A Scoping Review of Robotic Tails for Land-based Mobile Robot Locomotion

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ABSTRACT

The aim of this review was to systematically identify and review literature relating to the design, development and implementation of robotic tails that improve land-based mobile robot locomotion, including static and dynamic balance and jumping, to inform the design of future systems. A systematic literature review was conducted to identify papers relating to land-based robots utilising tails to improve performance in IEEE Xplore, Web of Science and Scopus between January 1980 and December 2018. 68 papers were identified, of which 47 papers included a physical robot or prototype, and 33 distinct physical robotic systems were determined. In order of prevalence, robotic tails have been utilised for aerial reorientation, locomotion stability, induced turning, turning stability and velocity change stability. The most common tail structure for individual robots was rigid (79%) with the majority of tails identified composed of a single tail segment (70%) and actuation predominately by revolute electric motors (91%). Control systems were predominately closed outer-loop type. The literature illustrates robotic tails can improve performance but existing work has been limited to low degree of freedom systems. The authors propose that increased robot performance should be contrasted with the additional energy consumption and storage requirements needed to facilitate this.

Keywords: keyword, keyword, keyword, keyword, keyword, keyword, keyword, keyword

1 INTRODUCTION

The motivation for mobile robotics has predominately been driven by the need for systems which can explore hazardous and extreme environments which are too dangerous for people. For example nuclear decommissioning, where radiation is potentially fatal, or planetary exploration, where it is not possible to send and retrieve astronauts. Mobile robots have been successfully developed and utilised to explore nuclear sites such as Sellafield and Fukushima as well as the Martian surface, however obstacles and challenging terrain limit activities and can lead to the loss of robots which are often non recoverable. Mobile robots have evolved from wheeled machines to legged systems, which can run, jump or hop. These abilities enable mobile robotic systems to better adapt and navigate adverse terrain; In other words mobile robotic systems are becoming increasingly agile. As mobile robots move more towards increased agility, dynamic abilities and biomimetics, this has influenced the direction of research into investigating strategies for improving dynamic performance and stability by exploring the use of robotic tails to improve performance and robustness. Saab & Rone Saab et al. (2018b) recently published a state-of-the-art review of robotic tails in which the authors considered the design, modelling, analysis and implementation of robotic tails for mobile robots. The authors highlighted that robotic tails can be utilised for enhancing stability, manoeuvrability and propulsion of mobile robots, accomplished by enabling inertial adjustment. The review summarises challenges for future development with respect to mechanical design, modelling and control.

In this paper we present the results of a systematic review of literature relating to robotic tails for land-based mobile robot locomotion. This research complements the work of Saab & Rone Saab et al. (2018b) identifying an additional 41 papers and 16 robotic systems. Furthermore, we provide details of tail structure and classification, control, actuation, mass, length, and tail functionality. In this paper we define "tail" as anything that is referred to in the literature as such that meets the inclusion criteria and the topic of the review. This includes tails that are static or unactuated, as they can still influence robot locomotion.

2 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.

2.1 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.

2.2 Study Selection Process

The first author (DC) conducted the initial database searches 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 by the first author (DC). The full-text of the selected studies were then independently screened against the selection and exclusion criteria by two authors (DC and AW). Any disagreements were resolved through another author acting as a reviewer (WH).

2.3 Data Extraction and Presentation

After literature that met the inclusion criteria had been identified it was analysed and synthesised to identify approaches and corresponding technical details. The following information was extracted and tabulated:

- The **Paper Structure**, which is one of three categories:
  - **Abstract Model:** Papers that discussed tailed robots as an abstract mathematical concept, based on free body models that were were based on first principles.
  - **Simulation:** Papers that discussed a detailed virtual model of a tailed robot similar to a physical prototype.
  - **Experimental:** Papers that used a physical prototype or existing robot to generate experimental data.
- The **Locomotion** of the robot or abstract mechanical model, which contains one or more of the following keywords:
  - **Walking:** Leg-based locomotion (bipedal, quadrupedal etc.) on a solid surface with no aerial phase (e.g. Human).
  - **Hopping:** Leg-based locomotion with an aerial phase (e.g. Kangaroo).
  - **Wheeled:** Wheel-based locomotion (e.g. Car).
  - **Tracked:** Track-based locomotion (e.g. Tank).
- The **Control System Architecture** which categorises the control systems into 4 different types based on a simplified control schema. The types are defined as (and illustrated in Figure **??**):
  1. A fully "blind" *open-loop* system with no feedback control whatsoever, the system is controlled by a fixed pattern or model that runs in a sequence and takes no inputs.
  2. An *inner-loop* system where position data from the tail actuators are used as inputs to the control system to control the tail position.
  3. An *outer-loop* system where sensor data from the robot (IMU, accelerometer, gyroscope etc.) are used as inputs to the control system to control the tail position.
  4. A *multi-loop* system where both sensor data from the robot *and* position data from the tail actuators are used as inputs to the control system to control the tail position.
- The **Tail Structure**, categorised into three types and described in Figure **??**.
  - **Rigid:** Tail is constructed from one or more *rigid* bodies connected by joints. The joints move in order to move the tail, the bodies do not deform.

- **Flexible:** Tail is constructed from one or more *flexible* bodies connected together rigidly. The bodies deform continuously in order to move the tail.
- **Pseudo-Flexible:** Tail is constructed from a large number of rigid bodies connected by joints, so many that they approximate a flexible body (this is also referred to in some publications as "serpentine", for example in Rone and Ben-Tzvi (2015, 2017); Saab and Ben-Tzvi (2016) and Saab et al. (2018a)).

- The **Number of Segments** in the tail, which corresponds to the number of bodies connected together with joints in the tail, not including the rest of the robot. Segments can be *Active* or *Passive*, depending on if they are directly controlled by an actuator.
- The **Tail Dimension Class**, which categorises the tails based on the movement space M of the tip of the tail (or end effector). If a volume V is conceptualised, centred around the base of the tail such that $M \subseteq V$, then M can be found on four distinct operations of V. The classes are defined as (and illustrated in Figure **??**):
  - **Class 1:** M is on a curve on the surface of V.
  - **Class 2:** M is on a section of V.
  - **Class 3:** M is on the surface of V.
  - **Class 4:** M is a volume within (or equal to) V.
- The **Tail Dimension Class**, which categorises the tails based on the movement space of the tip of the tail (or end effector). The classes are defined as (and illustrated in Figure **??**):
  1. A single revolute joint moves the tip along a circular arc on a plane.
  2. Multiple parallel revolute joints move the tip within a trimmed portion of a plane.
  3. Two perpendicular revolute joints move the tip within a trimmed portion of a spherical surface.
  4. Multiple perpendicular or parallel revolute joints move the tip within a volume.
- The **Tail Degrees of Freedom** which is typically the number of active segments multiplied by the dimensions each one can be actuated in.
- The **Actuator** that is used to move the active segments.
- The **Tail Mass**, in kilograms.
- The **Body Mass**, in kilograms.
- The **Tail Length**, in metres.

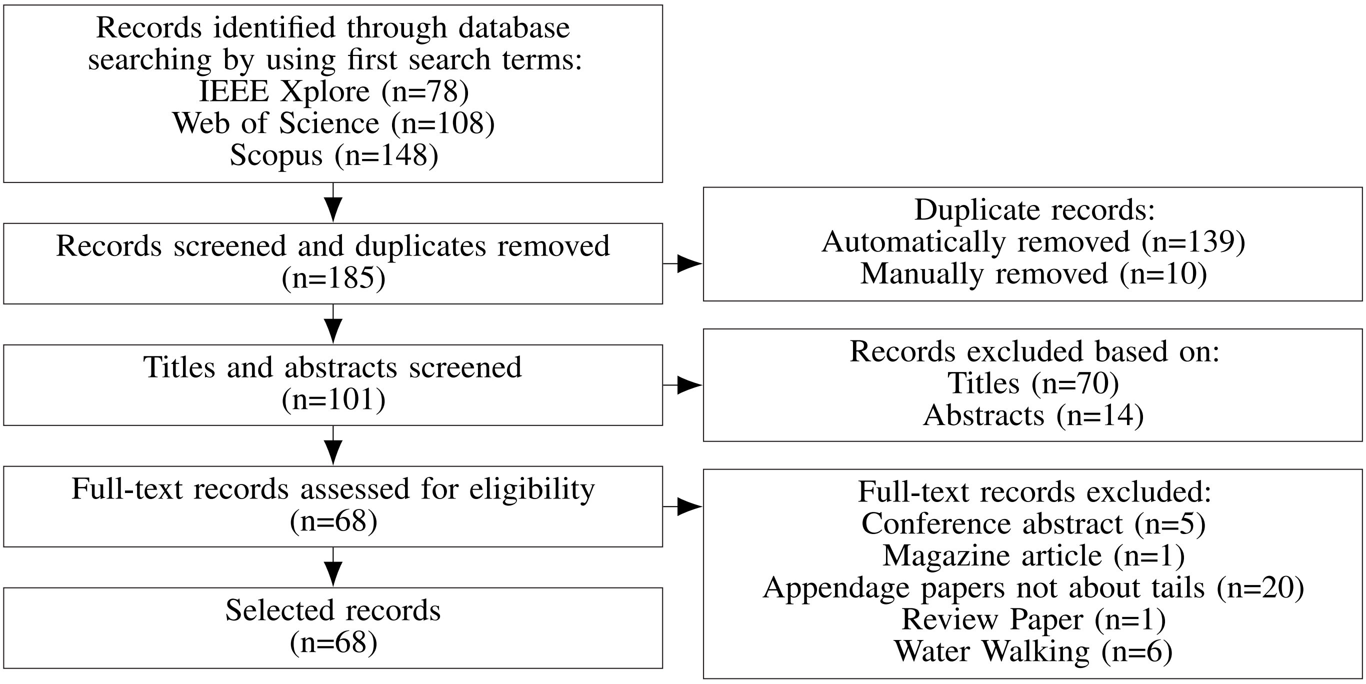


Figure 1. Flowchart of the study selection process.

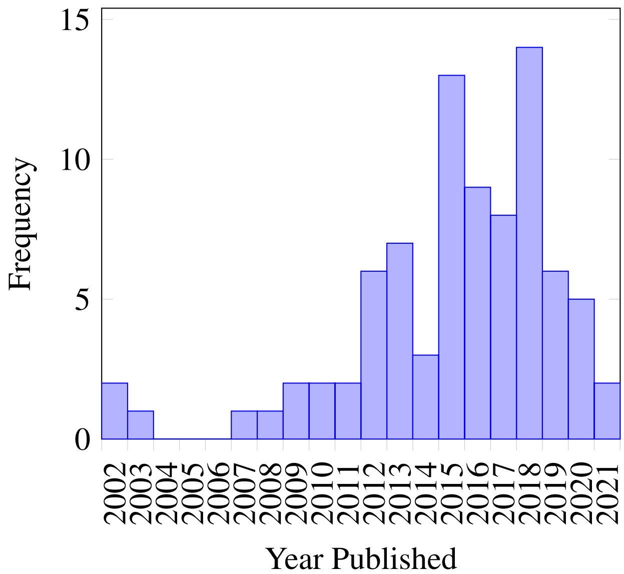


Figure 2. Histogram of the years the 68 selected records were published.

Figure 1 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 Saab et al. (2018b) (**1**).

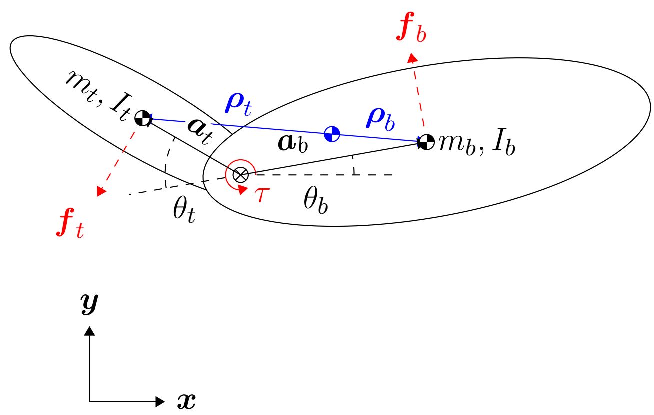


Figure 3. A planar rigid body diagram of a generic robot with a 1 DoF tail.

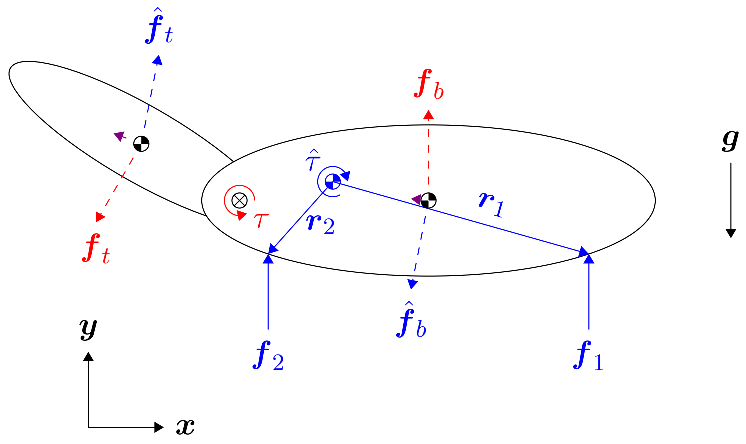
- The paper concerned robots walking on water, like a pond skater (**6**).

This process led to the remaining **68** studies being analysed with data extracted, as detailed in Table 5. **33** unique physical robots have been identified from the records (that were physically experimented on in an **Experimental** paper), as detailed in Table 2. 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 3. Papers which did not have a physical robot have this data displayed separately in Table 4. Figure 2 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.

3 TAIL FUNCTIONS

3.1 Rigid Body Models

In order to understand the diverse range of functions a robot tail can perform, a planar rigid body model can be used in order to simplify and abstract the dynamics of each application. In essence, any robot with a tail can be described as two bodies, the main robot body with mass m_b and inertia I_b, and the tail with mass m_t and inertia I_t, joined by a pivot which can generate a torque τ in one or more axes. For a robot with a multi-segment tail, any configuration of the joints in the tail can be abstracted into a single pseudo-body and a base pivot torque with suitable dynamics calculations. The other coefficients of the system are $\boldsymbol{a}_b$ and $\boldsymbol{a}_t$, which denote the vectors from each body's COM to the pivot. The kinematic state of the system can then be described with θ_b and θ_t, denoting the absolute rotation of the robot body and the relative rotation of the tail body to the robot body, and $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$, denoting the vectors from the origin $\boldsymbol{\rho}$ to each body. The origin can equal the COM of the model with the constraint $m_b\boldsymbol{\rho}_b + m_t\boldsymbol{\rho}_t = \boldsymbol{0}$. When no other external forces are present, the resultant torque $\boldsymbol{T}$ of the model is only influenced by the pivot torque. θ_b can then be calculated by integration from the sum of the moments of inertia and the resultant torque, as in equation 1 where $\boldsymbol{z}$ is the normal unit vector to the plane.



$$
\begin{aligned}
\boldsymbol{f}_b &= \boldsymbol{a}_b \times \tau \boldsymbol{z} \\
\boldsymbol{f}_t &= \boldsymbol{a}_t \times \tau \boldsymbol{z} \\
\boldsymbol{T} &= \boldsymbol{\rho}_b \times \boldsymbol{f}_b + \boldsymbol{\rho}_t \times \boldsymbol{f}_t \\
\ddot{\theta}_b &= \frac{I_b + I_t}{\boldsymbol{T}}
\end{aligned}
\tag{1}
$$

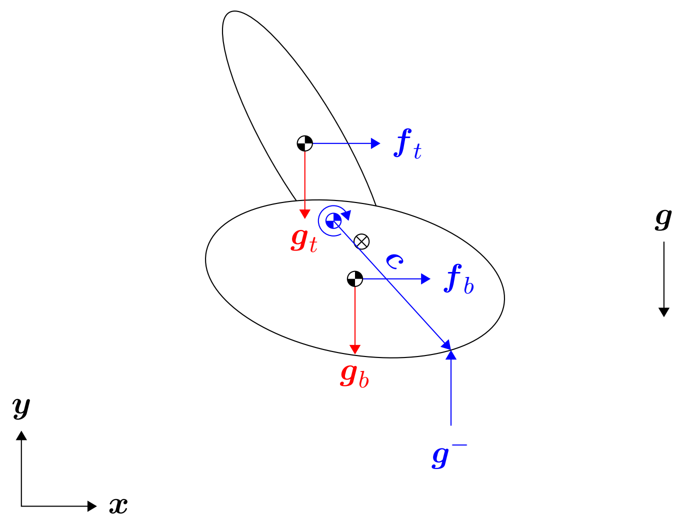
In all of the functions examined here, $\dot{\theta}_b$ is either being minimised or controlled. If it is being minimised it is due to a disturbance by unbalanced external forces that would otherwise push the robot into an unstable state. If it is being controlled it is deliberately changing the orientation of the robot in order to achieve an objective, such as skidding in order to change direction or landing vertically on a wall to climb up it .

3.2 Aerial Reorientation

3.2.1 Rigid Body Model

Many robots use jumping as a means of locomotion, or to reach otherwise inaccessible areas . Other robots are designed to drive off ledges . The "jump" can be described as impulse forces $\boldsymbol{f}_n$ on one or more points on the main robot body (such as the foot of a leg), where $\boldsymbol{r}_n$ describe the vectors from the robot COM to the points. As long as $\sum_{i=1}^{n} \boldsymbol{f}_i + (m_b + m_t)\boldsymbol{g} > (m_b + m_t)\boldsymbol{g}$, where $\boldsymbol{g}$ is the gravity vector, then the robot will be lifted into the air. However, if $\sum_{i=1}^{n} \boldsymbol{f}_i \times \boldsymbol{r}_i \neq \boldsymbol{0}$, then $\boldsymbol{T} \neq \boldsymbol{0}$, and therefore $\ddot{\theta}_b \neq 0$. This could result in the robot landing with an orientation that prevents locomotion or causes damage to the robot. This is certain to occur to some extent in a practical application, as even if all the contact points are evenly spaced from the COM ($\sum_{i=1}^{n} \boldsymbol{r}_i = \boldsymbol{0}$), all the elements of $\boldsymbol{f}_n$ are never going to be exactly equal due to differences in actuation.

In order to reduce this rotation so the robot remains stable, the pivot torque can provide an opposing torque on the model such that θ_b remains within an acceptable interval for stability upon landing. This can be done by keeping $\boldsymbol{T}$ as small as possible. Or rotation may want to be controlled so the robot's orientation is changed to a new interval that is stable for a new environment, such as climbing a wall. In which case, a controller can output a desired $\boldsymbol{T}$ for an angle error $q - \theta_b$, where q is the desired body angle.

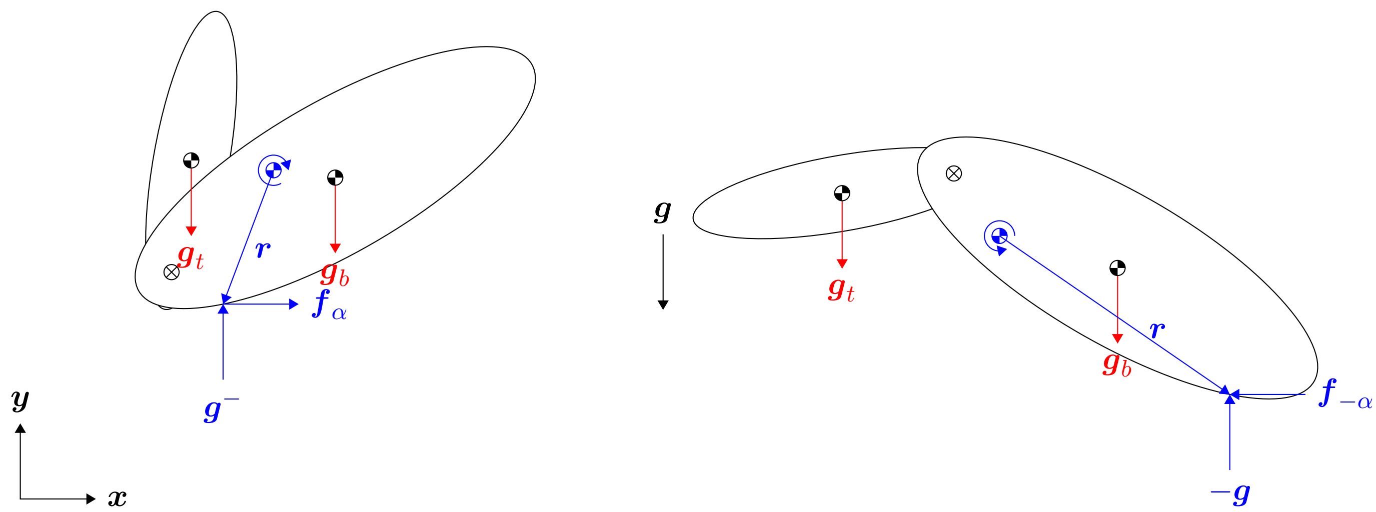


$$
\begin{aligned}
\hat{\tau} &= \sum_{i=1}^{n} \boldsymbol{f}_i \times \boldsymbol{r}_i \\
\hat{\boldsymbol{f}}_b &= \boldsymbol{\rho}_b \times \hat{\tau}\boldsymbol{z} \\
\hat{\boldsymbol{f}}_t &= \boldsymbol{\rho}_t \times \hat{\tau}\boldsymbol{z} \\
\boldsymbol{T} &= \boldsymbol{\rho}_b \times \left(\boldsymbol{f}_b + \hat{\boldsymbol{f}}_b\right) + \boldsymbol{\rho}_t \times \left(\boldsymbol{f}_t + \hat{\boldsymbol{f}}_t\right) = \boldsymbol{\rho}_b \times \boldsymbol{f}_b + \boldsymbol{\rho}_t \times \boldsymbol{f}_t + \hat{\tau}
\end{aligned}
\tag{2}
$$

3.3 Centrifugal Force Compensation

When a robot is turning at speed, the effects of centrifugal force can be significant. Depending on the height between the COM and the ground, this can result in a significant torque on the robot which can cause it to tip over during the turn once θ_b is outside a stable interval. The centrifugal force can be modelled as a force $\boldsymbol{f}_{b,t}$ on the body and tail of the model in the opposite direction to the turn. These depend on the mass of the body, the velocity of the robot v and the radius r of the turn. There is also a ground reaction force $-\boldsymbol{g}$ which acts on the contact point with the ground furthest in the centrifugal force direction.

In order to maintain θ_b within a stable interval, the tail can be used to shift the COM of the robot in the opposite direction of the centrifugal force. This may normally cause θ_b to be outside the other bound of the stable interval when the robot is not in a turn, but during the turn can be used to maintin stability as long as the position of the tail is reset once the turn is complete. This again can be done by keeping $\boldsymbol{T}$ as small as possible.



$$
\begin{aligned}
\boldsymbol{f}_b &= m_b \frac{v^2}{r}\boldsymbol{x} \\
\boldsymbol{f}_t &= m_t \frac{v^2}{r}\boldsymbol{x} \\
\boldsymbol{g}_b &= m_b \boldsymbol{g} \\
\boldsymbol{g}_t &= m_t \boldsymbol{g} \\
\boldsymbol{g}^- &= (m_b + m_t) \times -\boldsymbol{g} \\
\boldsymbol{T} &= \boldsymbol{\rho}_b \times (\boldsymbol{g}_b + \boldsymbol{f}_c) + \boldsymbol{\rho}_t \times (\boldsymbol{g}_t + \boldsymbol{f}_c) + \boldsymbol{c} \times \boldsymbol{g}^-
\end{aligned}
\tag{3}
$$

3.4 Start/Stop Inertia Compensation

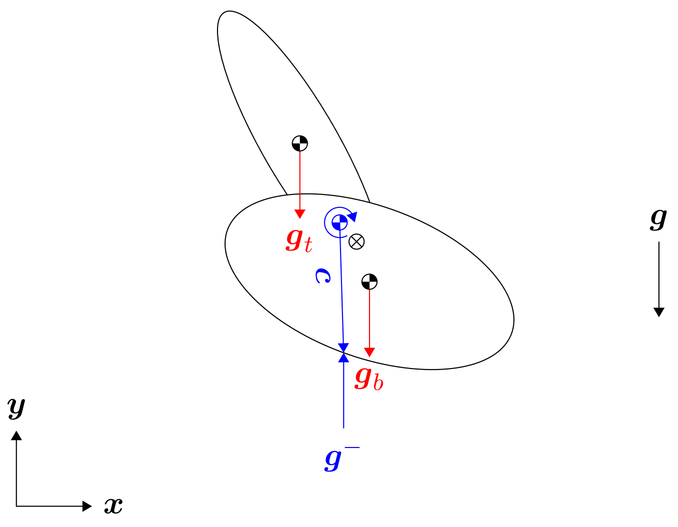
Much like when a robot turns at speed, when the robot starts and stops there are forces on the robot which can induce enough torque to cause instability. These are the acceleration $\boldsymbol{f}_\alpha$ and braking $\boldsymbol{f}_{-\alpha}$ forces which act on the contact point between the robot and the ground furthest in the direction of the force. This will cause the robot to tip forward or back, potentially putting θ_b outside the stable interval. These forces are generated by the actuation of legs, wheels, or other locomotion device, and depend on the robot's rate of acceleration and decelration.

Maintaining a stable interval involves a similar method to centrifugal force compensation, moving the tail to shift the COM.

$$
\boldsymbol{T} = \boldsymbol{\rho}_b \times \boldsymbol{g}_b + \boldsymbol{\rho}_t \times \boldsymbol{g}_t + \boldsymbol{r} \times \left(\boldsymbol{f}_{\alpha,-\alpha} + \boldsymbol{g}^-\right) \tag{4}
$$

3.5 Walking Stability

This function has a particularly broad scope, but can be generally considered in a similar fashion to centrifugal force compensation, but without the centrifugal force. Instead the instability can be caused by the suddenly changing location of ground reaction forces due to rough terrain , or an unpredictable external disturbance such as an impact Briggs et al. (2012). A simple example of this function can be modelled on an inverted double pendulum, analogous to walking on a tightrope. Even minute changes in ground



reaction force or very lateral small disturbances, will, if uncompensated, inevitably lead to θ_b being outside a stable interval.

Maintaining stability is again, similar to centrifugal force compensation, shifting the COM of the robot to counteract the change or disturbance.

$$\begin{aligned}
\boldsymbol{g}_b &= m_b \boldsymbol{g} \\
\boldsymbol{g}_t &= m_t \boldsymbol{g} \\
\boldsymbol{g}^- &= (m_b + m_t) \times -\boldsymbol{g} \\
\boldsymbol{T} &= \boldsymbol{\rho}_b \times \boldsymbol{g}_b + \boldsymbol{\rho}_t \times \boldsymbol{g}_t + \boldsymbol{c} \times \boldsymbol{g}^-
\end{aligned} \tag{5}$$

3.6 Induced Steering

This function is very similar to aerial reorientation in its model, but with no gravity to consider as the robot is on the ground. In this case the objective is to rotate the entire robot around the z axis for the purposes of changing the direction of locomotion. This can be achieved by changing the resultant torque T by changing τ for a target θ_b. This is useful for small, light robots where the friction force is low, allowing the robot to "skid" across a surface.

$$\boldsymbol{T} = \boldsymbol{\rho}_b \times \boldsymbol{f}_b + \boldsymbol{\rho}_t \times \boldsymbol{f}_t \tag{6}$$

3.7 Other Functions

4 DISCUSSION

4.1 Anthropomorphism

5 CONCLUSION

The desire for mobile robotic systems which can explore hazardous and extreme environments has led to the development of systems which have greater functionality, adaptability, autonomy and dynamic ability. The capability of mobile robots which can walk, run, hop and jump, has created a need for the investigation and development of systems which can improve dynamic performance and robustness of outcome. Many research groups have developed robotic tail models and physical systems for the purpose

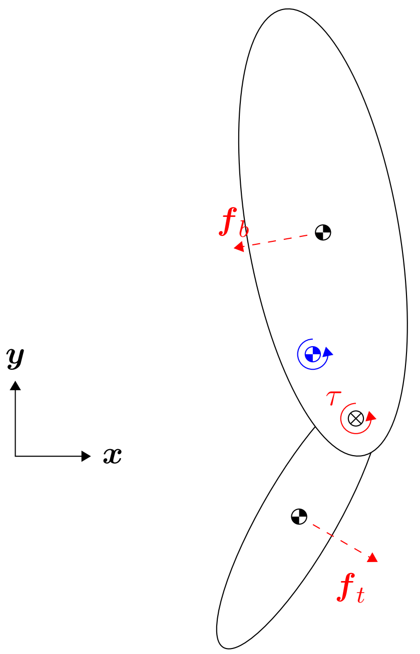


Figure 4.

of improving the dynamic performance of mobile robots. Mobile robots utilising tail actuators have demonstrated improvements in performance, predominately these have a limited number of degrees of freedom. Barriers that may inhibit the development of robotic tail systems for mobile robots include the additional storage/drain on system energy supply, high performance low mass actuation for multiple degrees of freedom and complexity of control. There is clearly the potential for further research in this field, which could see improved dynamic performance, and robustness for mobile robotic systems. Robotic tails offer great potential to improve the dynamic performance of mobile robotic platforms. Research in this area has grown over the last 10 years with modelling/simulation and experimental approaches adopted, demonstrating robotic tails can improve performance. The authors hope that this scoping review will provide a useful reference for those research groups working in this area and those who wish to contribute in the future.

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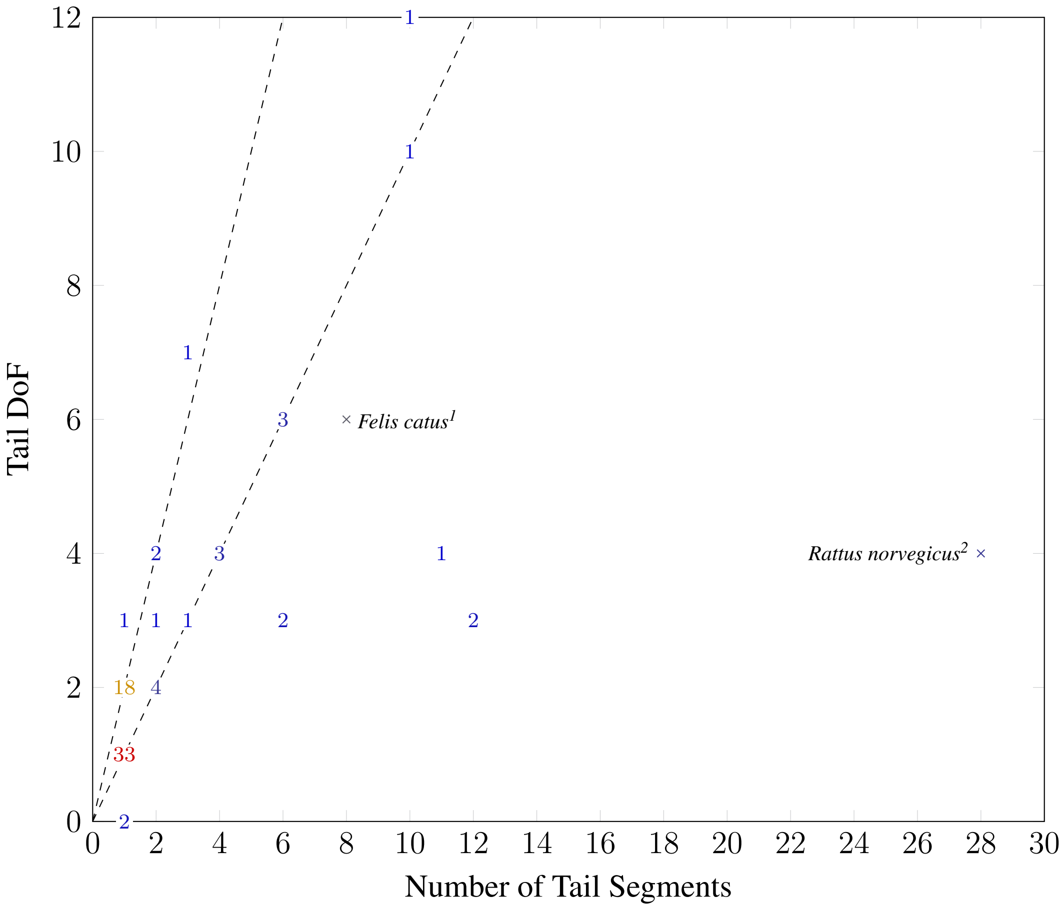

[1]Wada et al. (1994), [2]Hori et al. (2011)

Figure 5. Number of papers plotted against the number of tail segments and tail DoF. Dashed lines indicate where each segment has one and two DoF, the most common configurations. Underactuated tails have more segments than DoF.

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Table 1. Comparison of Robot Locomotion to Tail Dimension Class.

Locomotion	**Tail Dimension Class**					**Total**
	1	2	3	4	0 (Static)	
Walking	9	0	3	0	0	*12*
Hopping	1	2	1	0	0	*4*
Wheeled	2	1	2	1	1	*7*
Wheeled, Hopping	1	0	0	0	0	*1*
Tracked	1	0	0	0	0	*1*
None	1	1	2	4	0	*8*
Total	*15*	*4*	*8*	*5*	*1*	*33*

Table 2. 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**
Kessens and Dotterweich (2017)	3DoF No Catch	2017
Heim et al. (2016)	Cheetah-Cub	2016
Saab et al. (2018a)	DMST	2018
Xiuli et al. (2016)	Dcat	2016
Patel and Braae (2014, 2013)	Dima	2013
Patel and Boje (2015)	Dima II	2015
Guarnieri et al. (2009)	Helios VIII	2009
Ren and Hong (2010); Ren et al. (2009)	IMPASS	2009
Casarez and Fearing (2018)	LoadRoACH	2018
Briggs et al. (2012)	MIT Cheetah	2012
Jianguo et al. (2015a,b, 2013)	MSU Tailbot	2013
McInroe et al. (2016)	MuddyBot	2016
Pullin et al. (2012)	OctoRoACH	2012
De and Koditschek (2018); Shamsah et al. (2018); Wenger et al. (2016); De and Koditschek (2015); Brill et al. (2015)	Penn Jerboa	2015
Saab et al. (2018c)	R3-RT	2018
Kwak and Bae (2015)	RoMiRAMT	2015
Kohut et al. (2013, 2012)	TAYLRoACH	2012
Libby et al. (2012); Chang-Siu et al. (2011)	Tailbot	2011
Takita et al. (2003, 2002b,a)	Titrus III	2002
Rone et al. (2018)	USRT	2018
Casarez and Fearing (2017)	VelociRoACH	2017
Libby et al. (2016); Johnson et al. (2012)	XRL/RHex	2012
Berenguer and Monasterio-Huelin (2008)	Zappa	2008
Simon et al. (2018)	-	2018
Casarez et al. (2013)	-	2013
Chang-Siu et al. (2013)	-	2013
Jusufi et al. (2010)	-	2010
Guan-Horng et al. (2014)	-	2014
Aiello and Crespo (2013)	-	2013
Sato et al. (2016)	-	2016
Santiago et al. (2016)	-	2016
Kim and Shell (2018, 2017)	-	2017
Jovanova et al. (2018)	-	2018

Table 3. Table of the physical robots. "Tail DoF" refers to the total number of DoF, including passive joints. Robots with passive DoF are denoted with a superscript. Number of decimal places reflects the precision found in the references.

Reference	Locomotion	Tail Structure	Number of Segments	Tail Dimension Class	Tail DoF	Actuator	Tail Mass (kg)	Body Mass (kg)	Tail Length (m)
Kessens and Dotterweich (2017)	None	Rigid	2	4	3	Revolute Motor	0.33	0.99	N/A
Heim et al. (2016)	Walking	Rigid	1	1	1	Revolute Motor	0.053	1.197	0.128, 0.168
Saab et al. (2018a)	None	Pseudo-Flexible	2	3	2	Revolute Motor[3]	3.5	9.525	0.3
Xiuli et al. (2016)	Walking	Rigid	1	1	1	Revolute Motor	0.25	5.312	0.3
Patel and Braae (2014, 2013)	Wheeled	Rigid	1	3	2	Revolute Motor	0.4	5	0.5
Patel and Boje (2015)	Wheeled	Rigid	1	3	2	Revolute Motor	0.4	5	0.5
Guarnieri et al. (2009)	Tracked	Rigid	1	1	1	Revolute Motor	N/A	N/A	0.5
Ren and Hong (2010); Ren et al. (2009)	Wheeled	Rigid	1	0	0[1]	Static Tail	N/A	N/A	0.889
Casarez and Fearing (2018)	Walking	Rigid	1	1	1	Revolute Motor	N/A	N/A	0.09
Briggs et al. (2012)	Walking	Rigid	1	3	2	Revolute Motor	0.74	35	0.54
Jianguo et al. (2015a,b, 2013)	Wheeled, Hopping	Rigid	1	1	1	Revolute Motor	0.017	0.0252	0.127
McInroe et al. (2016)	Walking	Rigid	1	3	2	Revolute Motor	N/A	N/A	0.02
Pullin et al. (2012)	Walking	Rigid	1	1	1	Revolute Motor	0.017	0.035	0.1
De and Koditschek (2018); Shamsah et al. (2018); Wenger et al. (2016); De and Koditschek (2015); Brill et al. (2015)	Hopping	Rigid	1	3	2	Revolute Motor	0.15	2.269	0.21
Saab et al. (2018c)	None	Pseudo-Flexible	2	2	2	Revolute Motor	N/A	8.8	N/A
Kwak and Bae (2015)	Wheeled	Rigid	2	2	2	Revolute Motor	N/A	N/A	N/A
Kohut et al. (2013, 2012)	Walking	Rigid	1	1	1	Revolute Motor	0.004	0.045	0.115
Libby et al. (2012); Chang-Siu et al. (2011)	Wheeled	Rigid	1	1	1	Revolute Motor	0.017	0.16	0.127
Takita et al. (2003, 2002b,a)	Walking	Rigid	1	3	2	Revolute Motor	0.1	0.1	N/A
Rone et al. (2018)	None	Rigid	6	4	6	Revolute Motor[3]	0.51	6.507	0.48
Casarez and Fearing (2017)	Walking	Rigid	1	1	1	Revolute Motor	0.008	0.0767	0.09
Libby et al. (2016); Johnson et al. (2012)	Walking	Rigid	1	1	1	Revolute Motor	0.6	8.1	0.59
Berenguer and Monasterio-Huelin (2008)	Walking	Rigid	1	1	1	Revolute Motor	0.7	0.05	0.15
Simon et al. (2018)	Hopping	Flexible	4	2	4	Revolute Motor[3]	0.047	N/A	0.21
Casarez et al. (2013)	Walking	Rigid	1	1	1	Revolute Motor	0.005	0.0395	0.12
Chang-Siu et al. (2013)	None	Rigid	1	3	2	Revolute Motor	0.07	0.105	0.73
Jusufi et al. (2010)	None	Rigid	1	1	1	Spring	0.048	0.204	N/A
Guan-Horng et al. (2014)	Hopping	Rigid	1	1	1	Revolute Motor	0.371	0.423	0.177
Aiello and Crespo (2013)	Wheeled	Rigid	1	1	1	Revolute Motor	0.089	0.862	0.27
Sato et al. (2016)	Hopping	Pseudo-Flexible	6	2	6[2]	Revolute Motor	0.1	1.045	0.235
Santiago et al. (2016)	None	Flexible	2	4	4	Revolute Motor[3]	N/A	N/A	0.41
Kim and Shell (2018, 2017)	Wheeled	Flexible	∞	4	∞	Unactuated	0.035	0.7	0.7
Jovanova et al. (2018)	None	Flexible	3	4	7	Revolute Motor	N/A	N/A	N/A

[1](Static) [2](1 Active, 5 Passive) [3](Cable Driven)

Table 4. Table of all the papers that did not use physical robots. "Tail DoF" refers to the total number of DoF, including passive joints. Papers with passive DoF are denoted with a superscript. Number of decimal places reflects the precision found in the references.

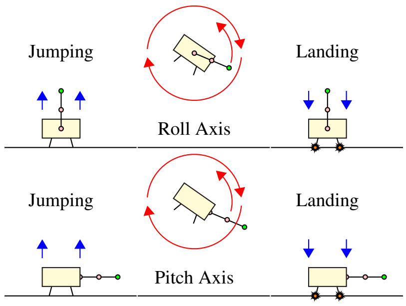
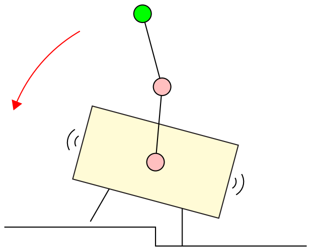
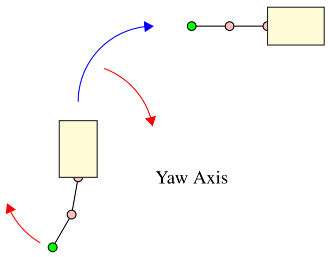
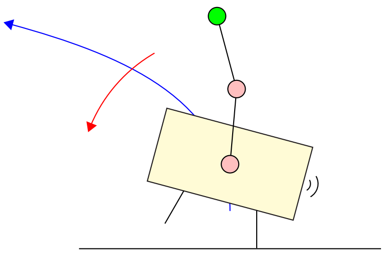
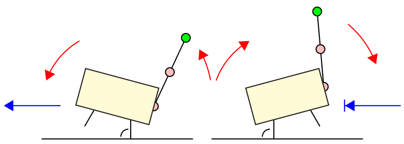
Reference	Locomotion	Tail Structure	Number of Segments	Tail Dimension Class	Tail DoF	Actuator	Tail Mass (kg)	Body Mass (kg)	Tail Length (m)
Berenguer and Monasterio-Huelin (2007)	Walking	Rigid	1	1	1	N/A	0.7	N/A	0.15
Graichen and Hentzelt (2015)	Hopping	Rigid	1	1	1	N/A	N/A	N/A	N/A
Iwamoto and Yamamoto (2015)	Wheeled	Pseudo-Flexible	10	1	10[1]	Revolute Motor	0.307	N/A	0.2
Iwamoto and Nishikawa (2018)	N/A	Rigid	N/A	N/A	Multiple	N/A	N/A	N/A	N/A
Karakasiliotis et al. (2012)	Walking	Flexible	10	2	12[2]	N/A	1327.96 (mg)	N/A	0.2659
Xiaoyun et al. (2015)	Wheeled	Rigid	1	1	1	N/A	N/A	N/A	N/A
Liu and Ben-Tzvi (2018)	Walking	Rigid	1	3	2	N/A	1.4347	26.9078	0.6
Machairas and Papadopoulos (2015b)	Walking	N/A	1	1	1	N/A	N/A	N/A	N/A
Machairas and Papadopoulos (2015a)	N/A	Rigid	1	1	1	N/A	0.5-4	N/A	0.2-0.5
Mutka et al. (2013)	Walking, Hopping	Rigid	1	3	2	N/A	N/A	N/A	0.1
Patel and Braae (2015)	Walking	Rigid	1	1	1	N/A	1	N/A	0.8
Rone and Ben-Tzvi (2014)	None	Flexible	1/2	3/4	2/4	Linear Screw Motor[3]	2.25	N/A	0.5
Rone and Ben-Tzvi (2015)	None	Pseudo-Flexible	2	3	4	Cable Driven	0.33585	N/A	0.44
Rone and Ben-Tzvi (2016)	Walking	Rigid	6	2	1–6	N/A	2.4	N/A	0.5
Rone et al. (2017)	None	Rigid	6	4	6	N/A	0.449	N/A	0.48
Rone and Ben-Tzvi (2017)	Walking	Pseudo-Flexible	12	4	3	Revolute Motor	3.96	N/A	0.5118
Saab and Ben-Tzvi (2016)	Walking	Pseudo-Flexible	2	3	2	Revolute Motor[3]	1	N/A	0.12
Saab and Ben-Tzvi (2017)	Walking	Rigid	1	1	1	N/A	0.3	15	1.0
Sadati and Meghdari (2017)	Walking	Rigid	1	3	2	N/A	0.026, 0.00753	N/A	0.106, 0.116
Shin et al. (2011)	Wheeled	Rigid	1	1	1	N/A	N/A	N/A	N/A
Yu et al. (2017)	Hopping	Rigid	1	1	1	N/A	1.5	28.5	0.4

[1](1 Active, 9 Stiffness Adjustment) [2](10 Active, 2 Passive) [3](Cable Driven)

Table 5. Comparison of control system classification with paper structure. In addition to the classifications specified in figure **??**, *0* indicates a tail with no control system.

	Control System Classification					
Paper Category	N/A	0	1	2	3	4
Abstract Model	Machairas and Papadopoulos (2015b); Rone and Ben-Tzvi (2014, 2016); Saab and Ben-Tzvi (2017)	Ren and Hong (2010)	Berenguer and Monasterio-Huelin (2007)	-	Graichen and Hentzelt (2015); Iwamoto and Yamamoto (2015); Mutka et al. (2013); Patel and Braae (2015); Xiaoyun et al. (2015); Yu et al. (2017)	Machairas and Papadopoulos (2015a); Sadati and Meghdari (2017); Shamsah et al. (2018); De and Koditschek (2018)
Modelling & Simulation	Rone and Ben-Tzvi (2015); Saab and Ben-Tzvi (2016); Shin et al. (2011); Rone et al. (2017); Iwamoto and Nishikawa (2018)	-	Karakasiliotis et al. (2012)	-	Rone and Ben-Tzvi (2017); Liu and Ben-Tzvi (2018)	-
Experimental	Brill et al. (2015)	Jusufi et al. (2010); Kim and Shell (2017); Ren et al. (2009); Kim and Shell (2018)	Casarez et al. (2013); Kohut et al. (2012); Patel and Boje (2015); Simon et al. (2018); Jovanova et al. (2018)	Berenguer and Monasterio-Huelin (2008); Heim et al. (2016); Kessens and Dotterweich (2017); Kwak and Bae (2015); McInroe et al. (2016); Santiago et al. (2016); Sato et al. (2016); Takita et al. (2002a,b, 2003); Xiuli et al. (2016); Rone et al. (2018); Saab et al. (2018a); Casarez and Fearing (2017, 2018)	Briggs et al. (2012); Chang-Siu et al. (2011); Jianguo et al. (2013, 2015b,a); Johnson et al. (2012); Kohut et al. (2013); Libby et al. (2012, 2016); Patel and Braae (2013)	Aiello and Crespo (2013); Chang-Siu et al. (2013); De and Koditschek (2015); Guarnieri et al. (2009); Guan-Horng et al. (2014); Patel and Braae (2014); Pullin et al. (2012); Wenger et al. (2016); Saab et al. (2018c)

Table 6. Non-unique tail functions operating in free space.

Function	Diagram	Description	Papers
Aerial Reorientation		The robot either jumps or moves off an edge. Whilst airborne, the tail is used to correct any torques induced on the robot so it lands with the correct orientation. This can be in the pitch or roll axis.	Briggs et al. (2012); Chang-Siu et al. (2011); De and Koditschek (2015); Jianguo et al. (2013, 2015b,a); Johnson et al. (2012); Libby et al. (2012, 2016); Guan-Horng et al. (2014); Wenger et al. (2016); Shamsah et al. (2018); De and Koditschek (2018); Yu et al. (2017) (Total: **14**)
Locomotion Stability	 Roll Axis	The robot walks or drives over a rough surface. The tail is used to correct torques induced by the unstable motion of the robot to prevent it falling over.	Berenguer and Monasterio-Huelin (2008); Heim et al. (2016); Takita et al. (2002a,b, 2003); Xiuli et al. (2016); Rone et al. (2017, 2018); Simon et al. (2018); Saab et al. (2018a); Iwamoto and Nishikawa (2018); Liu and Ben-Tzvi (2018); Saab et al. (2018c) (Total: **13**)
Induced Turning		The tail is used to initiate a yaw torque on the robot, enabling it to have a smaller turning circle.	Casarez et al. (2013); Kohut et al. (2012); Pullin et al. (2012); Saab and Ben-Tzvi (2017) (Total: **4**)
Turning Stability	 Roll Axis	When a fast moving robot makes a turn, the tail is used to minimise roll torques to prevent it falling over.	Aiello and Crespo (2013); Kohut et al. (2013); Patel and Braae (2013); Patel and Boje (2015) (Total: **4**)
Velocity Change Stability	 Pitch Axis	When a fast moving robot undergoes acceleration (or deceleration) the tail is used to minimise pitch torques to prevent it falling over.	Kwak and Bae (2015); Patel and Braae (2014) (Total: **2**)