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.

3 RESULTS

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 1 lists the physical robots by name, with the papers they were referenced in and the year the first paper mentioning the robot was published. Table 2 lists the physical robots by their properties. Table 3 lists all the papers that do not have physical robots connected with them.

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

References
Kessens and Dotterweich (2017)
Heim et al. (2016)
Saab et al. (2018a)
Xiuli et al. (2016)
Patel and Braae (2014, 2013)
Patel and Boje (2015)
Guarnieri et al. (2009)
Ren and Hong (2010); Ren et al. (2009)
Casarez and Fearing (2018)
Briggs et al. (2012)
Jianguo et al. (2015a,b, 2013)
McInroe et al. (2016)
Pullin et al. (2012)
De and Koditschek (2018); Shamsah et al. (2018); Wenger et al. (2016); De and Koditschek (2015); Brill et al. (20
Saab et al. (2018c)
Kwak and Bae (2015)
Kohut et al. (2013, 2012)
Libby et al. (2012); Chang-Siu et al. (2011)
Takita et al. (2003, 2002b,a)
Rone et al. (2018)
Casarez and Fearing (2017)
Libby et al. (2016); Johnson et al. (2012)
Berenguer and Monasterio-Huelin (2008)
Simon et al. (2018)
Casarez et al. (2013)
Chang-Siu et al. (2013)
Jusufi et al. (2010)
Guan-Horng et al. (2014)
Aiello and Crespo (2013)
Sato et al. (2016)
Santiago et al. (2016)
Kim and Shell (2018, 2017)
Jovanova et al. (2018)

3.3 Research Objectives of Robots Identified in the Literature

Table 4 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.

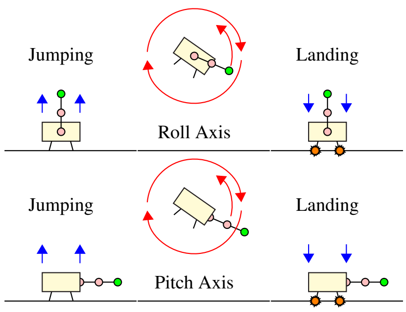
Table 2. Table of the physical robots. “Tail DoF” refers to the total number of DoF, including passive joints. Robots with passive DoF are denoted with a superscript. Number of decimal places reflects the precision found in the references.

Ref.	Locomotion	Tail Structure	Number of Segments	Tail Dimension Class	Tail DoF	Actuator	Tail Mass (kg)	Body Mass (kg)
Kessens and Dotterweich (2017)	None	Rigid	2	4	3	Revolute Motor	0.33	0.99
Heim et al. (2016)	Walking	Rigid	1	1	1	Revolute Motor	0.053	1.197
Saab et al. (2018a)	None	Pseudo-Flexible	2	3	2	Revolute Motor[3]	3.5	9.525
Xiuli et al. (2016)	Walking	Rigid	1	1	1	Revolute Motor	0.25	5.312
Patel and Braae (2014, 2013)	Wheeled	Rigid	1	3	2	Revolute Motor	0.4	5
Patel and Boje (2015)	Wheeled	Rigid	1	3	2	Revolute Motor	0.4	5
Guarnieri et al. (2009)	Tracked	Rigid	1	1	1	Revolute Motor	N/A	N/A
Ren and Hong (2010); Ren et al. (2009)	Wheeled	Rigid	1	0	0[1]	Static Tail	N/A	N/A
Casarez and Fearing (2018)	Walking	Rigid	1	1	1	Revolute Motor	N/A	N/A
Briggs et al. (2012)	Walking	Rigid	1	3	2	Revolute Motor	0.74	35
Jiang et al. (2015a,b, 2013)	Wheeled, Hopping	Rigid	1	1	1	Revolute Motor	0.017	0.0252
McInroe et al. (2016)	Walking	Rigid	1	3	2	Revolute Motor	N/A	N/A
Pullin et al. (2012)	Walking	Rigid	1	1	1	Revolute Motor	0.017	0.035

Table 3. 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)
Berenguel 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

Table 4. 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);

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.

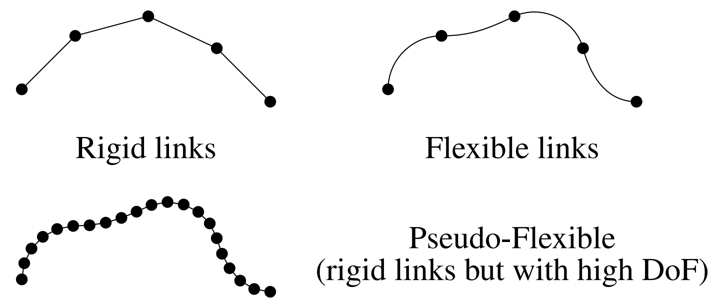


Figure 1. Tail structure classification. Black dots indicate individual joints which may be active or passive.

(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 2 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 1 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.

3.5.2 Tail Segmentation

Table 2 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 2 and 5 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 2 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

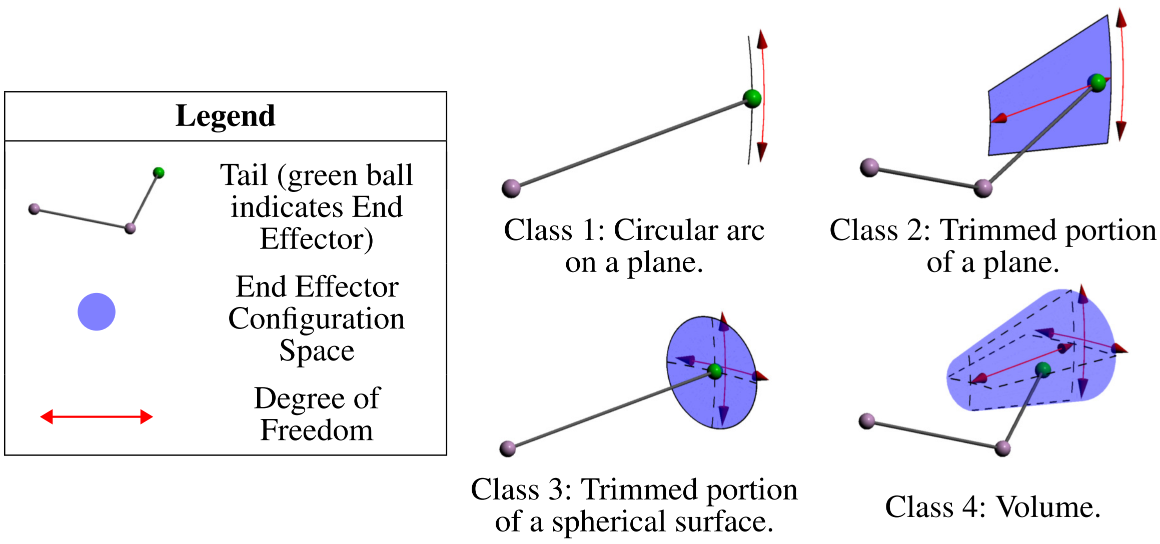


Figure 2. Tail Dimension Class visual illustration.

Table 5. 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**

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 5, 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 2, 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 3, 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 3 shows a block diagram of each controller/model). As can be seen in Table 6, 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 (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 5 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.

Table 6. Comparison of control system classification with paper structure. In addition to the classifications specified in figure 3, *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)

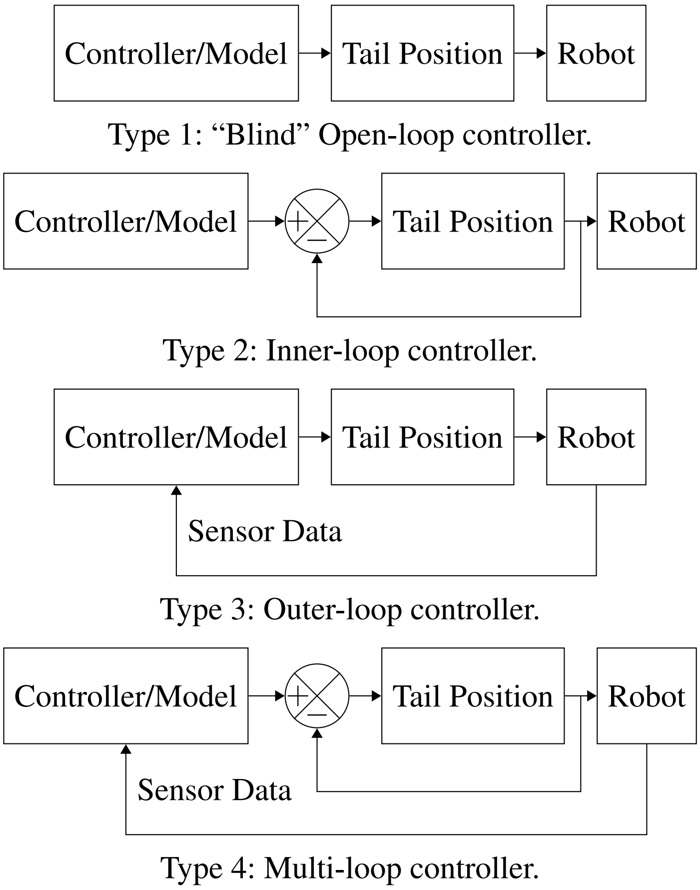


Figure 3. Control system classification for robotic tails.

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.

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