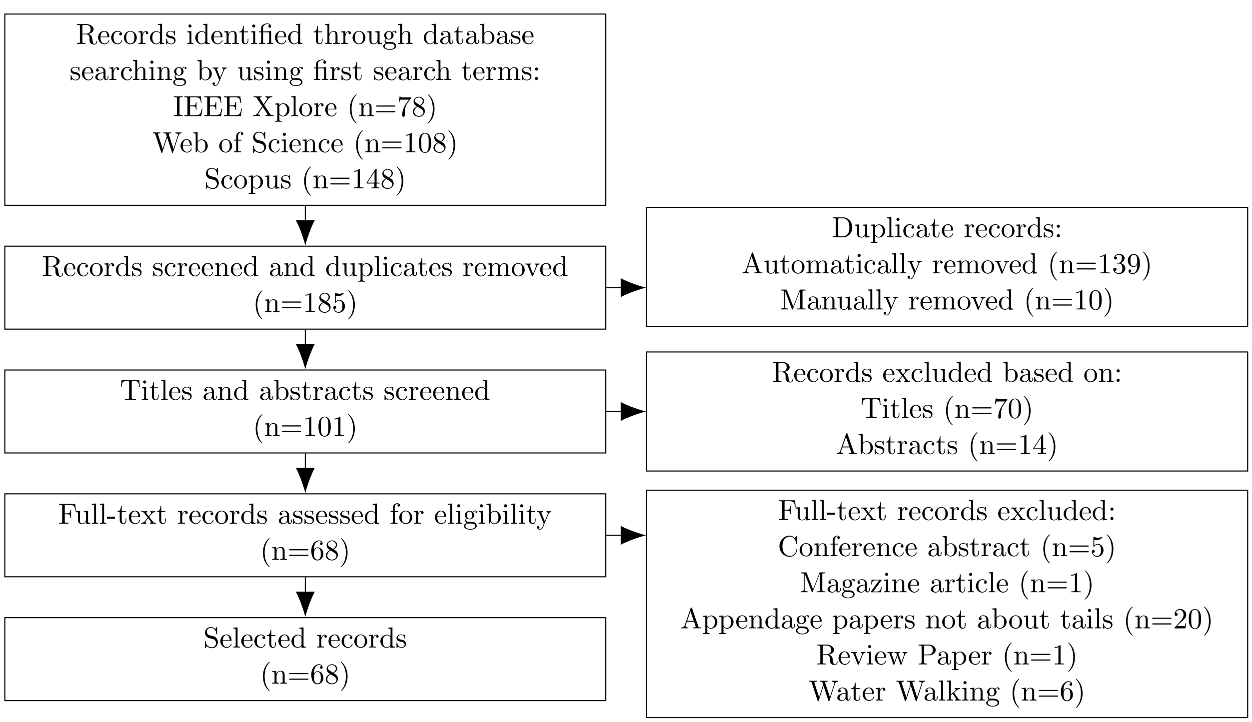

Figure 14: Flowchart of the study selection process.

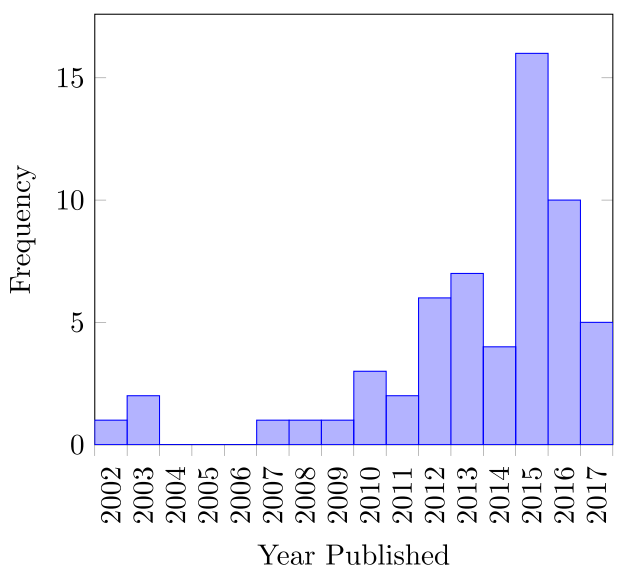

Figure 15: Histogram of the years the 59 selected records were published (note 2017 only includes papers published up to August, so cannot be directly compared with other years).