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Robotic tails: a state-of-the-art review

Wael Saab, William S. Rone and Pinhas Ben-Tzvi*

Robotics and Mechatronics Laboratory, Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, USA
E-mails: waelsaab@vt.edu, wsrone@vt.edu

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SUMMARY
This paper reviews the state-of-the-art in robotic tails intended for inertial adjustment applications on-board mobile robots. Inspired by biological tails observed in nature, robotic tails provide a separate means to enhance stabilization, and maneuverability from the mobile robot's main form of locomotion, such as legs or wheels. Research over the past decade has primarily focused on implementing single-body rigid pendulum-like tail mechanisms to demonstrate inertial adjustment capabilities on-board walking, jumping and wheeled mobile robots. Recently, there have been increased efforts aimed at leveraging the benefits of both articulated and continuum tail mechanism designs to enhance inertial adjustment capabilities and further emulate the structure and functionalities of tail usage found in nature. This paper discusses relevant research in design, modeling, analysis and implementation of robotic tails onto mobile robots, and highlight how this work is being used to build robotic systems with enhanced performance capabilities. The goal of this article is to outline progress and identify key challenges that lay ahead.

KEYWORDS: Biomimetic robots; Robot dynamics; Mobile robots; Legged robots; Novel applications of robotics.

1. Introduction

By observing nature, engineers can gain a source of inspiration to address major challenges within the field of robotics. For example, animals use their tails for a wide variety of tasks ranging from stabilization, maneuvering, propulsion and manipulation.[1] By studying fossil remains, scientists believe that the Tyrannosaurus Rex swung its tail laterally to counter-act the weight of its massive body while it walked forward.[2,3] Similarly, kangaroos have been observed to use their tails in a compliant mode as a counter balance while hopping,[4] and can stiffen their tails to provide an additional limb while standing on their hind legs or engaging in defensive boxing routines.[5] Kangaroo rats and lizards have been observed to swing their tails while in mid-air to reorient their bodies.[6,7] Green Iguanas are known to lash their tails against predators to escape dangerous situations.[8] Other examples of tail usage include monkeys climbing and grasping objects, an alligator rolling underwater, or the propulsion of fish through water. These stabilization, maneuvering and propulsive behaviors are examples of inertial adjustment, where a structure on-board a system is used to generate inertial forces and moments to modify the dynamics of the animal. While tails are the most obvious inertial adjustment mechanism used by animals, any motion of an appendage or body mass can be used for reorientation such as wings,[9] spines[10] or legs.[11,12] By observing these functionalities scaled over a wide range of sizes and uses, engineers have been inspired to apply inertial adjustment mechanisms to mobile robotics to further enhance stabilization and maneuverability of these systems.

The objective of this paper is to present and compare research contributions made to robotic tail design, analysis and implementation on-board mobile robots for inertial adjustment applications. While there are examples of inertial adjustment of legged robots and mobile platforms using torsos,[13] limbs[14] and robotic manipulators,[15] this review will focus on active mechanisms that mimic

* Corresponding author. E-mail: bentzvi@vt.edu

functionalities of biological tails observed in nature. The objective is to summarize the most recent and relevant advances in this field and outline the limitations and challenges pertaining to inertial adjustment applications of mobile robots via robotic tails.

2. Inertial Adjustment Mechanism Technology

Robotic engineers and scientists inspired by nature often face a scenario where meeting design requirements using traditional engineering approaches becomes challenging. In the case of a biological tail used for inertial adjustment applications, faithfully mimicking a biological structure in terms of design alone has not been demonstrated as a realistic option since animals have evolved over millions of years to exploit structural and organizational principles spanning multiple physical scales and operational modes to realize functional performance gains in an efficient manner.[16]

From an engineering perspective, the fundamental principles of an inertial adjustment mechanism is to offer the capability to adjust the center of mass (COM) location and generate control forces and moments about its attachment point to adjust the system orientation. These basic requirements have led to vast amounts of research to develop inertial adjustment mechanism technologies to meet these needs. However, for applications on-board mobile robots, the feasibility of such technologies must be carefully considered.

Engineered solutions for inertial adjustment mechanisms can be categorized based on their principles of operation: (1) substrate interaction mechanisms propel the surrounding environment to produce propulsive forces such as thrusters, gas jets, fins, turbojets and turbofans,[17,18] (2) translational mechanisms displace a reaction mass to adjust COM location,[19] (3) symmetric rotational mechanisms provide a reactive moment (no forces), such as reaction wheels,[20] to adjust orientation and (4) asymmetrical rotational mechanisms, such as pendulums (i.e. robotic tails), provide COM adjustments and generate control forces and moments.

Although category 1 mechanisms have demonstrated highly capable inertial adjustment capabilities on-board satellites, airplanes and spacecraft, the requirement of compressors and fuel make practical implementation on-board mobile robots challenging. Similarly, category 2 mechanisms rely on the translational stroke length of the reaction mass and requires a large foot print on-board a relatively compact mobile robot for significant inertial adjustment contributions. Therefore, the feasibility of category 3 and 4 mechanisms has been studied for inertial adjustment applications of mobile robots.

A category 3 reaction wheel consists of an axisymmetric mass that is capable of continuous rotation about a single axis of rotation and is used to impart a reactive moment about its attachment point. Although they can be designed to fit in small volumes, they are limited by the angular velocity of the actuator and mass constraints.[21] Category 4 pendulums are capable of generating both control forces and moments in addition to adjusting COM location. They can be designed with high inertia while maintaining a constant mass due to the quadratic relationship between pendulum length and effective inertia. However, pendula are often limited to a maximum range of motion due to potential contact with the environment or robot during operation.

In the work presented by Briggs *et al.*,[22] the results of comparative analysis between mobile robot implementations of a reaction wheel and a robotic tail, in the form of a single-body rigid pendulum, are summarized as follows: (1) the longer spatial dimension of a robotic tail provides the advantage of a greater moment of inertia at the cost of a constraint on maximum allowable relative rotation, (2) a reaction wheel is appropriate when there are tightly confining geometry constraints and the time of interest is long due to its ability to continuously rotate and (3) for an equivalent power input, effective moment of inertia and short time span, a robotic tail can produce a significantly higher angular impulse to affect the attached mobile robot. In a separate study presented by Machairas *et al.*,[21] that analyzed a pendulum-like tail and reaction wheel on-board a quadruped robot, for equivalent inertial properties and time span of motion that result in an equivalent heading angle adjustment in the yaw direction, results indicated that (1) less torque is required for the robotic tail motion because the inertial force at the tail base also contributes to the net torque relative to the system COM and (2) the motor needs to run at a much higher speed in the reaction wheel case; as a result, for the same net rotation, more power is required by the motor. The results from both[21,22] have concluded that robotic tails are the optimal means of inertial adjustment for mobile robotic applications.

3. Robotic Tails

This section reviews the design and implementation of robotic tails on-board mobile robots for inertial adjustment applications categorized by structural design and means of operation. Section 3.1 reviews work pertaining to single-body rigid pendulum-like tails that operate in planar (3.1.1) and spatial (3.1.2) workspaces. Section 3.2 discusses recent research on using articulated spatial tails that more closely resemble their biological counterparts and demonstrate an improved workspace, enhanced loading about its attachment point to a mobile robot and additional functionalities. Section 3.3 presents recent trends into soft robotics have led to mechanism designs that form continuum structures and closely mimic the motions and functionalities of biological tails found in nature. The aim of this section is to provide a comparative analysis and highlight the benefits and results of the proposed tail mechanism designs found in literature.

Many of the robotic tails proposed in the literature draw inspiration from a diverse variety of animals such as cheetahs,[22–25] kangaroos,[5,26–28] fish,[29,30] lizards[6,31,32] and dinosaurs.[7,33] To facilitate a comparative analysis of prior research into robotic tails, a sample of previous tail designs and their physical properties are collected in Table I. In terms of mechanical design, the majority of research has focused primarily on single-body planar pendulums and covers a wide range of masses (4 to 1418 g) and lengths (73 to 500 mm). Planar tails operate in a single-degree of freedom (DOF) either in the pitch,[6,26,28,31,34–38] yaw[33,39–41] or roll-direction.[24] Spatial pendulum-like tails are two-DOF mechanisms that operate in a combination of planes by utilizing active pitch and yaw DOFs.[22,27,32] Articulated tails utilize two or more active DOFs to enable spatial capabilities.[23,27,32,42–46] Planar tails provide enhanced performance about a single-body-axis with the advantage of simpler design and implementation. Spatial tails greatly increase workspace and provide multi-axis enhanced performance capabilities, but require increased actuator unit design complexity and control. Articulated tail designs utilize the concept of under-actuation (fewer actuators than DOFs) to produce spatial curvatures that provide the main advantage of increased moment loading about the tail base that can produce more desirable inertial adjustment capabilities. The continuum tails' earliest implementations dating back to the year 2014, not shown in Table I, are designed to closely emulate the natural motions and functionalities of biological tails and utilize various forms of actuation such as cable systems, pneumatic pressure and mechanical layer jamming.

Functionally, these tails may be classified as aiding stabilization, maneuvering, propulsion or manipulation. Tails for stabilization include static applications of COM adjustment that aid passive quasi-static walking,[41] and dynamic applications for disturbance rejection,[22] dynamic running,[33] pitch adjustment,[6,7,28,31,35,36,38,47] stabilization for high-speed maneuvers[23,24] and attitude control.[22,27,32] Tails for maneuvering enable yaw-angle turning.[39,40] Tails for propulsion have been demonstrated for underwater swimming applications.[29,30] Tails for manipulation enable environmental contact to provide an additional supporting limb.[5,33]

3.1. Single-body rigid pendulum tail mechanisms

3.1.1. Planar tail mechanisms. Planar tails, examples of which are shown in Fig. 1, provide enhanced performance about a single axis with the advantage of simple design and implementation. Based on an extensive literature review, the first system that appears to have utilized an inertial tail was the Uniroo robot[48] composed of a single leg constrained to hop along a circular path and a pitch DOF tail used to counterbalance leg motion, shown in Fig. 1(a). The authors used experimental observations and data to modify the control architecture and the tail's moment of inertia to achieve desirable behavior. The robot demonstrated a forward hoping velocity of 1.8 m/s. Based off this work, a number of pitch DOF tails have been further analyzed and implemented on numerous robots for dynamic mid-air pitch adjustment. Liu *et al.* investigated a kangaroo robot,[26] shown in Fig. 1(b), with two synchronized circular arc-shaped legs used to produce forward hopping motion while an active tail compensated for undesired angular momentum. The authors investigated performance of a stationary tail, and an active pitch DOF tail using both open-loop control (i.e., pre-calculated trajectories) and closed-loop control (updating tail trajectories using sensor data). Results indicated that an active tail can reduce pitch variation by up to 50%. With the open-loop active tail, the body pitch RMS error of the robot reduced by 52% in comparison to the robot with stationary tail. With the closed-loop active tail, the value is further reduced by 43%.

By studying a lizard's jump, transitioning between horizontal and vertical surfaces,[7] Chang-Siu, Johnson, Libby *et al.* explored the design space and performance enhancements a pitch DOF tail can provide Tailbot,[6,31] shown in Fig. 1(c), for mid-air pitch self-righting. Conservation of angular

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Table I. Comparison of robotic tail designs, actuation properties.

System	Ref. [28]	Ref. [41]	Refs. [6, 31]	Ref. [39]	Refs. [24, 37]	Ref. [26]	Ref. [32]	Ref. [23]	Ref. [27]	Ref. [44]	Ref. [42]	Ref. [43]
Year	1991	2008	2012	2012	2013	2014	2013	2015	2015	2017	2017	2016–17
Tail mass (g)	–	700	17	4	400	371	70	400	150	900	510	1418
Tail length (mm)	–	150	103	115	500	177	73	500	300	500	470	400
Rated motor power (W)	–	5.5	4	2.5	120	19	1.75	70 ea.	–	100 ea.	3 × 100, 3 × 70	5 ea.
Max speed (rpm)	–	6	3000	400	275	240	320	137	353	260	260	84
End-effector workspace (Deg)	–	180	255	265	224	220	135/135	70/180	180/180	270/∞	200/180	200/∞
Mechanical design	Planar						Spatial					
	Single-body rigid pendulum						Articulated					

– Not reported.

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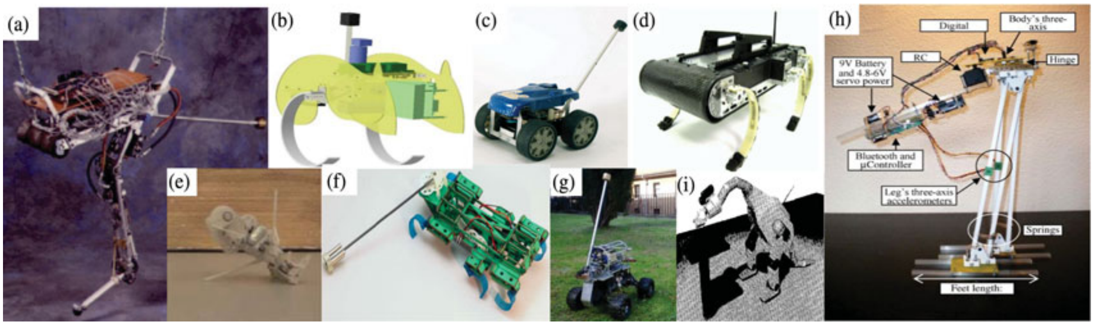

Fig. 1. Planar, pendulum-like tail mechanisms: (a) Uniroo robot,[48] (b) Kangaroo robot,[26] (c) Tailbot,[6,31] (d) X-Rhex,[35,38] (e) MSU Jumper,[47,50] (f) TAYLRoACH,[39,40] (g) Dima,[24,37] (h) Zappa[41] and (i) TITRUS.[33]

momentum of the robotic system, modeled as two rigid bodies (mobile robot and tail) connected by a revolute joint imposed a dimensionless index of rotational efficacy upon which the tail can be designed, and optimized in terms of tip mass and length specifications for mobile robots of various sizes and weights.[49] Further analysis demonstrated that (1) the duration of body reorientation depends upon the acceleration of the tail relative to the body and (2) the power density of the tail's actuator must increase quadratically with the robot's body length in order to achieve the same maneuver in the same relative time span of the tail motion. These results indicate that inertial adjustment gets more expensive for larger size scaled robots; therefore, larger robots may suffer from reduced tail-aided performance or must dedicate a larger proportion of total body mass, and power to tail actuation. Experimental results in this work demonstrated how the tail enables rapid pitch reorientation of the body up to 90° with relatively low tail tip mass (10%–20% of the robot body mass). The authors later implemented a similar tail on X-Rhex robot,[35,38] shown in Fig. 1(d), to demonstrate the robot's enhanced survivability in running off an elevated ledge and dynamically adjusting its pitch to land on its feet enabled via closed-loop, tail-aided body pitch control. A similar functionality was demonstrated by Zhao *et al.* on a miniature 28 g robot called the MSU Jumper,[47,50] shown in Fig. 1(e), that can translate using wheels, jump over obstacles using spring loaded legs and perform aerial pitch adjustments using an active tail. Therefore, the robot can control its landing posture to protect it from damage.

Tails that operate in the yaw DOF have been proposed to enhance maneuverability, and stabilization of mobile robots. Kohut *et al.* proposed a palm-sized, 45 g legged robot called TAYLRoACH,[39,40] shown in Fig. 1(f), to investigate the maneuverability improvement a tail can provide in terms of turning without reducing the its forward running speed. Modeling of the robotic system assumed that the tail torque occurs as soon as the tail is actuated and overwhelms static friction, causing a full-body rotation opposed by dynamic sliding friction at the feed. However, this model did not consider the effects of translation resulting from inertial forces generated by the tail. Using gyroscope sensory feedback, a bang-bang controller was developed to apply maximum motor torque within 5° of the desired body yaw angle. The robot demonstrated 90° turns up to 360°/s with an RMS error up to 13.2°. In a separate piece of work, Saab and Ben-Tzvi,[51] modeled a legged robot with a yaw DOF tail in the presence of friction to analyze the effects of both low-speed and high-speed tail actuations on the robotic system in terms of maneuverability defined as the resultant rotation and translation of the system caused by both inertial forces and moments generated during tail motion. Low-speed tail motions were used to maintain static stability that prevents the robot from moving while the tail configuration is set to a desired starting configuration, then high-speed tail motions were performed to induce maneuvering. Sensitivity analysis was then performed that utilized the developed models to compute optimal tail mass and length ratios with respect to the quadruped. Results indicated that past a certain mass ratio threshold, the addition of tail mass does not significantly cause large variations of heading angle. This trend physically makes sense because tail mass does increase the inertial forces transferred to the quadruped, but also increases the overall weight of the system, resulting in a larger friction induced moment that impedes motion of the system. A similar trend was observed for increasing length ratio. Past a certain threshold heading angle variation decreased due to inertial forces in the tangential and radial directions that counter act rotation of the system.

Inspired by recent biomechanics research of the cheetah,[52] Patel and Braae analyzed the enhanced stabilization a tail can provide the wheeled robot Dima, shown in Fig. 1(g), in terms of rapid forward motion acceleration/braking,[37] and turning.[24] For rapid acceleration/braking, the authors proposed a longitudinal maneuver template to model the complex control strategies of animal's hyper-redundant task-level behaviors using reduced-order models[53] that consisted of two rigid bodies, tail and robot, capable of rotating about a grounded joint where acceleration/braking forces were considered to be external forces acting on the system. In this case, the tail was used to maintain zero pitch angle during instances of rapid acceleration, and deceleration. For rapid turning, a Lagrangian method was used to model the system in the lateral plane where the robot was assumed to be rotating in the roll direction about a grounded joint. The centrifugal force resulting from high-speed turning was modeled as a disturbance to the system and a controller was developed to maintain a zero roll angle using counteractive tail motions. The authors utilized the analytical models of the system to select an optimal tail mass and actuator gearbox reduction ratio to maximize the resultant body angular adjustment resulting from a tail motion, and then studied the effects of a tailed and tailless robot. Both simulation and experimental results of this work indicated that the addition of the tail enabled the robot to perform up to a 40% increase in lateral acceleration, and a 50% increase in forward acceleration, without toppling over in comparison, to the tail-less version; therefore, enabling high-speed maneuverability. The authors then designed a new actuation unit to combine both pitch and yaw tail motions to construct a two-DOF spatial tail[23] to better approximate the conical motion of tail usage of the cheetah and impart a roll torque, about a single axis, on the Dima robot; however, in terms of functionality, the goal was to enhance turning of the robot about a single axis in the lateral direction. A tail controller was then developed to generate tail motions that constrained the tail workspace to a cone of specified width. Experimental results indicated that, on average, a tail-less system could only perform a turn at 6 m/s whereas the tailed system could initiate turns at 7 m/s since the tail can provide up to 70% more lateral acceleration.

Berenguer *et al*. proposed a passive, compliant bipedal robot called Zappa that is capable of walking using only one actuator that controls yaw rotation of a tail,[41] shown in Fig. 1(h). The authors demonstrated that the gait length and forward walking speed of the robot can be controlled by varying the frequency of tail oscillation that adjusts the robot's COM position to fall within the left/right support polygon. Results highlight the potential simplifications a tail can provide legged robots in terms of reduced mechanical design, and control complexity. Takita *et al*. proposed a bipedal robot called TITRUS,[33] shown in Fig. 1(i), designed to realize a practical mobile working platform. Both a pendulum-like neck and tail mechanism, attached to universal joints each controlled by two coupled differential drive motors, were used to swing the inertial appendages left and right in a horizontal plane (about a single axis) to walk statically and run dynamically by adjusting its projected COM and zero-moment point within the robots support polygon. This work demonstrates the first functionality how an inertial appendage with a spatial workspace can be used to provide a stable tripod like structure, while the neck can potentially perform tasks of manipulation or surveillance.

3.1.2. Spatial tail mechanisms. Spatial, single-body rigid pendulum tails, shown in Fig. 2, have been proposed that greatly increase workspace, and provide enhanced multi-axis capabilities at the cost of increased actuator unit design and control complexity. Although structurally similar to planar pendulum-like tails reviewed in Section 3.1.1, the main contributions of spatial pendulum-like tails falls within algorithm design to control the tail's pitch and yaw DOFs simultaneously to achieve a desired functionality. These tails have been used to experimentally demonstrate dynamic applications including disturbance rejection,[22] mid-air attitude control[32] and energy regulation.[27]

Inspired by video footage of a cheetah observed whipping its tail from side to side during a high-speed chase of its prey, Briggs *et al*. hypothesized that the tail provides a reactive moment to help roll the animal's body in mid-air to assist in turning motion. In this work, a two-DOF pendulum-like tail attached to the MIT Cheetah,[22] shown in Fig. 2(a), was modeled during mid-air-flight as two rigid bodies, tail and robot. The authors then developed a controller to reorient the body using tail motion by (1) defining an Euler axis along which the robot should rotate to the desired orientation, (2) computing the angular rotation needed to achieve the desired orientation, (3) calculating the current angular velocity of the body, (4) defining the desired angular velocity at the end configuration, (5) determining the desired angular momentum with the desired angular velocity, (6) computing the desired change in angular momentum to compute the desired torque tail input and (7) projecting

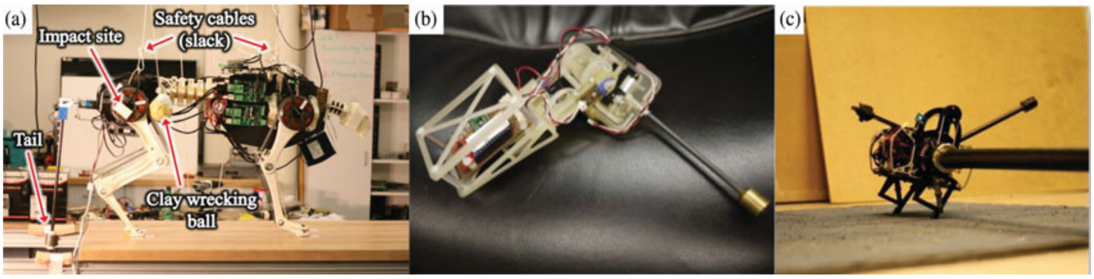

Fig. 2. Spatial, pendulum-like tail mechanisms: (a) MIT Cheetah,[22] (b) 2-DOF Tailbot[32] and (c) Penn Jerboa.[27]

the desired torque on the achievable space of torques along the axis of the tail actuators. In this analysis, only inertial moments were considered for inertial adjustment applications; inertial forces generated by the tail were neglected due to the complexity of its consideration since these forces either aid or hinder rotation of the robot based on its instantaneous state as discussed by the authors. The simulated controller failed to achieve a desired orientation when the initial tail orientation was arbitrarily selected, but was successful when the initial tail orientation was optimized. The authors then experimentally demonstrated how the tail can be used to reject external disturbances, by swinging it in an opposite orientation of its body rotation, to prevent the robot from tipping over while in contact with the ground.

Chang-Siu *et al*. proposed a control scheme for attitude control of a falling, two-DOF tailbot, shown in Fig. 2(b), with the tail capable of rotating in the pitch and yaw directions.[32] By choosing a body angular velocity vector parallel to the axis of error rotation, the controller steers the robot toward its desired orientation. However, the attachment point of the tail to the robot was assumed to be at the COM, therefore neglecting the effects of generated inertial forces on the orientation of the robot. The proposed scheme was accomplished through feedback laws as opposed to feed forward trajectory generation, and demonstrated a fair robustness to model uncertainties. The authors implemented the control approach on a simple controller on a small (175 g) robot platform. Experimental trials, after inertial adjustment using the tail, demonstrated an angular orientation error up to 18° attributed to friction in the inexpensive motors and lack of an integrator in the controller.

De and Koditschk proposed the Penn Jerboa,[27] shown in Fig. 2(c), a passive-compliant four-DOF tailed monoped fastened to a boom to restrict motion in the sagittal plane. The platform's locomotion is powered by the hip motor that adjusts the leg touchdown angle in flight and balance in stance, along with a tail motor that adjusts body shape in flight and drives energy into the passive leg shank spring during stance. Although the two-DOF tail is spatial, spatial inertial reorientation analysis was presented but was only demonstrated for the robotic system constrained in the sagittal plane with the tail operating in the pitch DOF. The authors adopt a template-anchor framework[53] to represent this machine's four-DOF steady sagittal plane running as the hierarchical composition of the low DOF constituents described as (1) tail energy pump, (2) Raibert Stepping, (3) Raibert pitch correction and (4) shape reorientation. The authors apply the four decoupled one- DOF control laws associated with these isolated templates directly to the (highly dynamically coupled) physical platform and demonstrate empirically steady sagittal plane running whose body motions reveal, when viewed in the appropriate coordinates, striking similarity to the corresponding isolated one-DOF constituents.

3.2. Articulated, spatial tail mechanisms

Recent research has studied the effect of tail structures, ranging from a single-body rigid pendulum to a six-DOF articulated tail, on the maneuverability of legged robots along the yaw direction.[54] A dynamic model was developed that calculated the tail base loading (inertial moments and forces) based on prescribed joint angle trajectories. A split-cycle acceleration profile with different duration half-periods for the acceleration, and deceleration phases of the tail motion were used to help overcome static friction at the feet. Case studies were presented that analyze the actuation effectiveness (what loading contributes most to net rotation), the effectiveness of a split-cycle trajectory approach, the effect of maximum tail velocity on yaw angle maneuverability and the impact of increased tail articulation for equivalent angle trajectories. Significant results of this work emphasizes the relatively

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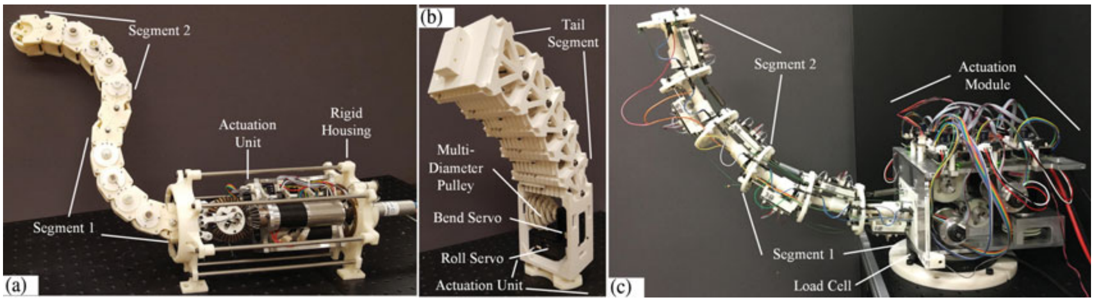

Fig. 3. Articulated, spatial tail mechanisms: (a) roll-revolute-revolute robotic tail,[44] (b) discrete modular serpentine tail[43,46] and (c) universal serpentine robotic tail.[42,45]

equal importance of the tail's centripetal and tangential inertial force loading for trajectory planning (with centripetal loading slightly more important) in affecting yaw angle maneuverability, the benefit of split-cycle frequency modulation for controlling the relative magnitude of joint acceleration and the benefit of multi-DOF/articulated tail structures. Results indicate that higher articulation in the tail structure results in larger angular displacements that correspond to larger velocities and accelerations of the tail segments that increase inertial loading in comparison to single-body rigid pendulums undergoing equivalent tail motions. For similar tail trajectories, a six-DOF tail provided a greater net yaw angle rotation of a quadruped robot equivalent to 33.8° in comparison to a single DOF tail that provided a yaw angle rotation of 25.5°. However, increased articulation requires more complex mechanical designs and control of the additional DOFs. Therefore, some researchers investigated cable-driven, under actuated, hyper-redundant spatial mechanisms for the use as articulated, spatial tail mechanisms shown in Fig. 3.

The first articulated tail to be proposed was the Roll-Revolute-Revolute Robotic Tail (R3-RT),[44] shown in Fig. 3(a). The tail is three DOFs that is composed of three main subsystems: (1) rigid housing, (2) actuation unit and (3) two independently actuated, scalable tail segments each composed of six links. The rigid housing incorporates bearings to enable a roll DOF along with a miniature, high-current-capacity slip ring which enables continuous roll of the actuation unit and tail segments; thus, enabling it to operate both as a reaction wheel to provide reactive moments and as an asymmetrical inertial adjustment mechanism. The remaining two motors rotate pulleys that transfer motion to the tail segments via cables. Novel contributions in terms of the cable driven manipulator include the use of contoured cylindrical links that maintain equal antagonistic cable displacements, to enable two active cables to be connected to a single driving pulley. For resolving redundancy within a segment, pairs of gears with equal pitch diameter are mounted along the segment to prescribe equal relative link rotation within the segments. Furthermore, considerations were made to mechanically decouple actuation of two tail segments. This was achieved by using an S-shaped cable routing scheme for the segment 2 cables through the segment 1 portion of the tail that undergoes equal extension and contraction under the constraint that neighboring linkages rotate by equal relative angular displacements.

The authors demonstrated how the R3-RT produces a higher dimensionality end-effector workspace, in comparison to pendulum-like tails, due to the increased articulation of two independently actuated segments. This feature enables a greater domain for COM positioning, which is important for static stabilization applications. Kinematic and dynamic loading models of the tail mechanism were developed to analyze the inertial forces and moments generated due to tail motions. Furthermore, the first experimental evaluation of articulated versus pendulum-like tails analyzed the loading benefits at the tail base that are transferred to a mobile robot. In this experiment, the articulated single segment R3-RT was transformed into a pendulum by immobilizing gears to maintain consistent mass properties between the two structures under consideration, and constant cable tensions were used to produce tail motions with equal cable displacements. For various cable tensions, the generated inertial loading about the tail base, forces and moments, was measured using a six-axis load cell. Results indicated that the articulated tail, in comparison to the pendulum-like tail, on average provided a 53% increase in generated inertial moment, and a net 44% reduction in generated inertial forces. Further analysis showed that the moments are more significant than forces for producing inertial adjustment because tails are usually attached near the COM of the mobile robot; thus, reducing the

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effects that forces have on rotating the system. For precise COM positioning, important for static stabilization applications, experiments measured the repeatability of the mechanism to be between ± 2 and $\pm 5.1^\circ$ for segment 1 and between $\pm$ 3.1 and $\pm 6.7^\circ$ for segment 2 with the largest angular error up to 10° at the tail tip linkage attributed to gear backlash and play.

A simulation-based study[55] using the R3-RT with a quadrupedal robot[56,57] has shown the tail's capabilities in affecting the yaw, pitch and roll dynamics of a mobile robot. Similar to previous analyses, the yaw-angle case study relates to utilizing the tail to steer the robot. For the roll-angle case study, the tail's gravitational loading is utilized to reject an external disturbance applied to the legged platform that would otherwise destabilize and tip the robot. For the pitch-angle case study, the tail prevents backward pitch-angle tipping in response to an externally applied disturbance due to the tail's contact with the ground in a tripod stance. Depending on the pitch angle at contact, if the system does not naturally fall after the external disturbance is dissipated, the tail can be used to pitch the robot forward.

The Discrete Modular Serpentine Tail (DMST)[43,46] is a spatial articulated tail that utilizes modular segments, shown in Fig. 3(b), to construct a tail. Multiple segments can be connected in series to enable multiple tail curvatures, and modular end-effectors such as a robotic gripper can be attached to enable manipulation capabilities. A single two-DOF tail module is composed of an actuation unit and a serial chain of links. The roll DOF, also capable of continuous rotation to enable reaction wheel like performance, changes the orientation of the bending plane to distribute loading. Similar to the R3-RT, tail linkages are shaped with circular contours to maintain equal antagonistic cable displacement but require two actuation cables per link to produce motion, each connected to the multi-diameter pulley. Therefore, tail curvatures are produced upon rotation of the multi-diameter pulley and can be modified by varying the coupling ratios between the linkages and pulley. Kinematic and dynamic loading models of the cable-driven mechanism were developed to analyze the impact of trajectory and design parameters, such as tail motion time spans, roll angle, mass distribution and coupling ratios, on the loading profiles transferred through the tail base. For precise COM positioning, experiments measured the repeatability of the mechanism to be $\pm 0.8^\circ$ with an angular error of up to 2.3°–3.1°. The authors demonstrated using multi-body dynamic physics simulations, how the DMST attached to an inherently unstable planar biped can be used enable a stable forward walking gait by regulating COM position above the legged robot's support polygon. Furthermore, the authors developed a disturbance rejection control algorithm to demonstrate how the tail can be used for pitch-angle disturbance rejection of up to 20.4 N-m to prevent tipping over.

The Universal Spatial Robotic Tail (USRT),[42,45] shown in Fig. 3(c), is an articulated, spatial tail that utilizes a hybrid design approach in constructing a novel tail mechanism that most closely resembles a biological tail in terms of its flexibility and range of motion, by using a combination of universal joints encased within longitudinally oriented compression springs. The universal joint enables bending in the pitch and yaw directions, but not in the undesirable roll rotation between tail links. In addition, an extension spring is added vertically above each universal joint to aid in counteracting gravitational loading. Unlike the R3-RT and DMST that utilize rigid coupling to distribute angles among linkages, the compression springs surrounding each universal joint are used to equally resist bending in all directions and aid in distributing the actuation loading along a tail segment. Optimizations were constructed to select spring stiffnesses that balanced consideration for the tail's zero actuation configuration, vertical bending actuation requirements and horizontal actuation bending requirements. To enable real-time tail configuration sensing, two displacement sensors were mounted between the links separating each joint to measure the distances between pairs of fixed points on each link that are used to compute the pitch and yaw joint angles of each universal joint. Furthermore, inertial measurement units were mounted onto each link to provide body fixed angular velocity and relative orientation information used. The loading capabilities of the tail were analyzed, and an experimental prototype for comparison to the dynamic model. In addition, as a preliminary case study, the tail was virtually integrated with a simulated biped to analyze the tail's maneuvering capabilities.

3.3. Continuum tail mechanisms

A recent surge of interest into soft robots, capable of forming continuous curvatures, has been motivated by the perceived observations and performance of traditional rigid body robotic manipulators that exhibit a mechanically a stiff interface with the surrounding environment.[58] The

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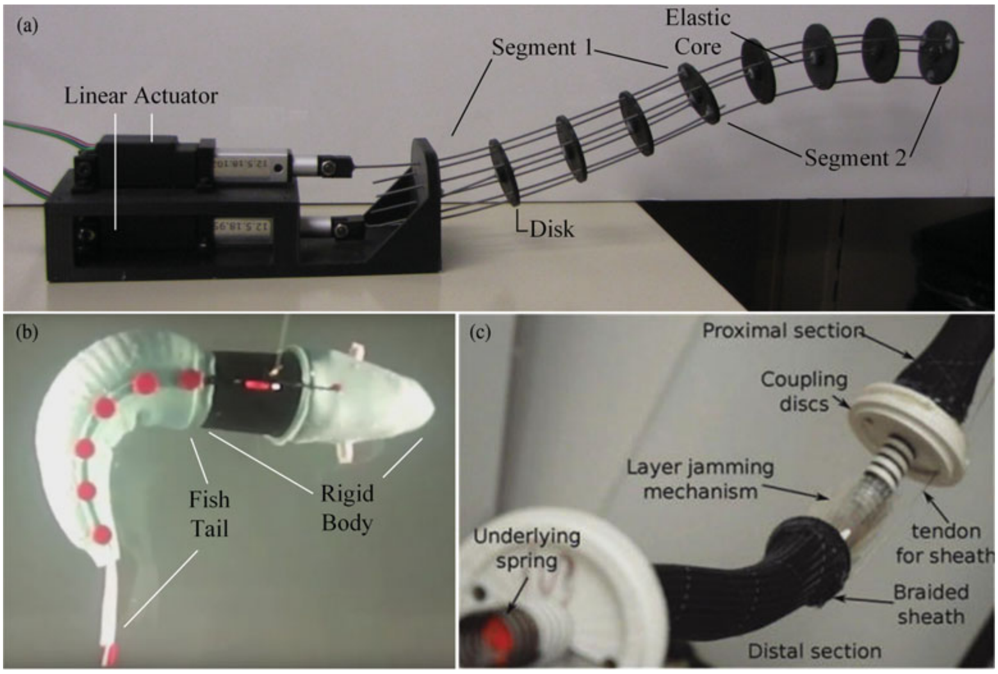

Fig. 4. Soft robotic tail mechanisms: (a) continuum robotic tail,[60–62] (b) autonomous soft robotic fish[29] (image courtesy of MIT News)[64] and (c) continuum kangaroo tail via mechanical layer jamming.[5]

body compliance of soft robots is a salient feature found in many natural systems that offers inherent robustness to uncertainty, adaptability to environmental uncertainties and the capacity to distribute forces at the cost of reduced repeatability and accuracy.[59]

Rone *et al*. proposed the use continuum robotic tails for inertial adjustment applications,[60] shown in Fig. 4(a). The tail was composed of eight disks rigidly mounted along an elastic core. The two-segment structure, capable of forming two curvatures, also called mode-shapes, was composed of six rods that provide structural support. Three rods were terminated at the fourth and eighth disks in each segment. Two active rods are displaced via linear motors to create planar tail curvatures. The authors also proposed a two segment cable-driven variation, driven by three linear motors, capable of forming spatial curvatures. These preliminary prototypes were used to validate a novel method of dynamic modeling that captures curvature variations along segments using the principle of virtual power.[61,62] For stabilization and maneuvering applications, the authors analyzed the impact of both trajectory and design factors on the loading profiles about the tail base resulting from tail motions of the continuum structure. Trajectory factors considered include the mode-shape, speed, bending magnitude and bending plane angle. Design factors considered for a fixed mass tail include segment length(s) and mass distribution. Results indicated that a shorter segment 1 length, in a two segment continuum tail, provides a greater range of motion of the tail tip and will enable more rapid tail motions due to less required actuation displacement and allocating a larger mass concentration in segment 2 toward the tip provides larger bending moments and greater fidelity of control over the applied moment. Furthermore, the two mode-shapes in the tail structure were shown to increase the manifold of inertial loading about the base of the tail by actuating various mode shapes during tail motions.

However, challenges associated with scaling the continuum designs up to the macro-scale led the authors to consider the serpentine tail structures discussed in Section 3.2, particularly the USRT, Fig. 3(c). First, the uniform elasticity of the single continuum core did not allow for the tail's stiffness to vary in different directions (i.e., vertical and horizontal) or along the structure. Higher stiffness to counteract gravity in the vertical direction would be more desirable, along with higher stiffness at joints closer to the tail base, as they have to support larger gravitational moments. Second, for uniform horizontal bending with minimal actuation, it is desirable to have a low, consistent horizontal stiffness. In addition, on the macro-scale, when the continuum structure bends out of the plane, the core's torsional deflection causes undesired sag in the tail that must be accounted for in the modeling and further impedes uniform bending. Third, the continuum robot's theoretically infinite-DOF joint space provided significant challenges in planning strategies for real-time interoceptive sensing. In the USRT (Section 3.2), the first challenge was addressed by incorporating an extension spring vertically above the universal joint to counteract gravity without impacting the horizontal bending stiffness provided by a compression spring surrounding the universal joint. The second challenge was addressed by using two-DOF universal joints (pitch/yaw) that constrain relative roll between disks instead of three-DOF continuum subsegments (vertical/horizontal bending and torsion) that allow for relative twist. The third challenge was addressed simply by utilizing a rigid-link structure with a finite number of joint angle states.

Marchese *et al*. proposed an autonomous soft-bodied fish robot that is both self-contained and capable of rapid, continuum-body motion[29]. The robot, shown in Fig. 4(b), is composed of a rigid body structure that houses the electronics, sensors and a fluidic actuation unit. The fish tail is composed of fluidic elastomer actuators that expand and contract with fluidic pressure; thus, creating left or right bending curvatures. The major implications of this work demonstrate how the continuum tail can emulate natural motions in forward swimming and rapid escape response maneuvers in the form of C-shape heading angle turning with a maximum measured rate of 320°/s. The kinematics and controllability of the soft-bodied robot during escape response maneuvers were shown to have similar input–output relationships to those observed in biological fish. In a later piece of work by Liu *et al*., a soft, continuum-bodied robotic fish[30] with a tail actuated via three servo motors controlling discrete joints demonstrated a C-shape escape maneuver with a maximum measured heading angle turning rate of 120°/s. The comparison of measured yaw rate maneuvering between[29] and,[30] indicate one of the very first quantitative experimentally validated performance advantages that a continuum tail actuated via pneumatic pressure can provide versus a conventionally actuated fish tail mechanism.

To mimic the functionalities of kangaroo tail usage in nature, Santiago *et al*. proposed a continuum robotic structure that can modulate compliance via mechanical layer jamming.[5] The mechanism utilized a novel mechanical approach to layer jamming, shifting away from fluidic actuation and vacuum pressure as originally proposed in ref. [63]. The tail, shown in Fig. 4(c), is composed of a proximal and distal section, each driven by three active cables routed through coupling disks and terminated at the section ends. Displacement of these cables enables spatial tail curvatures. The structure is composed of an underlying spring back bone that runs along the manipulator's length. The layer jamming mechanism is composed of laser cut flaps enclosed within a nylon braided sheath, similar to that used for artificial muscles. Extension/pulling of the sheath via tendons causes it to shrink in diameter resulting in additional friction due to the internal flaps rubbing against the spring steal core, therefore, stiffening the structure. The authors presented a novel application of the tail attached to a stuffed kangaroo toy. In a stiff state, the tail was used to provide an additional anchoring limb to enable additional stability while standing on its hind limbs. In the unstiffened state, the kangaroo was unable to support its weight and slowly collapsed to the ground. As part of future work, the authors plan to taper the diameter of the tail to better emulate a kangaroo tail structure and functionality. Contrary to previous implementation of robotic tails that exploit tail motions to aid inertial adjustment applications, this work represents the first application into studying environmental contact and variable softness/compliance of a tail.

4. Challenges

Since the early implementations of robotic tails, mechanical design, modeling and control aspects have been continuously improving. The extent to which the promise of robotic tails can be realized depends on the robustness of its design, the accuracy of modeling and the effectiveness of the control system to demonstrate the full range of functionalities of tail usage observed in nature that involves both inertial adjustment capabilities (stabilization, maneuvering) and manipulation. However, several key steps are necessary for robotic tails to realize their full potential that can be broken down into challenges in mechanical design, modeling and control.

4.1. Mechanical design challenges

Performance of robotic tails is highly dependent on its mechanical design. To date, with reference to Table I, tail designs have evolved from planar to spatial pendulums and most recent progress has shifted to articulated, spatial mechanisms. These advancements have been coupled to enhanced workspace, functionalities and inertial loading capabilities for more desirable effects of inertial adjustment applications. Furthermore, articulated tail designs have begun exploring applications of manipulation to extend the capabilities of tails on-board mobile robots. However, an optimal and general purpose tail design has yet to be proposed. The fundamental challenges that govern this problem include the following:

- Design optimization and considerations on the minimal number of active DOF's required to produce a spatial workspace with distributed motion about its tail length for enhanced inertial loading capabilities. The added mass of the actuators contributes a change to system dynamics and is directly related to the cost inertial adjustment capabilities.
- Limits on strength, and precision of the tail mechanism that can perform both dynamic motions for inertial adjustment applications and provide the accuracy required for quasi-static applications that involve precise COM positioning for static stabilization and manipulation.
- Limits on motor power and energy efficiency to maintain a cantilevered configuration with minimal energy consumption.

Given the broad base of tail designs presented in the literature, rigorous comparative analysis is needed of the merits and shortcomings of these designs in relation to one another and in relation to the various types of mobile robotic platforms (e.g., biped, quadruped and wheeled) on which they may be deployed.

4.2. Modeling and control challenges

Although modeling and control approaches have been developed and implemented over a wide range of applications, inertially adjusting a mobile robot using a robotic tail is a challenging task due to modeling of a highly coupled, non-linear dynamic, under actuated system. Since the tail attachment point to a mobile robot is usually located at its rear end, offset from the robot COM, during inertial adjustment applications, tail motions generate both a reactive moment and lateral forces, caused by eccentric mass distribution of the tail that are transferred to the mobile robot. These forces also induce a moment due to this positional offset that introduces challenges in modeling and control. Depending on the state at each instant, this may either augment or diminish the resultant moment produced by the tail, complicating analysis considerably. This problem requires optimization to find good control policies. To address these challenges, common methods employed by researchers include simplifying assumptions that have neglected the effects of inertial forces,[6,22,24,31,35,37–40] on the mobile robot and have constrained the robotic system dynamics to a single plane.[26–28] The challenges that remain to be addressed both in low-level control and high-level planning to overcome realistic constraints include the following:

- Designing algorithms for maneuvering that also account for the stability of the system that may be compromised during tail motions.
- Designing algorithms for computing an optimal tail trajectory with a constrained workspace that considers the effects of both inertial forces and moments to maximize desirable effects of inertial adjustment.

Broadly speaking, efforts are needed to reconcile the effects of a tail within existing frameworks for analyzing the stability of a mobile robot. In doing so, the stability analysis can be used to generate tail control inputs to generate inertial loading and adjust gravitational loading in a similar manner as leg control inputs are formulated to generate desired ground contact loading.

5. Conclusion

Robotic tails have shown potential to enhance the stability, maneuverability and propulsion of mobile robots by providing a means, separate from its main form of locomotion, to enable inertial adjustment capabilities and have demonstrated significant technological advances to the field robotics in general with recent applications demonstrating manipulation. Despite the achievements accomplished with robotic tails, based on the current state-of-the-art, significant challenges still persist in regards to mechanical design, modeling and control to provide a full range of capabilities based on tail usage observed in nature, and fully understand the effects of both inertial forces and moments and its impact on the mobile robot.

For many prospective researchers, fully understanding the current state-of-the-art will provide a valuable starting point. The authors hope that the material presented in this review paper will provide a better understanding of the remaining challenges attributed to robotic tail design, analysis and implementation, and from that, initiate further developments with the objective of enabling multiple functionalities on-board mobile robots ranging from stabilization, maneuvering and manipulation.

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