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

Damian Crosby [1,*], Joaquin Carrasco [2], William Heath [2] and Andrew Weightman [1]

[1] *Department of Mechanical, Aerospace and Civil Engineering, School of Engineering, Faculty of Science and Engineering, The University of Manchester, Manchester, United Kingdom*
[2] *Department of Electrical and Electronic Engineering, School of Engineering, Faculty of Science and Engineering, The University of Manchester, Manchester, United Kingdom*

Correspondence*:
Damian Crosby
damian.crosby@manchester.ac.uk

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 5):
  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 3.
  - **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 4):
  - **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 4):
  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.

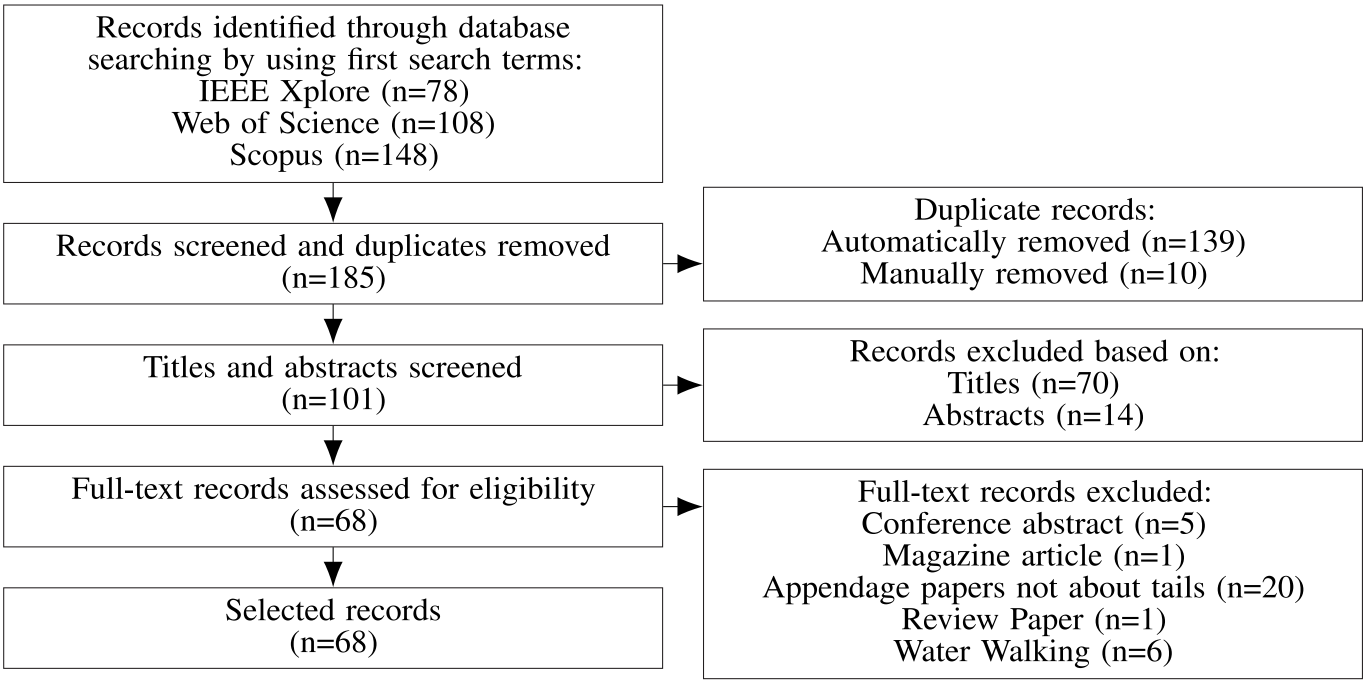


Figure 1. Flowchart of the study selection process.

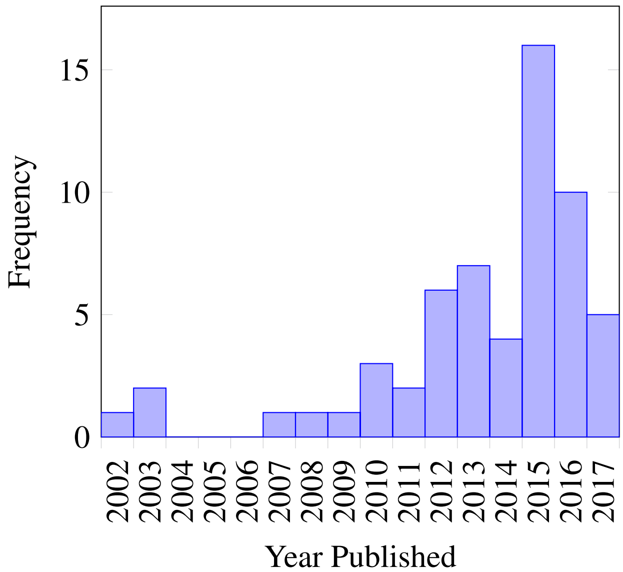


Figure 2. Histogram of the years the 59 selected records were published (note 2017 only includes papers published up to August, so cannot be directly compared with other years).

3 RESULTS

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**).
- 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.

3.1 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.

3.2 Physical Robots

As explained previously, all **Experimental** papers included a physical robot or prototype. In total, 33 unique physical robots were found (*images can be found in the supplementary material, all images have been sourced from selected papers unless specified*). Out of these, 9 were used in multiple papers. 23 named robots were identified from the literature, the rest of the robots had no name and had only a single paper associated with them apart from Kim and Shell (2017) and Kim and Shell (2018). Table 2 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 3 lists the physical robots by their properties. Table 4 lists all the papers that do not have physical robots connected with them.

3.3 Research Objectives of Robots Identified in the Literature

Table 6 shows diagrams of non-unique research objectives that involved the tail operating in free space (i.e. not in contact with the ground or other objects). All of them involved counteracting or reducing torques.

3.3.1 Legged, Wheeled and Tracked

Of the 43 **Experimental** papers that included walking, wheeled, tracked or hopping robots, 11 had the objective of correcting any torques induced on the robot so it lands with the correct orientation (Briggs et al. (2012); Chang-Siu et al. (2011); De and Koditschek (2015); Johnson et al. (2012); Libby et al. (2012, 2016); Guan-Horng et al. (2014); Wenger et al. (2016); Jianguo et al. (2013, 2015b,a)), 8 had the objective of correcting torques induced by the unstable motion of the robot to prevent it falling over (Berenguer and Monasterio-Huelin (2008); Heim et al. (2016); Saab et al. (2018c); Simon et al. (2018); Takita et al. (2002a,b, 2003); Xiuli et al. (2016)), 4 had the objective of minimising roll torques to prevent the robot falling over during a turn (Aiello and Crespo (2013); Kohut et al. (2013); Patel and Braae (2013); Patel and Boje (2015)), and 3 had the objective of initiating 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)). 7 papers dealt with "tail-dragging" robots (Casarez and Fearing (2018); Guarnieri et al. (2009); Kim and Shell (2017, 2018); Kwak and Bae (2015); McInroe et al. (2016); Ren et al. (2009)), that had the tail acting as an appendage for additional stability, locomotion or object manipulation. Briggs et al. (2012) also considered use of a tail (along with rejecting angular momentum) to rebalance the robot following a disturbance, in their example, a "wrecking ball" impacting the torso of the robot. Sato et al. (2016) used the tail to allow their hopping robot to jump higher. The remaining 2 papers (Brill et al. (2015); De and Koditschek (2015)) did not state a specific objective.

3.3.2 No Locomotion

For the 11 papers that dealt with robots with no locomotion, the objectives were more varied. 5 had the objective of testing mechanisms for later inclusion on a legged robot (Rone and Ben-Tzvi (2014); Rone et al. (2017, 2018); Saab et al. (2018a); Iwamoto and Nishikawa (2018)). Chang-Siu et al. (2013) and Jusufi et al. (2010) had the objective of re-orienting a robot when dropped, Santiago et al. (2016) had a tail that was designed to vary its stiffness using a novel mechanism, in order for it to be used as both a "hard" appendage when used as a ground support, and a "soft" appendage for other functions. Kessens and Dotterweich (2017) used the tail as a self-righting mechanism, and Jovanova et al. (2018) considered a novel actuation system for a robot appendage based on a scorpion tail. 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 enablers for the development of the next generation of mobile robotic systems include:

1. Increased simulation capabilities such that designs can be optimised before prototyping,
2. Advances in embedded computing power improving sensing and intelligent control systems. 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 of improving the dynamic performance of mobile robots. Mobile robots utilising tail actuators have demonstrated improvements in performance, and they predominately have a limited number of degrees of freedom (Briggs et al. (2012); Heim et al. (2016); Libby et al. (2016); Sato et al. (2016)). There are several distinct areas for future research.

3.4 Robot Physical Properties

3.4.1 Walking Robots

Of the 12 walking robots, 3 were Bipedal (McInroe et al. (2016); Takita et al. (2002a,b, 2003); Berenguer and Monasterio-Huelin (2008)), 3 were Quadrupedal (Briggs et al. (2012); Heim et al. (2016); Xiuli et al. (2016)), 5 were Hexapedal (Kohut et al. (2012, 2013); Libby et al. (2016); Casarez et al. (2013); Casarez and Fearing (2018)), and 1 was Octopedal (Pullin et al. (2012)). (McInroe et al. (2016)) was Bipedal, but used the tail as a "third leg", technically making it Tripedal.

3.5 Tail Physical Properties

3.5.1 Tail Structure

Table 3 illustrates that a rigid tail, made up of rigid bodies connected by joints, is the commonest physical tail structure with 31 robots, followed by a flexible structure, made up of flexible bodies that act as joints, with 4 robots, and pseudo-flexible, made up of a large number of mostly passive rigid joints that closely approximate a flexible body, with 3 robots (Figure 3 gives an illustration of this difference). Most of the non rigid robots were static experiments with no locomotion, apart from (Kim and Shell (2017, 2018)), though several (Rone et al. (2018); Saab et al. (2018a,c)) were testing static systems with an eventual aim of mounting on a legged robot.

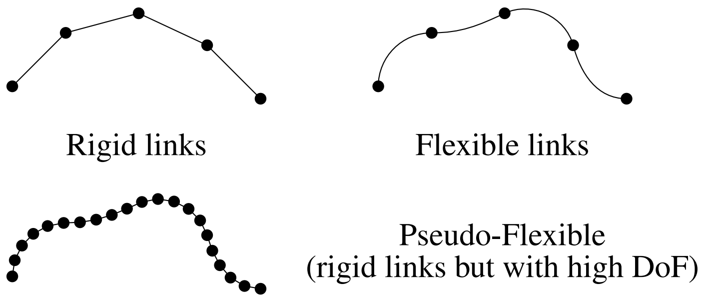


Figure 3. Tail structure classification. Black dots indicate individual joints which may be active or passive.

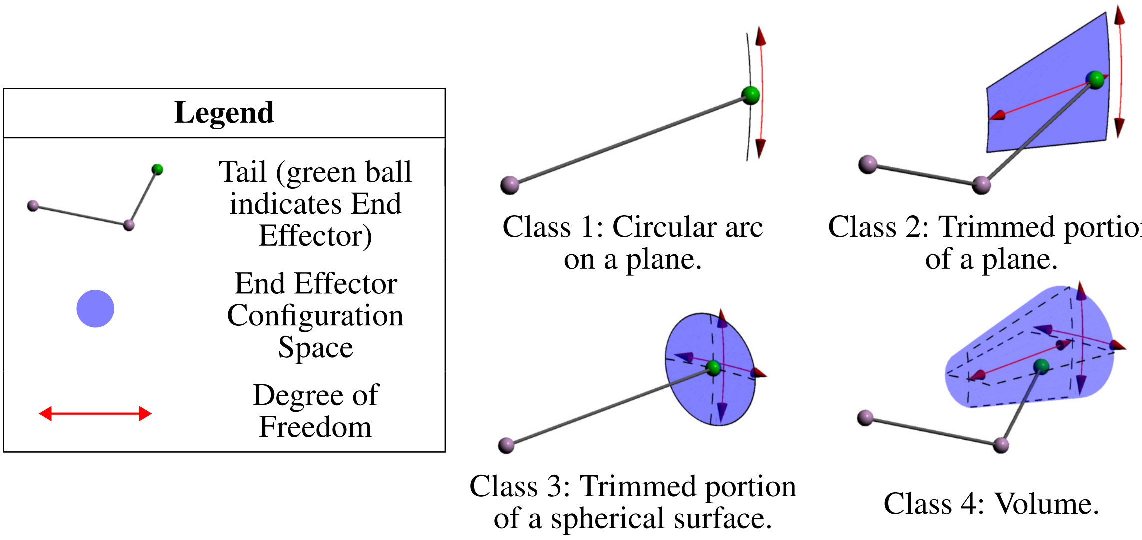


Figure 4. Tail Dimension Class visual illustration.

3.5.2 Tail Segmentation

Table 3 illustrates that 22 robots had one tail segment, and 9 robots had more than one tail segment. Out of the 9 robots with more than one tail segment: 5 had 2-segments, 1 had 3-segments, 1 had 4-segments and 2 had 6-segments. Kim and Shell (2017, 2018) was a piece of unactuated flexible rope, which could be considered to have a nearly infinite number of segments. A common justification for an increased number of segments was the increased reaction torque available for a given length, as found in Rone and Ben-Tzvi (2016). This came at the cost of requiring additional actuators, except in Sato et al. (2016) which used a passive system, though the gains were marginal in that case (a 7% increase in jump height).

3.5.3 Tail Dimension Class

Tables 3 and 1 illustrate that 17 robots had a tail dimension class of **1**, where the range of motion for the tail end effector is restricted to a circular arc on a plane, typically a simple "pendulum" design of a mass on the end (or along) a rod of negligible mass with a rotary joint that allowed the robot to adjust its moment of inertia in one axis when performing a manoeuvre. 9 robots had a similar design but with an extra degree of freedom to turn the the single revolute joint into two perpendicular revolute joints, giving the tail a dimension class of **3**, where the end effector range is restricted to the trimmed surface of a sphere, typically for the purpose of allowing the robot to induce torques in two axes instead of one (such as aerial reorientation in both pitch and roll axes). Inducing torques in all three axes did not appear to be considered, as in stability applications maintaining yaw angle was not required. More complicated multi-segment designs were also found in 9 robots, which all had a tail dimension class of **2**, where the end effector is restricted to a planar cross-section of a volume, or **4**, where the end effector is free to move within a volume, typically for increased reaction torques as mentioned previously (Figure 4 gives an illustration of the different classes). Finally, 3 robots had a static tail. Of the 12 physical robots which have been developed for walking, 9 had a tail dimension class of **1**, and 3 robots had a class of **3**. For the other types of locomotion, hopping, wheeled, wheeled and hopping, and tracked there were too few papers and different class categories to determine correlations.

3.5.4 Tail Degrees of Freedom

As can be seen from Table 1, 17 robots had 1 degree of freedom, 11 robots had 2 degrees of freedom, 1 robot had 3 DoF, 2 robots had 4 DoF, 1 robot had 6 DoF and 1 robot had 7 DoF. 1 robot had a static tail (Ren et al. (2009); Ren and Hong (2010)) and 1 robot (Kim and Shell (2017, 2018)) had an unactuated rope which had infinite degrees of freedom. Higher degrees of freedom than 2 exclusively corresponded to multi-segment designs with the corresponding performance improvements, whereas 2 degrees of freedom was a mix of additional torque axis (dimension class 3) and multi-segment designs (dimension class 2).

3.6 Tail Actuation

As can be seen from Table 3, 26 robots, or 91% used a **Revolute Motor** to actuate the tail. 4 robots used revolute motors to move cables via pulleys. For the other 9%, 1 robot had a static tail (Ren et al. (2009); Ren and Hong (2010)), 1 robot had an unactuated completely passive tail (Kim and Shell (2017, 2018)), and 1 robot also used stored energy via a spring instead of stored electrical energy (Jusufi et al. (2010)).

3.7 Control Systems

3.7.1 Controller/Model

As can be seen in Figure 5, each system can be described as having a Controller/Model, where the commands for controlling the tail actuators (whether real or virtual) are generated. These can be described as “fixed” or “variable”. Fixed systems (type 1 and type 2) do not accept external input from the robot, running a periodic sequence or pattern, or following remote commands sent by a user. This is a simple control system to implement, and in some highly deterministic stability applications or experiments it is sufficient for satisfactory performance. Variable systems (type 3 and type 4) use sensor data from the robot to influence the output of the Controller/Model, typically when using the tail to correct or induce force, in a quasi feedback loop (Figure 5 shows a block diagram of each controller/model). As can be seen in Table 5, 7 papers described a type 1 (open-loop) system, 15 papers described a type 2 (inner-loop) system (typically due to the use of servo motors, which turn any system they are implemented in into at least inner-loop), 18 papers described a type 3 (outer-loop) system, and 13 papers described a type 4 (multi-loop) system. 5 papers were either static or uncontrolled systems, and 10 papers did not consider, or did not have enough information to determine, a control system.

There didn’t appear to be any noticeable correlations between the control system and other properties of the robots, as it depended on the experimental setup, and whether the system was designed to apply to determined torques induced by robot actions (such as a walking or hopping motion) or undetermined torques from the environment (such as driving off a ledge or navigating uneven terrain).

3.7.2 Feedback Control Systems

For position feedback of the tail joints (type 2 and type 4), P (Berenguer and Monasterio-Huelin (2008)), PD (Berenguer and Monasterio-Huelin (2008); Chang-Siu et al. (2013); Guan-Horng et al. (2014); Machairas and Papadopoulos (2015a); Sato et al. (2016)), PI (Patel and Braae (2014)), PID (Kwak and Bae

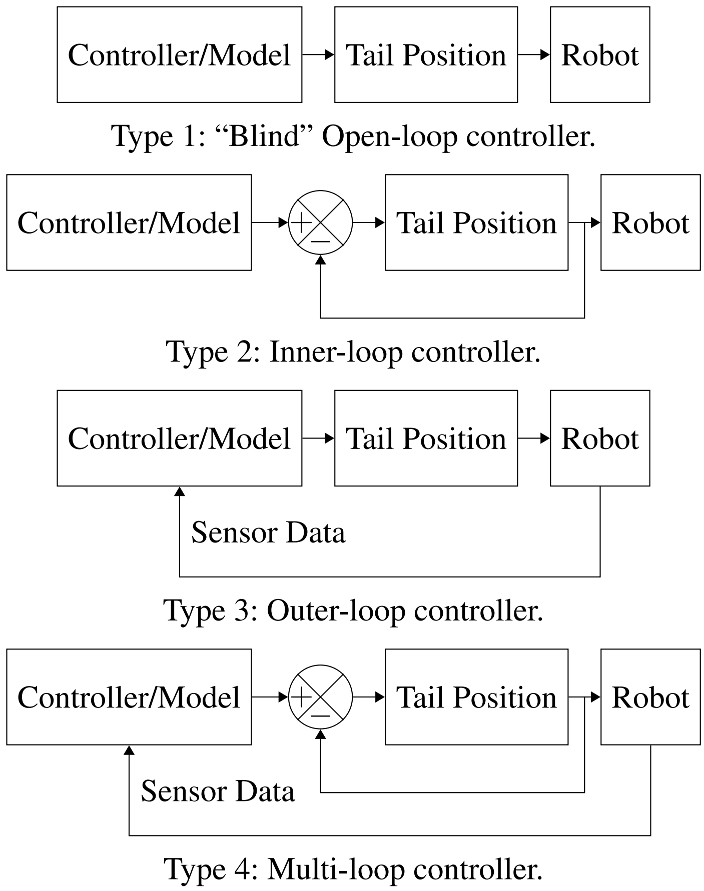


Figure 5. Control system classification for robotic tails.

(2015); Pullin et al. (2012); Casarez and Fearing (2017); Saab et al. (2018c)) and State Feedback (Patel and Braae (2014)) control systems were used.

For variable Controller/Model systems (type 3 and type 4), P (Chang-Siu et al. (2013); Mutka et al. (2013)), PD, (Chang-Siu et al. (2011, 2013); Graichen and Hentzelt (2015); Jianguo et al. (2013, 2015b); Johnson et al. (2012); Libby et al. (2012, 2016); Machairas and Papadopoulos (2015a); Rone and Ben-Tzvi (2017); Xiaoyun et al. (2015)), PI (Patel and Braae (2013, 2014)) PID (Pullin et al. (2012)) and State Feedback (Patel and Braae (2013)) control systems relating sensor data to tail joint position. Kohut et al. (2013) used a simple Bang/Bang control system due to the variable friction present on the model.

Regarding performance of different control systems, Berenguer and Monasterio-Huelin (2007) outlined a simulation comparing a P and PD control law, and found a marginal but noticeable increase in performance in the PD control law (a 6% increase in "crossed distance" and a 9% reduction in mechanical energy), and Jianguo et al. (2015b) compared PD and sliding mode control, again finding an increase in performance (a 75% reduction in overshoot for the tail controller) for sliding mode control.

3.8 Locomotion/Tail Dimension Class

Table 1 shows the relationship between the robot locomotion and the tail dimension class. Class 1 was the most prevalent in all of the mobile robots, followed by class 3, whereas static experiments typically used more complex tails. Tail dimension class was generally associated with the axes the tail was designed to induce torques on, with class 1 only able to induce torque on a single axis, and class 2 being a multi segment version of class 1. Class 3 and 4 could induce torques on 2 or more axes, allowing for enhanced functionality, such as being able to control both the pitch and roll angle of the robot in aerial reorientation.

4 DISCUSSION

4.1 Potential Future Research

4.1.1 Dynamically Changing Plant

All the studies appear to consider robots (when without their tails) that had a static mass, centre of mass and tensor of inertia. Future work could consider robots with these properties changing dynamically. It is likely that mobile robotic systems will pick up and manoeuvre payloads, carry unstable payloads such as a container filled with fluid, or will have an appendage such as a manipulator arm that is independent of locomotion. As such there will be a motivation for robotic tails to be utilised to compensate for this dynamic behaviour.

4.1.2 Energy Consumption and Storage

The use of energy in control systems is a well understood topic that has been the subject of many publications, such as Ortega et al. (2001), hence the control of the tail may be associated with the consumption of energy. However, the literature reviewed does not indicate there has been significant consideration regarding the energy consumption of the robotic tails. There are some calculations presented regarding peak power output in order to determine actuator specifications (Johnson et al. (2012)), but nothing considering actual energy consumption. There is likely to be a trade-off between energy consumption and the improved robot agility that a robotic tail enables. Furthermore, there are few details in the literature regarding the energy storage needs to enable the increased actuation of a robotic tail, clearly additional storage needs will add mass and therefore impact the dynamic behaviour of the mobile robotic system. The authors would encourage the community to provide more details regarding their systems to enable comparisons between different actuator, sensor and controller configurations.

4.2 Actuator Technologies

The choice of actuator for mobile robotics systems is crucial for achieving the potential increased agility desired. DC brushed and brushless electric motors offer good speed and torque characteristics but will add significant mass and for large numbers of degrees of freedom increase control complexity. Stepper motors decrease control complexity in comparison to DC brushed/brushless motors but will add significant mass and have limited capability for high-speed operation. Relative to electric motor solutions artificial muscles are much lighter whilst having suitable force characteristics, their main limitations include hysteretic behaviour and bandwidth. The search for low mass, high force/torque, high bandwidth actuators will no doubt continue.

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 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.

REFERENCES

Aiello, A. and Crespo, J. (2013). Using a tail-like appendage system to control roll movement in wheeled robots. In *Intelligent Engineering Systems (INES), 2013 IEEE 17th International Conference on* (IEEE), 277–280. doi:10.1109/INES.2013.6632826

Berenguer, F. J. and Monasterio-Huelin, F. (2007). Stability and smoothness improvements for an underactuated biped with a tail. In *Industrial Electronics, 2007. ISIE 2007. IEEE International Symposium on* (IEEE), 2083–2088. doi:10.1109/ISIE.2007.4374929

Berenguer, F. J. and Monasterio-Huelin, F. M. (2008). Zappa, a quasi-passive biped walking robot with a tail: Modeling, behavior, and kinematic estimation using accelerometers. *IEEE Transactions on Industrial Electronics* 55, 3281–3289. doi:10.1109/TIE.2008.927982

Briggs, R., Lee, J.-W., Haberland, M., and Kim, S.-B. (2012). Tails in biomimetic design: Analysis, simulation, and experiment. In *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on* (IEEE), 1473–1480. doi:10.1109/IROS.2012.6386240

Brill, A. L., De, A., Johnson, A. M., and Koditschek, D. E. (2015). Tail-assisted rigid and compliant legged leaping. In *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on* (IEEE), 6304–6311. doi:10.1109/IROS.2015.7354277

Casarez, C., Penskiy, I., and Bergbreiter, S. (2013). Using an inertial tail for rapid turns on a miniature legged robot. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on* (IEEE), 5469–5474. doi:10.1109/ICRA.2013.6631361

Casarez, C. S. and Fearing, R. S. (2017). Dynamic terrestrial self-righting with a minimal tail. In *Intelligent Robots and Systems (IROS), 2017 IEEE/RSJ International Conference on* (IEEE), 314–321

Casarez, C. S. and Fearing, R. S. (2018). Steering of an underactuated legged robot through terrain contact with an active tail. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (IEEE), 2739–2746

Chang-Siu, E., Libby, T., Brown, M., Full, R. J., and Tomizuka, M. (2013). A nonlinear feedback controller for aerial self-righting by a tailed robot. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on* (IEEE), 32–39. doi:10.1109/ICRA.2013.6630553

Chang-Siu, E., Libby, T., Tomizuka, M., and Full, R. J. (2011). A lizard-inspired active tail enables rapid maneuvers and dynamic stabilization in a terrestrial robot. In *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on* (IEEE), 1887–1894. doi:10.1109/IROS.2011.6094658

De, A. and Koditschek, D. E. (2015). Parallel composition of templates for tail-energized planar hopping. In *Robotics and Automation (ICRA), 2015 IEEE International Conference on* (IEEE), 4562–4569. doi:10.1109/ICRA.2015.7139831

De, A. and Koditschek, D. E. (2018). Averaged anchoring of decoupled templates in a tail-energized monoped. In *Robotics Research* (Springer). 269–285

Graichen, K. and Hentzelt, S. (2015). A bi-level nonlinear predictive control scheme for hopping robots with hip and tail actuation. In *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on* (IEEE), 4480–4485. doi:10.1109/IROS.2015.7354013

Guan-Horng, L., Hou-Yi, L., Huai-Yu, L., Shao-Tuan, C., and Pei-Chun, L. (2014). A bio-inspired hopping kangaroo robot with an active tail. *Journal of Bionic Engineering* 11, 541–555. doi:10.1016/S1672-6529(14)60066-4

Guarnieri, M., Debenest, P., Inoh, T., Takita, K., Masuda, H., Kurazume, R., et al. (2009). Helios carrier: Tail-like mechanism and control algorithm for stable motion in unknown environments. In *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on* (IEEE), 1851–1856. doi:10.1109/ROBOT.2009.5152513

Heim, S. W., Ajallooeian, M., Eckert, P., Vespignani, M., and Ijspeert, A. J. (2016). On designing an active tail for legged robots: simplifying control via decoupling of control objectives. *Industrial Robot: An International Journal* 43, 338–346. doi:10.1108/IR-10-2015-0190

Iwamoto, N. and Nishikawa, A. (2018). Distributed model predictive control-based approach for flexible robotic tail. *IFAC-PapersOnLine* 51, 31–36

Iwamoto, N. and Yamamoto, M. (2015). Jumping motion control planning for 4-wheeled robot with a tail. In *System Integration (SII), 2015 IEEE/SICE International Symposium on* (IEEE), 871–876. doi:10.1109/SII.2015.7405114

Jianguo, Z., Hongyi, S., and Ning, X. (2015a). Non-vector space landing control for a miniature tailed robot. In *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on* (IEEE), 2154–2159. doi:10.1109/IROS.2015.7353665

Jianguo, Z., Tianyu, Z., Ning, X., Cintrón, F. J., Mutka, M. W., and Li, X. (2013). Controlling aerial maneuvering of a miniature jumping robot using its tail. In *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on* (IEEE), 3802–3807. doi:10.1109/IROS.2013.6696900

Jianguo, Z., Tianyu, Z., Ning, X., Mutka, M. W., and Li, X. (2015b). Msu tailbot: Controlling aerial maneuver of a miniature-tailed jumping robot. *IEEE/ASME Transactions on Mechatronics* 20, 2903–2914. doi:10.1109/TMECH.2015.2411513

Johnson, A. M., Libby, T., Chang-Siu, E., Tomizuka, M., Full, R. J., and Koditschek, D. E. (2012). Tail assisted dynamic self righting doi:10.1142/9789814415958_0079

Jovanova, J., Anachkova, M., Gavriloski, V., Petrevski, D., Grazhdani, F., and Pecioski, D. (2018). Modular origami robot inspired by a scorpion tail. In *ASME 2018 Conference on Smart Materials, Adaptive Structures and Intelligent Systems* (American Society of Mechanical Engineers), V002T06A014–V002T06A014

Jusufi, A., Kawano, D., Libby, T., and Full, R. J. (2010). Righting and turning in mid-air using appendage inertia: reptile tails, analytical models and bio-inspired robots. *Bioinspiration & biomimetics* 5, 045001. doi:10.1088/1748-3182/5/4/045001

Karakasiliotis, K., D'Août, K., Aerts, P., and Ijspeert, A. J. (2012). Locomotion studies and modeling of the long-tailed lizard takydromus sexlineatus. In *Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on* (IEEE), 943–948. doi:10.1109/BioRob.2012.6290836

Kessens, C. C. and Dotterweich, J. (2017). Ground-based self-righting using inertial appendage methods. In *Unmanned Systems Technology XIX* (International Society for Optics and Photonics), vol. 10195, 1019505. doi:10.1117/12.2262535

Kim, Y.-H. and Shell, D. A. (2017). Using a compliant, unactuated tail to manipulate objects. *IEEE Robotics and Automation Letters* 2, 223–230. doi:10.1109/LRA.2016.2590581

Kim, Y.-H. and Shell, D. A. (2018). Bound to help: cooperative manipulation of objects via compliant, unactuated tails. *Autonomous Robots* , 1–20

Kohut, N., Haldane, D., Zarrouk, D., and Fearing, R. (2012). Effect of inertial tail on yaw rate of 45 gram legged robot. In *Int. Conf. Climbing Walk. Robot. Support Technol. Mob. Mach.* 157–164. doi:10.1142/9789814415958_0023

Kohut, N. J., Pullin, A. O., Haldane, D. W., Zarrouk, D., and Fearing, R. S. (2013). Precise dynamic turning of a 10 cm legged robot on a low friction surface using a tail. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on* (IEEE), 3299–3306. doi:10.1109/ICRA.2013.6631037

Kwak, B. and Bae, J. (2015). Design and analysis of a rotational leg-type miniature robot with an actuated middle joint and a tail (romiramt). In *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on* (IEEE), 2148–2153. doi:10.1109/IROS.2015.7353664

Libby, T., Johnson, A. M., Chang-Siu, E., Full, R. J., and Koditschek, D. E. (2016). Comparative design, scaling, and control of appendages for inertial reorientation. *IEEE Transactions on Robotics* 32, 1380–1398. doi:10.1109/TRO.2016.2597316

Libby, T., Moore, T., Chang-Siu, E., Li, D., Jusufi, J., Cohen, D., et al. (2012). Tail assisted pitch control in a lizard, robot, and dinosaur. In *Integrative and Comparative Biology* (Oxford univ press inc journals dept, 2001 Evans rd, Cary, NC 27513 USA), vol. 52, E106–E106. doi:10.1038/nature10710

Liu, Y. and Ben-Tzvi, P. (2018). Dynamic modeling of a quadruped with a robotic tail using virtual work principle. In *ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (American Society of Mechanical Engineers), V05BT07A021–V05BT07A021

Machairas, K. and Papadopoulos, E. (2015a). On attitude dynamics and control of legged robots using tail-like systems. In *ECCOMAS Thematic Conference on Multibody Dynamics*

Machairas, K. and Papadopoulos, E. (2015b). On quadruped attitude dynamics and control using reaction wheels and tails. In *Control Conference (ECC), 2015 European* (IEEE), 753–758. doi:10.1109/ECC.2015.7330633

McInroe, B., Astley, H. C., Gong, C., Kawano, S. M., Schiebel, P. E., Rieser, J. M., et al. (2016). Tail use improves performance on soft substrates in models of early vertebrate land locomotors. *Science* 353, 154–158. doi:10.1126/science.aaf0984

Mutka, A., Orsag, M., and Kovacic, Z. (2013). Stabilizing a quadruped robot locomotion using a two degree of freedom tail. In *Control & Automation (MED), 2013 21st Mediterranean Conference on* (IEEE), 1336–1342. doi:10.1109/MED.2013.6608893

Ortega, R., Schaft, A. J. V. D., Mareels, I., and Maschke, B. (2001). Putting energy back in control. *IEEE Control Systems* 21, 18–33. doi:10.1109/37.915398

Patel, A. and Boje, E. (2015). On the conical motion of a two-degree-of-freedom tail inspired by the cheetah. *IEEE Transactions on Robotics* 31, 1555–1560. doi:10.1109/TRO.2015.2495004

Patel, A. and Braae, M. (2013). Rapid turning at high-speed: Inspirations from the cheetah's tail. In *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on* (IEEE), 5506–5511. doi:10.1109/IROS.2013.6697154

Patel, A. and Braae, M. (2014). Rapid acceleration and braking: Inspirations from the cheetah's tail. In *Robotics and Automation (ICRA), 2014 IEEE International Conference on* (IEEE), 793–799. doi:10.1109/ICRA.2014.6906945

Patel, A. and Braae, M. (2015). An actuated tail increases rapid acceleration manoeuvres in quadruped robots. In *Innovations and Advances in Computing, Informatics, Systems Sciences, Networking and Engineering* (Springer). 69–76. doi:10.1007/978-3-319-06773-5_10

Pullin, A. O., Kohut, N. J., Zarrouk, D., and Fearing, R. S. (2012). Dynamic turning of 13 cm robot comparing tail and differential drive. In *Robotics and Automation (ICRA), 2012 IEEE International*

Conference on (IEEE), 5086–5093. doi:10.1109/ICRA.2012.6225261

Ren, P. and Hong, D. (2010). Forward and inverse displacement analysis of an actuated spoke wheel robot with two spokes and a tail contact with the ground. In *ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (American Society of Mechanical Engineers), 1437–1445. doi:10.1115/DETC2010-28998

Ren, P., Jeans, J. B., and Hong, D. (2009). Kinematic analysis and experimental verification on the steering characteristics of a two actuated spoke wheel robot with a tail. In *33rd ASME Mechanisms and Robotics Conference* (American Society of Mechanical Engineers). doi:10.1115/DETC2009-87076

Rone, W., Saab, W., and Ben-Tzvi, P. (2017). Design, modeling and optimization of the universal-spatial robotic tail. In *ASME 2017 International Mechanical Engineering Congress and Exposition* (American Society of Mechanical Engineers), V04AT05A020–V04AT05A020

Rone, W. S. and Ben-Tzvi, P. (2014). Continuum robotic tail loading analysis for mobile robot stabilization and maneuvering. In *ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2014* (American Society of Mechanical Engineers). doi:10.1115/DETC2014-34678

Rone, W. S. and Ben-Tzvi, P. (2015). Static modeling of a multi-segment serpentine robotic tail (American Society of Mechanical Engineers). doi:10.1115/DETC2015-46655

Rone, W. S. and Ben-Tzvi, P. (2016). Dynamic modeling and simulation of a yaw-angle quadruped maneuvering with a planar robotic tail. *Journal of Dynamic Systems, Measurement, and Control* 138, 084502. doi:10.1115/1.4033103

Rone, W. S. and Ben-Tzvi, P. (2017). Maneuvering and stabilizing control of a quadrupedal robot using a serpentine robotic tail. In *Control Technology and Applications (CCTA), 2017 IEEE Conference on* (IEEE), 1763–1768. doi:10.1109/CCTA.2017.8062712

Rone, W. S., Saab, W., and Ben-Tzvi, P. (2018). Design, modeling, and integration of a flexible universal spatial robotic tail. *Journal of Mechanisms and Robotics* 10, 041001

Saab, W. and Ben-Tzvi, P. (2016). Design and analysis of a discrete modular serpentine robotic tail for improved performance of mobile robots. In *ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2016* (American Society of Mechanical Engineers). doi:10.1115/DETC2016-59387

Saab, W. and Ben-Tzvi, P. (2017). Maneuverability and heading control of a quadruped robot utilizing tail dynamics. In *ASME 2017 Dynamic Systems and Control Conference* (American Society of Mechanical Engineers), V002T21A010–V002T21A010

Saab, W., Rone, W. S., and Ben-Tzvi, P. (2018a). Discrete modular serpentine robotic tail: Design, analysis and experimentation. *Robotica* , 1–25

Saab, W., Rone, W. S., and Ben-Tzvi, P. (2018b). Robotic tails: a state-of-the-art review. *Robotica* 36, 1263–1277. doi:10.1017/S0263574718000425

Saab, W., Yang, J., and Ben-Tzvi, P. (2018c). Modeling and control of an articulated tail for maneuvering a reduced degree of freedom legged robot. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (IEEE), 2695–2700

Sadati, S. H. and Meghdari, A. (2017). Singularity-free planning for a robot cat free-fall with control delay: Role of limbs and tail. In *Mechanical and Aerospace Engineering (ICMAE), 2017 8th International Conference on* (IEEE), 215–221. doi:10.1109/ICMAE.2017.8038645

Santiago, J. L. C., Godage, I. S., Gonthina, P., and Walker, I. D. (2016). Soft robots and kangaroo tails: Modulating compliance in continuum structures through mechanical layer jamming. *Soft Robotics* 3, 54–63. doi:10.1089/soro.2015.0021

Sato, R., Hashimoto, S., Ming, A., and Shimojo, M. (2016). Development of a flexible tail for legged robot. In *Mechatronics and Automation (ICMA), 2016 IEEE International Conference on* (IEEE), 683–688. doi:10.1109/ICMA.2016.7558645

Shamsah, A., De, A., and Koditschek, D. E. (2018). Analytically-guided design of a tailed bipedal hopping robot. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (IEEE), 2237–2244

Shin, D.-H., An, J., and Kang, Y.-S. (2011). Design consideration for shock-absorbing spring at the tail of firefighter-assistive robot. In *Control, Automation and Systems (ICCAS), 2011 11th International Conference on* (IEEE), 1702–1705

Simon, B., Sato, R., Choley, J.-Y., and Ming, A. (2018). Development of a bio-inspired flexible tail system. In *2018 12th France-Japan and 10th Europe-Asia Congress on Mechatronics* (IEEE), 230–235

Takita, K., Katayama, T., and Hirose, S. (2002a). Development of dinosaur-like robot titrus-motion control of the head and tail of miniature robot titrus-iii. In *SICE 2002. Proceedings of the 41st SICE Annual Conference* (IEEE), vol. 5, 2984–2989. doi:10.1109/SICE.2002.1195580

Takita, K., Katayama, T., and Hirose, S. (2002b). The efficacy of the neck and tail of miniature dinosaur-like robot titrus-iii. In *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on* (IEEE), vol. 3, 2593–2598. doi:10.1109/IRDS.2002.1041661

Takita, K., Katayama, T., and Hirose, S. (2003). Development of dinosaur-like robot titrus-its dynamics and the motion utilizing the dynamic effect of the neck and tail. In *Intelligent Robots and Systems, 2003.(IROS 2003). Proceedings. 2003 IEEE/RSJ International Conference on* (IEEE), vol. 1, 607–612. doi:10.1109/IROS.2003.1250696

Wenger, G., De, A., and Koditschek, D. E. (2016). Frontal plane stabilization and hopping with a 2dof tail. In *Intelligent Robots and Systems (IROS), 2016 IEEE/RSJ International Conference on* (IEEE), 567–573. doi:10.1109/IROS.2016.7759110

Xiaoyun, L., Zhihong, J., Hui, L., Yang, M., Mingjie, Z., and Qiang (2015). Dynamic stability control for a bio-robot with primates-inspired active tail. In *Mechatronics and Automation (ICMA), 2015 IEEE International Conference on* (IEEE), 2035–2040. doi:10.1109/ICMA.2015.7237799

Xiuli, Z., Jiaqing, G., and Yanan, Y. (2016). Effects of head and tail as swinging appendages on the dynamic walking performance of a quadruped robot. *Robotica* 34, 2878–2891. doi:10.1017/S0263574716000011

Yu, H., Li, C., Yuan, B., Gao, H., and Deng, Z. (2017). Planar hopping control strategy for tail-actuated slip model traversing varied terrains. In *Intelligent Robots and Systems (IROS), 2017 IEEE/RSJ International Conference on* (IEEE), 3231–3238

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

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)

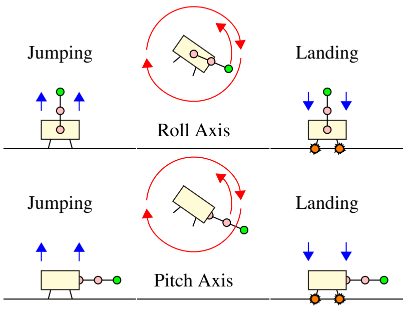
Table 4. Table of all the papers that did not use physical robots. “Tail DoF” refers to the total number of DoF, including passive joints. Papers with passive DoF are denoted with a superscript. Number of decimal places reflects the precision found in the references.

Ref.	Locomotion	Tail Structure	Number of Segments	Tail Dimension Class	Tail DoF	Actuator	Tail Mass (kg)
Berenguer and Monasterio-Huelin (2007)	Walking	Rigid	1	1	1	N/A	0.7
Graichen and Hentzelt (2015)	Hopping	Rigid	1	1	1	N/A	N/A
Iwamoto and Yamamoto (2015)	Wheeled	Pseudo-Flexible	10	1	10[1]	Revolute Motor	0.307
Iwamoto and Nishikawa (2018)	N/A	Rigid	N/A	N/A	Multiple	N/A	N/A
Karakasiliotis et al. (2012)	Walking	Flexible	10	2	12[2]	N/A	1327.9
Xiaoyun et al. (2015)	Wheeled	Rigid	1	1	1	N/A	N/A
Liu and Ben-Tzvi (2018)	Walking	Rigid	1	3	2	N/A	1.4347
Machairas and Papadopoulos (2015b)	Walking	N/A	1	1	1	N/A	N/A
Machairas and Papadopoulos (2015a)	N/A	Rigid	1	1	1	N/A	0.5-4
Mutka et al. (2013)	Walking, Hopping	Rigid	1	3	2	N/A	N/A
Patel and Braae (2015)	Walking	Rigid	1	1	1	N/A	1
[illegible]	None	Flexible	1/2	3/4	2/4	Linear Servo Motor[3]	2.25

Table 5. Comparison of control system classification with paper structure. In addition to the classifications specified in figure 5, *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**)
			Berenguer and Monasterio-Huelin (2008); Heim et al. (2016); Takita et al. (2002a,b, 2003); Xiuli et al. (2016);