

# Biologically inspired jumping robots: A comprehensive review

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## ABSTRACT

Applying concepts and methods of bionics to endow autonomous robots with elegant and agile mobility just like **natural** living beings is gradually becoming a hot research topic in intelligent robot field. Compared with walking, crawling, rolling and other motion modes, jumping performs considerable advantages that can leap across obstacles and move to different heights in agility and flexibility. In this paper, we specifically review the developments of biologically inspired jumping robots in the past decades, and give comprehensive analysis on some key technologies for implementing a practical jumping robot effectively. First, the jumping mechanism of frog (amphibian, quadruped), locust (arthropod, hexapod), kangaroo (mammality, bipedalism) as examples of typical animals good at jumping is introduced and analyzed, from which it is concluded that power sources, limbs coordination and control are key elements for excellent jumping performances, which should be synthetically improved by combination with structure design and model establishment. Then, spring loaded inverted pendulum (SLIP), bio-inspired open-chain and closed-chain multi-linkage as representative jumping mechanical structures, their characteristics are explored accompanied with dynamic analysis. After a detailed analysis to actuators and energy storage devices and a comprehensive summarization to functional and soft materials commonly applied in jumping robots, different control methods and strategies adopted to achieve better jumping performance are reviewed and analyzed, from self-righting, driving control to path planning. Especially, how to analyze the stability of a jumping control system and how to stabilize it are explained theoretically by taking a vertical monopodal jumping robot as an example and via limit cycle analysis. Finally, some feasible and potential future developments in bio-inspired jumping robots are also presented after detailed discussions on current status and existing deficiencies.

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## 1. Introduction

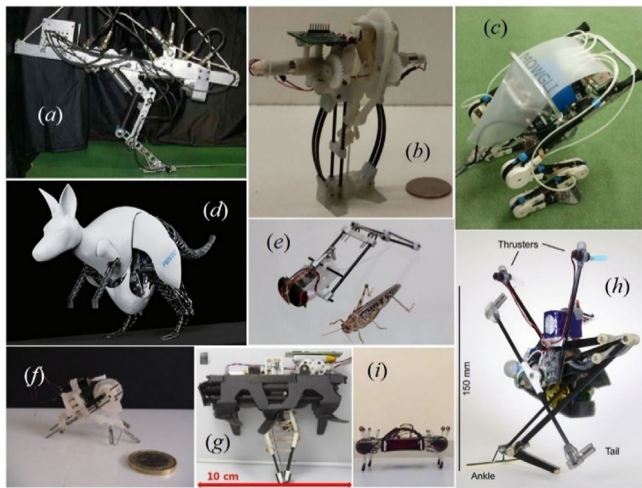
As a significant type of locomotion with the reputation of high mobility, jumping motion can support animals which live in forests, jungles or marshes to pass over obstacles in complex environments, escape natural predators and obtain sustenance [1–5]. Compared with walk and crawl, jump has advantages of high energy density, efficient obstacle negotiation, rapid terrain transition and so on [2,6]. For example, a goat can leap across mountain stream, a frog jumps from a branch to another one [1], a burrowed click beetle uses ejection to avoid hunting of enemies [7], an oceanic dolphin leaps from the sea to get rid of parasites [8], etc. In robotics, a robot via jump may move through different heights and irregular terrain, and further may realize more convenient freight transportation, patient care, disaster relief [9]

and rescue [10], interstellar exploration, etc. Nevertheless, directly designing jumping structures for robots without biological inspiration usually faces many difficulties, such as low energy efficiency, irrational mechanical constructions, etc. Several researchers were motivated by animals which are good at jumping and began to consider how to imitate and utilize physiological structures and functions of animals to design jumping robots in current decades [8,11–15].

Research on jumping robot was originated from NASA in 1969. NASA wanted to utilize this robot embarked in Apollo series to explore surface of the moon [16]. In academia, the earliest researches *3D hopper* and *Acrobot* were developed in the 1980s. *3D hopper* [17] was designed as a monopodal robot with two degrees of freedom. One was the rotation joint between body and foot, and the other was the translation joint pointing to body along leg. Thus, it could realize the jumping and landing motions in a vertical plane, and could be improved by adding a hinge joint to move in the three-dimensional space. Modeled as double pendulums, the structure of *Acrobot* [18] was similar to *3D hopper* and only had one actuated joint to make power and keep balance

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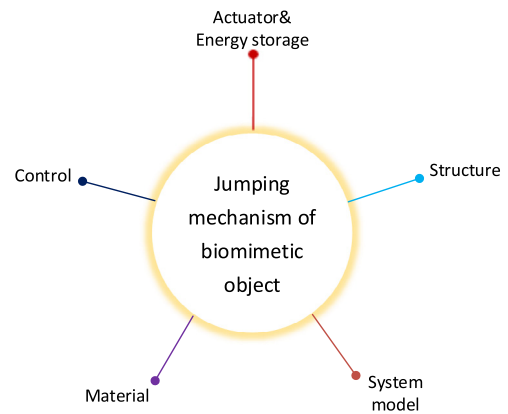
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**Fig. 1.** Several typical bio-inspired jumping robots. (a). *Kenken* [25], (b). *MSU jump-runner* [26], (c). *Mowgli* [27], (d). *Bionic-Kangaroo* [28], (e). *TAUB* [29], (f). *Grillo I* [30], (g). *JumpRoACH* [31], (h). *Salto -1P* [32], (i). *Miniature* [33].

synchronously. During the stance phase it was controlled to keep inverted for trajectory tracking while periodically accelerating its mass of center vertically. During the flight phase it could rotate its leg to enable landing as the same configuration as it took off. Subsequently, several significant theories and designs based on these two jumping robot models had been developed [19–23]. However, these early studies were hard to help researchers to build practical experimental platform because a lot of restrictions and assumptions which were almost impossible to be realized in the real world had been attached in their models [24]. For example, the experimental prototypes designed by Raibert and his partners needed many auxiliary equipments to keep balance or supply energy to help robot achieve jumping motion.

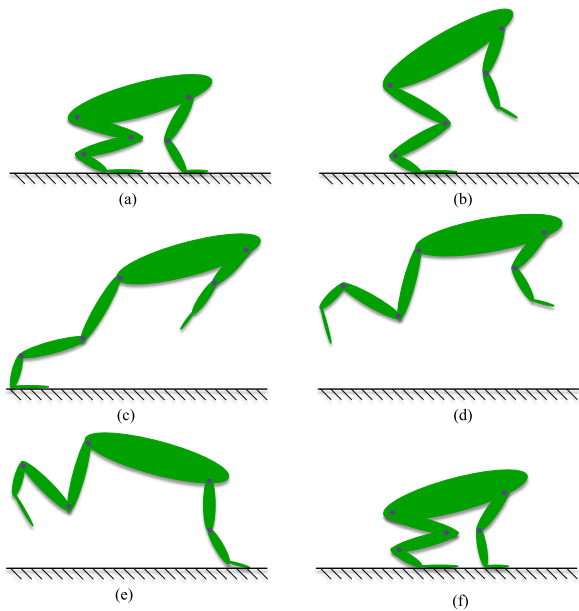
In recent years, a large number of studies about bio-inspired jumping robots have been developed and several typical researches can be seen in Fig. 1. U. Scarfogliero [30,34] presented a long jumping quadruped mini robot *Grillo* with 15 g of weight and 50 mm of length that could overcome obstacles and move in unstructured environment. The loaded springs connecting to hindlimbs were used to store energy and help to achieve a forward speed about 1.5 m/s while taking off. Inspired by desert locusts, M. Kovač [35] designed a 5 cm, 7 g jumping robot which could jump 27 times higher than its own size with initial take-off speed at 5.96 m/s. It used many light components such as POM gears, aluminous legs, PEEK body and others to reduce weight of the robot and obtain excellent jumping performance. S.-H. Hyon [25] took full advantages of energy storage of tendon and muscle, and presented a one-legged robot *Kenken* with motions of run and jump by imitating dogs. The power to jump came from tendons loaded by spring and muscle designed by hydraulic actuators. Even though its controller and stability had not been solved well, the jumping and running motions still showed relatively outstanding performances via a huge weight of 13.26 kg. R. Ni-yama [27] designed a pneumatic actuated bipedal robot *Mowgli* and realized its robot motion control of jumping and landing softly and robustly. Each leg of *Mowgli* consists of three actuated joints (namely hip, knee, and ankle) with McKibben pneumatic muscle actuators and passive springs, and one unactuated joint. J. Zhao presented a series of bio-inspired miniature jumping robots *MSU Jumper*. The robot in [36] with weight of 23.5 g could realize continuous steerable jumping via its self-righting and steerable capabilities with only one actuator. Inspired by the aerial maneuvering ability of lizards, *MSU Tailbot* [37] improved



**Fig. 2.** Key factors of designing biologically inspired jumping robots in system simulation and machine manufacturing.

its performances by special mechanical structure (an inertial tail to keep balance) and advanced control algorithms (sliding mode control to improve jumping trajectory). Aiming to solve high energy depletion of pure jump, [26] used gear train to address running locomotion while kept jumping performance to the maximum extent over  $143.6 \pm 2.2$  cm in height and  $59.3 \pm 4.3$  cm in distance. According to vampire bats' locomotion, M. Woodward presented a miniature robot *MultiMo-Bat* [38] with the abilities of jumping and gliding, which utilized components sharing (nearly 70% of robot mass had been used in two locomotion modes and over 80% jumping performance had been preserved) to reduce weight and achieve multi-modal motions. V. Zaitsev [29] designed a locust-inspired miniature jumping robot *TAUB*, whose motor, battery and microcontroller were produced by 3D printer using acrylonitrile butadiene styrene (ABS). It mimicked structure and motion of locust and applied torsional spring to store energy, and achieved excellent jumping performance about 3.1 m in height and 3 m in distance. Based on jumping agility of galago, W. Haldane presented a monopodal vertical jumping robot *Salto* [39, 40] with series-elastic power modulation, and a spatial jumping robot *Salto -1P* [32] with repetitive high acceleration. The power modulation in *Salto* could increase peak power for jumping and release more energy than muscle providing alone. The highest vertical jumping agility of *Salto* could reach 2.2 m/s which had greatly exceeded other jumping robots. Compared with *Salto*, *Salto -1P* modeled by spring loaded inverted pendulum (SLIP), had the repetitive jumping function and could achieve an extreme acceleration of 14 times of earth gravity while it was taking off the ground. The time of stance phase possessed about 7.7% during the overall jumping phase but its agility reduced to 1.83 m/s due to the loaded battery for repeated jumping. M. Loepfe [41] presented a roly-poly soft jumping robot which was combustion-driven powered by nitrous oxide-propane/butane gas mixtures. The robot had an elastomeric silicone body with incorporated combustion chamber and without tether and battery. It could jump about 0.2 m in height and 0.5 m in distance.

The above description gives a brief review for several typical bio-inspired jumping robots in the past decades. In addition, there are many other excellent jumping robots have been presented. We conclude them into Table 1 due to the length limitations. In Table 1, we provide the mass, jumping height and distance of these typical jumping robots, and give some key analysis on their highlights and deficiencies. From this table, it can also be concluded that: (1) In terms of performance index, the design of jumping robots mainly focuses on jumping height, jumping distance, agility, maneuverability and jumping mode, etc. In order to realize the required performance indices, firstly, a relatively



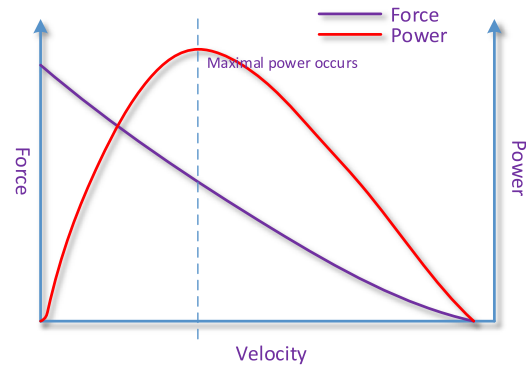
**Fig. 3.** 2D lateral view of jumping process of *rana dybowskii*. (a). Crouched state to prepare for take-off; (b). Take-off from initial time to the forelimbs off the ground; (c). Take-off from the forelimbs off the ground to the hindlimbs off the ground; (d). Flight phase; (e). Preparation for landing; (f). Landing.

appropriate jumping mechanism needs to be determined based on biology and biomimetics. Then the choice of materials is of importance to achieve efficient jumping and solid robot body. Next, the accurate actuators, including motion mechanism and energy storage mechanism, need to be designed flexibly for energy saving and structure optimization. At last, by taking all the above factors into consideration comprehensively, accurate system model should be established and elegant controller should be proposed to try to achieve the required jumping performance. (2) Design a jumping robots with universal performances is of difficulty because of the technical restrictions. Thus, with regard to different design purposes, the concerned key factors are also distinct. For instance, *TAUB* [29] only considered its extreme jumping performances in distance and height, but *Bionic-Kangaroo* must design special controller to keep attitude balance rather than pursuing ultimate jumping performances. In Fig. 2, key factors which are significant to design a jumping robot are shown based on bio-inspired jumping mechanism. We will illustrate the specific effects and design thoughts of these key factors in the following sections.

The reminder of this paper is organized as follows. Jumping mechanism of animals always taken as bionic objects will be introduced in Section 2, including their muscle force, power, coordination and kinematics. In Section 3, Bionic mechanical structures design and dynamic modelings are illustrated. The design and application of actuators and energy storages are elaborated in Section 4. Section 5 introduces the material choice and utilization in jumping robots design. Section 6 focuses on the problems of control and stability. Sensors and typical control systems are also introduced in order to learn about system design of jumping robots. Several existing problems are discussed and future developments are elaborated in Section 7. Finally, some conclusions are illustrated in Section 8.

## 2. Jumping mechanism of animals

In order to obtain sustenance, avoid predators or pass through uneven terrains like forests, jungles or marshes, many kinds of



**Fig. 4.** Relationship of force-velocity and power-velocity during jumping [58].

animals choose jump as an effective way to overcome challenges and difficulties mentioned above in the real world. As typical animals which have outstanding jumping abilities, frog, locust and kangaroo possess powerful muscles in hindlimbs for remote jumping and excellent body's coordination capacities for keeping balance. The movements abilities of these animals often exceed current engineering performances via their power-amplified systems combining muscles and nerves [54]. Then we will illustrate jumping mechanism of frog, locust and kangaroo as representatives of animals with skilled jumping. In animal taxonomy, frog, locust and kangaroo can be used to embody the features of amphibian, arthropod and mammality, respectively; and in morphology, they can be served to represent the characteristics of quadruped, bipedalism and hexapod, respectively. Specifically, we elaborate frog in detail from the view of muscle force, power, coordination of limbs, kinematical control, etc.

### 2.1. Jumping mechanism of frog

A simple diagram of jumping process which introduces a species of frog named *rana dybowskii* can be seen in Fig. 3. With regard to a frog, jumping ability is closely related to the high-power output from the leg's retractor and extensor muscles [55, 56]. Then we will illustrate jumping mechanism of frogs from the view of muscle force, power, coordination of limbs, kinematical control, etc.

#### 2.1.1. Muscle force and power

A high level of mechanical power is of importance to realize jumping with high performances. In order to obtain it, strong muscular system is required to deliver these high powers [57]. A frog can accelerate fleetly from a static crouched attitude to high vertical and forward velocities in about 100 ms for the maximal jumping locomotion.

For obtaining enough power to jump effectively, during power generation three necessary conditions should be satisfied: muscles are operated at optimal sarcomere lengths (SL) over the plateau region of the force-length relationship, shortened at an appropriate velocity for maximizing generated power, and activated by moving filaments one another at an optimal speed. A simple sketch map to indicate the relationships between force-velocity and power-velocity is shown in Fig. 4 [58]. From Fig. 4, it can be seen that the force of semimembranosus muscle (SM) decreases while the velocity of muscle fibers increase. However, the power of SM shows convex with a peak value occurring at the appropriate  $V/V_{\max} = 1/3$  for maximal power generation (where  $V$  represents shortening velocity during jumping, and  $V_{\max}$  is the maximum velocity of shortening). Confirmed by further research, knee and hip extensors have similar characters like SM [59].

**Table 1**  
Jumping height and distance of bio-inspired jumping robots in the recent decade.

Year	Name	Mass	Jumping distance	Jumping height	Actuators and energy storages	Highlights	Deficiencies
2018	<i>Ascento</i> [42]	10.4 kg	N/A	40 cm	Hip motor, torsional spring.	High agility, jumping with rolling, vision navigation, spring compensation.	Hard to overcome rough terrain, complex controller design.
2017	<i>Salto-1P</i> [32]	98 g	>2 m	125 cm	Torsional spring, thruster.	High agility, continuous jumping, light weight.	Distance limitation of wireless communication, cannot achieve intermittent jumping.
2016	<i>Salto</i> [39]	100 g	N/A	120 cm	Torsional spring.	High agility, two-stage jump for increasing height, light weight.	Cannot jump forward, need artificial assistance.
2016	<i>JumpRoACH</i> [43], [31]	59.4 g	60 cm	162 cm	Latex rubber, torsional spring.	Adaptive jumping height, active clutch mechanism for energy storage, self-righting design.	Without mechanism of attitude regulation in the air and landing phase.
2016	<i>Minitaur</i> [33], [44]	5 kg	N/A	48 cm	Brushless DC motor, parallel spring.	Mechanical robustness, backlash avoidance, high-actuation bandwidth and power increase.	Without mechanism of energy storage, low torque, low compliance.
2015	<i>Roly-poly Soft Robot</i> [41]	2.1 kg	N/A	20 cm	Combustion.	Combustion drive, soft material design.	Low jumping frequency, hard to control jumping direction.
2015	<i>TAUB</i> [29]	23 g	>300 cm	310 cm	Torsional spring, wire.	High jumping distance and height, light weight, torsional spring.	Without attitude and landing control, cannot achieve continuous jumping.
2015	<i>Jumping Rolling</i> [45]	66 g	21.8 cm	23 cm	Torsional spring, slider, hook.	Jumping and rolling by one DC motor, SMA-actuated, circular frame.	Low jumping frequency, no experimental results.
2014	<i>Jump Glide</i> [46]	67.5 g	>8 m	>1 m	Carbon fiber spring, motor, clutch.	High jumping distance and height, ballistic jumping, high glide ratio.	Hard to optimize and control flight trajectory.
2014	<i>MultiMo-Bat</i> [38]	115.6 g	232 cm	305 cm	Linear spring, SMA wire, cable, clutch.	High jumping distance and height, jumping with gliding, component sharing.	Lack of glide control and wings regulation, cannot change take-off angle.
2014	<i>MSU Jump-runner</i> [26]	25 g	59 cm	143 cm	Elastic strip, cable, rotation link.	Jumping with running, self-righting design, elastic rod, light weight.	Hard to adapt to tough terrain, low jumping frequency.
2014	<i>MSU-tailbot</i> [37]	26.5 g	90 cm	87 cm	Torsional spring, rotation link, cable.	Inertial tail, sliding mode control, self-righting design.	Low jumping frequency, lack of landing control.
2014	<i>Parrot Jumping Sumo</i> [47]	192 g	80 cm	80 cm	Spring.	High jumping performance, low cost, operated by smartphone.	Low endurance, lack of landing buffer device.
2013	<i>MSU-jumper</i> [36]	23.5 g	90 cm	87 cm	Torsional spring, rotation link, cable.	Continuous steerable jumping, minimum actuation, light weight.	Lack of landing control, attitude stabilization.
2012	<i>Locust-inspired</i> [48]	7 g	100 cm	71 cm	Cam, linear spring.	Light weight, jumping with high performance, clicking mechanism.	Cannot regulate stored energy and achieve continuous jumping.
2012	<i>Flea-inspired robot</i> [13]	1.104 g	35 cm	64 cm	Catapult mechanism, SMA spring.	Light weight, SMA-actuated, high performance of jumping.	Hard to build autonomous system, lack of self-righting mechanism, without take-off control.
2012	<i>Grillo III</i> [49]	22 g	20 cm	10 cm	Linear spring.	Model-based jumping force optimization, continuous jumping.	Lack of autonomy, incomplete control system.
2011	<i>EPFL jumpglider</i> [50,51]	16.5 g	30.2 cm	12 cm	Torsional spring, cam.	Jumping with gliding, high gliding distance, impact force reduction, infrared remote control.	Without pitch control, gliding is ineffective while jumping from the ground.
2010	<i>Buckling</i> [52]	18 g	95 cm	15 cm	Elastic strip, snap.	Elastic energy from bend and twist of strip, high impulsive force frequency.	Need external power supply, incomplete synchronization control.
2010	<i>Controllable jumping robot</i> [53]	54.1 g	N/A	20 cm	Extension spring, cable.	Continuous jumping, self-righting mechanism.	Low jumping frequency, lack of take-off and landing control.
2008	<i>7 g Miniature</i> [35]	7 g	N/A	138 cm	Torsional spring, cam.	Lightweight material, click mechanism, adjustable take-off angle, high endurance.	Lack of self-righting mechanism and landing control.

Therefore, all the extensors in hindlimbs of frog should operate at optimal conditions to produce maximal power to support extreme jumping. Also, differing from other animals moving in a cycle, muscle force of a frog keeps constant during shortening to guarantee the maximal power generation [60].

In addition to the above opinion, some other researches illustrate that the series elastic elements can be used to amplify the peak power output of the muscle–tendon unit during jumping [55,61,62]. But this function is usually found in arthropods like locusts. It remains to be seen whether frogs also have the similar mechanism to arthropods.



### 2.1.2. Effects of hindlimbs and forelimbs

Powerful hindlimbs are key factors to realize jumping with high performances in height and distance for frogs. However, the function of forelimbs during jumping is rarely involved in the relative literatures. In the most studies forelimbs are considered as a role to balance body attitude in the air and determine a suitable landing position [63]. [64] explores the effects of hindlimbs and forelimbs by measuring ground reaction forces. The authors divide the take-off into two phases: phase one keeps from the initial time to the forelimbs off the ground, and phase two keeps from forelimbs lift-off to the hindlimbs off the ground. Through experiments and analysis of the position of the center of mass (COM) and pivot point of frog during phase one, it is concluded that the forelimbs are of importance on elevating the COM. Thus, frogs can raise COM by using their hindlimbs and forelimbs synchronously. In the specific joints, the shoulder joint, rather than the elbow joint in forelimbs plays relatively greater impact on lifting body during early jumping.

Forelimbs can also control jumping trajectory by adjusting the body to an appropriate gesture to affect take-off angle during jumping in phase one. Then in phase two hindlimbs complete power output to accelerate the body and control the flying trajectory in this jumping process [64]. For the most quadrupeds, hindlimbs and forelimbs are working cooperatively to realize high-speed jumping motion with the help of nervous system and perception information obtained by eyes and skins [65–67].

### 2.1.3. Kinematic control

Kinematic flexibility of frog hindlimbs is a significant characteristic that makes frogs move through different motion modes with excellent performances, for example, walk and swim, steep and swallow jump respectively. Research on kinematic flexibility is helpful for designing mobile robots with multi-modal movements. [1] uses inverse kinematic analysis and dynamic catch mechanism to learn how to take advantage of muscle modulation to control take-off angle from frogs. The authors consider that frogs adjust take-off angle by posture preparation and dynamic modulation of joint kinematics. In the initial phase of jumping, the crouched magnitude of body may predict the jumping angle. Also, the shift from swallow jump from steep jump may attribute to a mechanism by controlling the rotation axes of hip, knee and ankle joints to modulate the take-off angle.

The limb segments (muscles in thigh, shank and proximal foot) behaviors include protraction/retraction which means rearward rotation pushing the body forward, abduction/ adduction which means downward rotation raising the body, and body pitching velocity which has notable contribution to steep jumping. Those drive frogs to realize jumping with different take-off angle [1,68,69]. The main effects of retraction and adduction are concentrated on the phase two of take-off process through 3D extension of hip, knee and ankle. For retraction, in the actual experiment the thigh and proximal foot retract in coincidence and remain parallel in dorsal view, but the shank remains nearly constant in the early stage before retracting during jumping. For adduction, the angle varies differentially among segments in the initial time. It is noteworthy that the average shank remains almost horizontal in steep jumping which means a rapid increase of adduction in the final take-off time. The jumping velocity angle is influenced by knee and ankle joints, and body pitching velocity is controlled by knee axis orientation and forelimbs. While raising the COM, leg joints can pitch the body upward since the knee rotation axis inclines away from vertical [64].

## 2.2. Jumping mechanism of locust

As a typical example of arthropods, locusts (*locusta migratoria*) are also chosen as bionic objects to guide jumping robots design. They can jump into the air efficiently and agilely via their long hindlimbs which are powered by contractions of femoral muscles extending the tibiae [70,71]. In general, the jumping process of locust can be divided into three phases. In the cocking phase, the forelimbs and middle limbs of a locust are placed on the ground symmetrically, and the coxae of hindlimbs are depressed. Then in order to restrain the tibiae by locking mechanism, the tibiae in hindlimbs are fully flexed against femora in hindlimbs. The coxae are depressed further until the femora in hindlimbs parallel with the ground [72]. In the co-contraction phase, the flexor and extensor tibiae muscles in hindlimbs are contracted synchronously. It makes some structural components of the femur deformed and the apodemes of the extensor stretched. In the trigger phase, the flexor tibiae muscles are relaxed because the flexor motor neurons are inhibited. The flexor tendons are released from the locked position. Then the tibiae about femora in hindlimbs are extended rapidly by extensor apodemes, and the energy stored in the cocking and co-contraction phases are converted to kinetic energy to support powerful jumping locomotion [73].

In addition, with the cooperations of neural system, biomechanical mechanism and all the limbs, a locust can control the jumping speed, azimuth and elevation components towards target [74,75]. A locust uses its forelimbs to point its body in the appropriate direction to realize azimuth control before jumping. The proprioceptors and motor neurons of it may have important effects on azimuth regulation. Speed control are realized by varying tension in the extensor tibiae muscles in hindlimbs. The neural control mechanism may be similar to azimuth control according to the research in [76]. The elevation control is depended on initial position of the hindlimbs. The motor neurons and proprioceptors at the coxae are of significance in the control process [74].

## 2.3. Jumping mechanism of kangaroo

Kangaroo (*macropodidae*) is a kind of mammal which is famous for its excellent bipedal jumping ability. In [77], the jumping locomotion is divided into two phases: a contact phase when the feet are on the ground and a floating phase when the feet are off the ground. During the contact phase, in the longitudinal direction, the kangaroo decelerates in the first half, and then accelerates in the last half. In the vertical direction, acceleration keeps positive in most contact phase and the peak value of force can achieve three to five times body weight. [34] also points that the ground react force (both longitudinal and vertical directions are included) of a kind of kangaroo rat can achieve eight times body weight. From perspective of joint movements, when the kangaroo is preparing for jumping, the ankle and knee are extended and the hip is flexed. In the first half of contact phase, the ankle and knee begin to flex while the hip remains constant comparatively. Subsequently, the ankle, knee and hip are all extended. During the floating phase, the hip is flexed to make the feet forward, at the same time, the ankle and knee are flexed and then extended. The authors [77] also find that at different take-up speed the joint movement are not quite the same. The movement range of the knee would be larger relatively at high speed. In [78], the effect of tail is also analyzed in attitude regulation and stable landing.

## 2.4. Comparisons of jumping mechanisms

The above aspects discussed in jumping mechanisms of frogs and other animals with excellent jumping abilities respectively involve power sources, limbs coordination and control, which are exactly what researchers concern for designing and manufacturing a jumping robot with excellent performances. By analyzing and comparing the jumping mechanisms and movement modes of frogs and some other animals who are good at motion in details, some conclusions can be obtained, which include:

- (1) In the take-off stage, hindlimbs have significant effects on power generation and body support. All the limbs cooperate to realize attitude regulation in the flight and landing phases. Some animals also can use wings to regulate body attitudes for stable gliding and landing, such as locust, beetle and sparrow.
- (2) Animals good at jumping all have strong muscles in hindlimbs. The length of muscle, myfiber and activation are closely associated with tension of muscle. Perfect coordination of flexor and extensor provide enough power for frog, locust and kangaroo to complete extreme jumping.
- (3) In terms of ratio between jumping height and body size, locust has the smallest body size but possesses the largest ratio which benefits from its special arthroid elastin proteins and powerful hindlimbs that are longer than length of body. The ratio between jumping height and body size of frog is smaller than locust but larger than kangaroo. Nevertheless, from the aspect of absolute jumping ability, kangaroo has the maximum height and distance.
- (4) Different jumping abilities of the above three animals are depended on different body structures and muscle types. Therefore, when designing a jumping robot based on biomimetics, the specific applications and performance indices must be determined at first. Jumping robots which imitate locusts are often aimed to obtain extreme jumping height and distance, however, which imitate frogs or kangaroos are often inclined to realize autonomous and continuous obstacle surmounting.

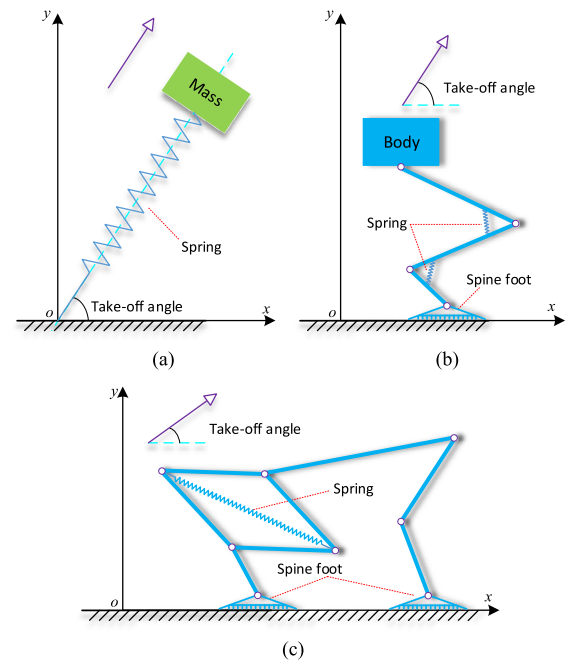
The analysis and study for the biological jumping mechanisms provide bionic foundations for achieving efficient jumping motion and inspire researchers to design and optimize robotic structures and frameworks. In the current researches, the biomimetic objects which have been frequently used include arthropods (such as locust [11,29,35,79,80], flea [5,13], cricket [30,34], cockroach [43], spider [81], water strider [3,82,83], etc.), amphibians (such as frog [84–86], lizard [37], etc.), primates (such as monkey [32,39], cheetah [87], human [27,88,89], etc.) and other animals who have excellent jumping abilities (such as bat [38], jumping bean [90], vertebrate [25,91], etc.). Therefore, it is feasible to design jumping robots in the way of biomimetics.

## 3. Bionic mechanical structures and dynamic models

### 3.1. Bionic mechanical models

From the perspective of mechanical model, the bio-inspired jumping robots can be classified into SLIP, bio-inspired open-chain or closed-chain multi-linkage mechanisms. In general, SLIP is usually designed as monopodal and bipedal jumping robots ([92], *Salto* [39] and *Atlas* [93] for example), and the type of bio-inspired open-chain and closed-chain linkage mechanisms are often used in multi-legged robots (*BigDog* [94] and the robot [95] for example).

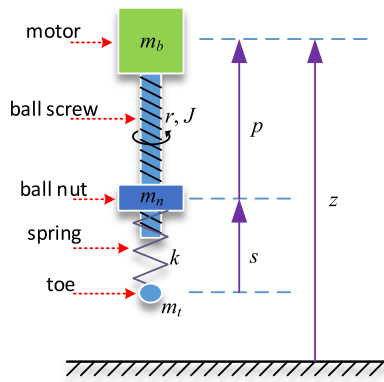
A basic SLIP (Fig. 5(a)) consisting of a massless spring attached to a point mass usually is usually applied to build mathematical



**Fig. 5.** Common mechanical models in bio-inspired jumping robots. (a). SLIP, (b). open-chain multi-linkage mechanism, (c). closed-chain multi-linkage mechanism.

model for robot jumping and running [96]. For example, the authors in [39] use inverted pendulum and loaded spring to build dynamic models with series structure and improve energy utilization efficiency via power modulation. The advantages of SLIP include computing simplification, lower degree-of-freedom (DOF), high power density, and so on [97]. However, SLIP is difficult to achieve stable landing control because of its essential instability in mechanical structure. Reasonable static phase is hard to be kept for path programming or sensor measurement when robots use continuous jump so that intelligent autonomous action and endurance could be affected to a large extent. With regard to intermittent jump, supporting devices must be required to help robot recovering to the initial attitude for next jumping. In addition, except particular nonlinear spring forces without gravity, SLIP dynamics cannot be integrated to obtain a closed-form solution [98], which results only approximate solution can be acquired and brings difficulties on high accuracy control.

Bio-inspired open-chain and closed-chain multi-linkage structures (Fig. 5(b) and (c) respectively) not only imitate jumping mechanism of animals but also try to design similar appearance to biomimetic target. Researchers using this approach are apt to obtain a robot with high maneuverability and multi-modal locomotion modes, which can jump over obstacle and walk or run on ground. Compared with SLIP, this approach is easier to adjust take-off angle and control landing attitude. Stability of bio-inspired jumping structures can be explained by animal mechanism, and proved via dynamics and control theory [37]. Because the open-chain multi-linkage structure has excellent properties of decoupling and flexibility, it is often used to design multi legged jumping robots, such as humanoid robot [99]. The closed-chain multi-linkage structure is often used to design actuator and its framework. For example, a diamond structure is designed to install linear spring [38,84], and a hexagon energy storage framework is designed to load four torsional springs [37]. Nevertheless, using this thought to build mathematical model is much more difficult than SLIP. In order to reduce complexity of modeling, some researchers try to decouple different limbs and simplify a single linkage as inverted pendulum [84,100]. Also, oriented graph



**Fig. 6.** A vertical jumping robot model [19]. Model symbols and parameters:  $m_b$  is mass of motor,  $m_n$  is mass of ball nut,  $r$  is radius of ball screw,  $J$  is moment of inertia of motor,  $k$  is elasticity coefficients of spring,  $z$  is body height,  $p$  is actuator length, and  $s$  is current spring length.

method is utilized to analyze closed-chain link structure and build dynamic equation in [101]. Adaptive coordination and synchronization control of multiple legs is also a complex problem to be solved further. Central pattern generator (CPG) motivated by central nervous system of vertebrates and time scale-based action sequence method is chosen by some researchers to realize limbs coordination and rhythm for multi-legged robots in unstructured environments [102,103].

### 3.2. Dynamics

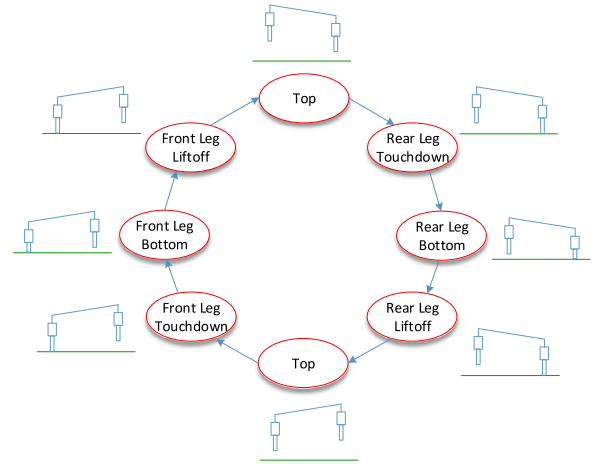
#### 3.2.1. SLIP

The commonly dynamic methods, such as Newton–Euler method, Lagrangian method, Kane method, and so on [84] are often applied to build mathematical model of jumping robots [72, 104–107]. In general, the dynamic modeling of monopodal or bipedal robots usually uses SLIP as basic structures. Here, we introduce an example [19,108] using Lagrangian method to build motion equations for vertical hopping robot based on SLIP shown in Fig. 6. The authors considered stance and flight phases separately for clearly describing robot action states. First, kinetic energy and potential energy in the stance phase can be obtained by analyzing energy relationships of SLIP.

The generalized dissipative forces originated from actuator torque, dry frictions for the sliding parts and viscous frictions for the spring losses respectively would be obtained by applying virtual work principle. Then according to Lagrangian dynamics  $L = T - V$ , the robotic motion equation can be obtained. Based on the dynamic equation, the state-space equation during stance phase could be further obtained. Similarly, dynamics of jumping robot during flight phase also could be analyzed using this method or other dynamic analysis methods [84,109].

#### 3.2.2. Open-chain or closed-chain multi-linkage mechanisms

The majority of robotic modeling methods are aiming at SLIP (monopodal or bipedal robots) because it is relatively easy to deduce and design. For the multi-legged robots with open-chain or closed-chain multi-linkage mechanism (quadruped, six-legged or wheeled robots), SLIP is insufficient to describe the system dynamic models. Relatively speaking, a jumping robot with this structure is hard to build an accurate model considering the highly nonlinearities and structural complexities. Thus, researchers who are engaged in multi-legged jumping robots put more focuses on mechanical structure and actuator design. Through theoretic analysis for designing overall jumping robots



**Fig. 7.** Bounding phase sequences in [106].

is seldom studied [84]. Besides, due to the symmetry of multi-legged jumping robots, unilateral dynamics is used to reduce the complexity of model building [106,110]. For example, dynamic analysis of bounding process for a two-degree-of-freedom quadruped robot in [106] was simplified by unilateral dynamic analysis. The authors divided the bounding phase sequences of the unilateral robot into “Top-to-Touchdown”, “Touchdown-to-Bottom”, “Bottom-to-Liftoff”, and “Liftoff-to-Top” using Poincaré map (Fig. 7). The two half cycles “rear” and “front” were included in a complete stride. Due to the asymmetry of rear and front, the authors built motion equations of rear and front half-cycle of bounding respectively. All the motion equations were constituted a switched system which were switched by the magnitude of forces as well as position and speed of legs. In order to avoid complex analysis, no force acting on the other leg was assumed when the robot was in one half-cycle. Then corresponding motion equations of different phases mentioned above for rear and front legs were established respectively [106,111].

### 4. Actuators and energy storage

Because of high energy density characteristic of jumping robot, most application of actuators is accompanied by energy storing and releasing. Only a few jumping robots are driven by electric motors or hydraulic system directly, and ordinarily, jump is often utilized as an auxiliary locomotion in this kind of mobile robots [93,112]. In the most designs of jumping robots, electric motors are applied to control energy storing and releasing through speed regulating [33,37]. Several actuators and energy storage devices of typical jumping robots are listed in Table 2.

The most popular energy storage method is elastic device (several typical methods are shown in Fig. 8(a), (b)), such as various springs (linear suppression, extension or torsion) and elastic rods [29,36,38,48,51]. Energy storage and release of springs or elastic rods involve the interconversions between elastic potential energy and kinetic energy. For example, the quadruped frog hopper in [84] used motors to extend linear springs to store energy and converted elastic potential energy into kinetic energy rapidly for jumping. *MSU jumper* in [36] loaded eight torsional springs respectively at the places between body/foot and upper/lower links and took advantages of cable and rotation link providing power to suppress and extend springs. Bipedal robot with jumping and walking locomotion modes in [123] also utilized torsional springs which were placed between body and thigh to store elastic potential energy. Wheeled mobile robot in [124] and [114] applied diamond structure that was similar to [84] to extend

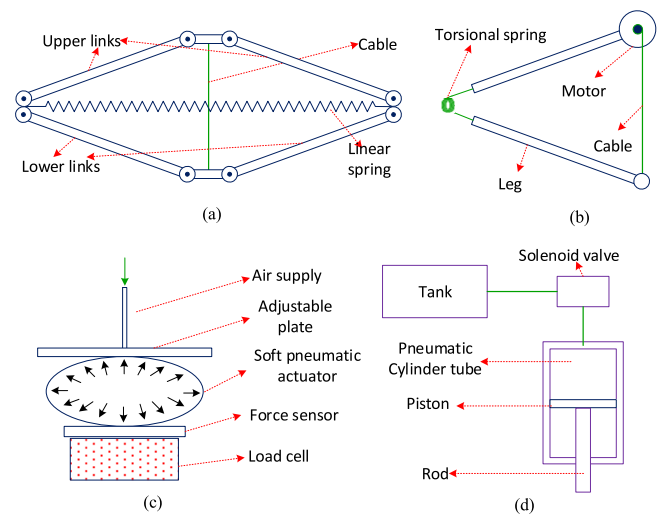
**Table 2**

Typical actuators and energy storages, as well as their characteristics in jumping robots design.

Actuator and energy storage methods	Types	Characteristics
No energy storage	Electronic motor [33]	High mechanical efficiency, high mechanical stiffness, high actuation bandwidth, hard to coordinate motor torque and speed.
Elastic storage	Linear spring [3], [9], [13], [38], [84], [113], [53], [114]	Simple mechanical structure, high energy storage efficiency, easy to realize series elastic actuator.
	Torsional spring [11], [34,35], [36], [29]	High energy storage efficiency, correspond to bionic muscular tendon, high vibration suppression effect.
	Elastic strip [26], [52]	High elasticity, easy to embed to robotic structure, high nonlinearity, hard to build a mathematical model.
	SMA [13], [38], [91], [115], [116]	Pseudo-elasticity, phase transition via temperature, energy saving on board, easily affected by the ambient temperature.
Pneumatic storage	Cylinder [10], [81]	High precision energy control, easy to be modified, heavy weight, low energy utilization efficiency.
	Artificial muscle [27], [117,118], [95], [119,120], [121]	Correspond to bionic muscular tendon, avoid using complex gears, excellent flexibility, high nonlinearity.
	Soft pneumatic device [12]	High elasticity and flexibility, large volume, low energy utilization efficiency, need exogenous air supply.
Hydraulic storage	Hydraulic pump [24], [81]	High precision energy control, high impedance, low energy utilization efficiency.
Chemical fuel	Combustion [41], [122]	High energy density, energy saving on board, difficult to design and control, complex structure.

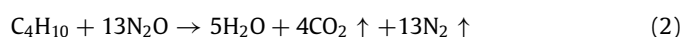
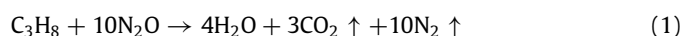
and suppress linear springs. *TAUB* in [29] exploited torsional springs to store energy, and tendon-like wires and cam which were driven by electric motor to suppress and release springs. A compact jumping robot in [52] tried to bend and twist elastic strip to obtain energy for extreme jump. In [125], the authors improved strip structure and combined it with a two-wheeled framework to design a mobile robot with repeated jumping and rolling. Due to the energy dissipation of strip and weight of main body, the jumping height could be improved by reducing weight or using new strip with high elasticity coefficient. Shape memory alloy (SMA) as excellent deformable material which has favorable power-to-weight ratio [126–128] also can provide sufficient energy to help robot jumping. In [38], clutch made by SMA was used to store more energy in spring compression by increasing actuator stroke. In [13], flea-inspired catapult mechanism was realized by a smart composite microstructure and SMA spring actuators to replace conventional actuators, transmissions, and elastic elements for reducing body size. In [91], a four-legged robot used only SMA wires which imitated musculoskeletal systems of vertebrates as actuators to realize vertical and forward jumps. The authors in [115] utilized spring-type SMA actuators and expansion spring to supply energy for a miniature jumping robot. In [129], the authors tried to use a kind of SMA named Nitinol which could provide large deformations without breaking to manufacture energy storage device.

Another common method of actuator and energy storage is using pneumatic devices (several typical methods are shown in Fig. 8(c), (d)) which include pneumatic artificial muscle [10,117–119,130,131], elastic ball [12], etc. [118] analyzed force/length hysteresis of pneumatic artificial muscle (PAM, also known as McKibben muscle) using Maxwell-slip model, and illustrated its control characteristics based on obtained model and friction analysis. In [10], the authors designed a higher jumping rescue robot driven by pneumatic cylinder and RC servo motor which could jump over 0.8 m. In [81], the authors thought that fluidic actuators had the characteristics of versatility, agility and powerful motions. Based on this perspective, they presented a spider-inspired joint mechanism which applied pneumatics and electrically actuators to drive simultaneously, and evaluated its jumping performance by regarding it as a one-legged robot. In [117], a theoretical model describing static response of elastic bladder was developed. It is concluded that small deformation will occur when



**Fig. 8.** Common types of actuator and energy storage. (a). Diamond framework with linear spring [38,114], (b). Torsional spring-actuated [29], (c). Soft pneumatic actuator [12], (d). Pneumatic cylinder-actuated [10].

the fiber is pressurized, which can be computed by the force of balancing equation. In [12], the designed jumping robot used soft silicone elastomer (SSE) based on pneumatic actuators to enable robot jump. Differing from PAM, SSE could take advantage of elastic and pneumatic properties synthetically by supplying air. In addition, chemical fuels that can release a lot of gases rapidly through burning and exploding also can be used as actuators of jumping robots. For example, [41] designed a roly-poly soft robot driven by combustion of nitrous oxide–propane/butane gas mixtures. Several chemical fuels that can be applied as actuator and energy storage should have the following traits: rapid reaction to release a large amount of gas, high combustion efficiency, low volume and mass, etc. The chemical reactions chosen in [41] are shown as follows:





**Table 3**  
Typical materials and their characteristics in jumping robots design.

Material name	Material characteristics	Applied components
POM	High tensile strength and bending strength, anti-fatigue, creep and shock resistance.	Cam and gears [35]
PEEK	Thermostability, creep and corrosion resistance, excellent stiffness.	Robot body [35]
DuraForm HST	High strength and stiffness, thermostability.	Robot body [36]
Carbon fiber	High strength and modulus, corrosion resistance	Elastic rods [26], skeletal frame [27]
ABS	Thermostability, high tenacity and elasticity, corrosion resistance, easily processed.	Robot body, microcontroller battery and motor [29]
SMA	Pseudo-elasticity, one-way and two-way shape memory property, high elasticity and modulus.	Clutch [38], wires [91], [129], spring actuator [13], [115]

where  $C_3H_8$  is propane,  $C_4H_{10}$  is butane, and  $N_2O$  is nitrous oxide. The energy densities of (1) is  $11.5 \text{ J/cm}^3$  and (2) is  $11.7 \text{ J/cm}^3$  [41].

It is true that the pneumatic and chemical actuators have the advantage of high energy densities. But they also have the shortcoming of intense nonlinearities that are hard to be modeled and analyzed. Besides, the properties of easily to swell, inflammable and explosive may bring certain dangers in robot experiments.

## 5. Materials

The material applications of jumping robot mainly focus on using lightweight as well as sturdy materials to build robot skeletons [35] and designing special components for better jumping performances [132]. Table 3 shows the typical new materials application in jumping robots design. In [35], because of the properties of low weight and low surface friction coefficient, Polyoxymethylene (POM) was used to manufacture cam and gears, and because of the properties of high strength-to-weight ratio, Polyetheretherketone (PEEK) was used to fabricate critical structural parts in body and legs. In order to make the skeletal frame lightweight and high-impact durable, *Mowgli* [27] was designed by oilless polymer bearings, nylon joint parts and carbon FRP bones. Most of the robotic components in [36] were fabricated by using the selective laser sintering with the DuraForm HST material which had a low density of  $1.20 \text{ g/cm}^3$ . [26] used elastic rods made by carbon fiber to replace springs in [36] for better energy efficiency in mid-air. In [29], the robotic body and its motor, the battery and the microcontroller were produced by a 3D printer using Acrylonitrile Butadiene Styrene (ABS) for minimizing weight to strength ratio. The overall frame of the robot in [52] was designed by wood for making robot as light as possible, and catapult was made by an elastic steel strip which had been processed through hardening and cold rolling. In [122], the explosive actuator was made by tough silicon rubber to withstand the power and sudden increase in pressure during combustion, and the pneumatic actuator was a micro diaphragm pump and controlled by three three-way solenoid valves for pressurizing butane and oxygen better.

## 6. Control and stability

Problems of control and stability are of extreme significance in take-off, flight, landing, attitude regulation and trajectory planning of bio-inspired jumping robots [19,22,53,70,80,102,108,133,



**Fig. 9.** The stabilizing structure of jumping robot in [139].

[134]. Due to the characteristics of intensity and explosion of jumping locomotion, controller design and stability analysis contribute to regulate jumping performances, reduce mechanical vibration, improve motion accuracies, and achieve further continuous jumps smoothly, flexibly and stably.

### 6.1. Sensors

Sensors are of importance for jumping robot to perceive environment and position information, and then realize trajectory planning, attitude control, localization and navigation. With regard to jumping robot, position sensor such as encoder or potentiometer are often equipped on the robot body to measure leg or body position [25,135]. For a single jump, position sensors which are used to measure vertical and horizontal displacements are often not loaded on robot platform but directly measured by straightedge for reducing robot mass and system complexity [36]. Velocity/ acceleration sensors can be used to measure take-off velocity and acceleration respectively in the take-off phase, and send measurement information to computer or micro controller [98]. Angle/angle velocity sensors such as gyroscope are often used to provide posture and angle motion information to determine attitude angles and their variations of robot body for take-off, flight and landing [123]. Visual information can also be applied to measure robot motion attitudes. In [10], CCD camera was used to measure jumping height of robot. In [136], high speed camera was used to capture sequential images of jumps at rates of 8000 frame per second with an exposure time of 0.125 ms. In [98], the authors used motion capture system to capture robot motions to judge what phase robot was in and take advantage of this information to determine how to regulate and control in the next step. In [137] and [138], video transmission or external observer was utilized to help miniature robot localizing itself in the real world.

### 6.2. Control strategies and applications

Controller design of jumping robots throughout the overall motion process. Specifically, during the stance phase, researchers must consider driving force control of motors for energy storage and COM regulation. Jumping height, distance, and direction should be computed and converted prior for determining take-off angle and jumping force. Besides, coordination of different motors and rhythm behaviors of multi-legged robots are significant control problems for high explosive take-off, too. Control problems in the flight phase are usually considered for attitude stabilizing in the air and stable landing. Body attitude is often deemed to guarantee stable flying and further gliding by regulating pitch and yaw angles. Gliding wings and inertial tail are frequently-used to adjust body angle via electric or hydraulic motors. While the robot is preparing for landing, the landing angle of robot body and each leg should be controlled in order to eliminate mechanical

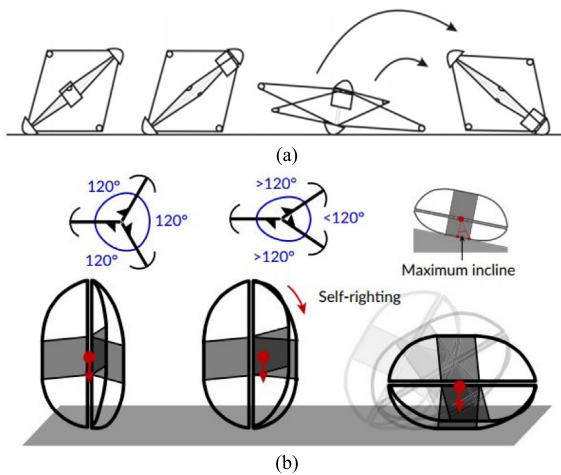


Fig. 10. Self-righting processes of Glumper (a) [140] and Tribot (b) [141].

vibrations and adjust for next jump. With regard to actual motion, jumping trajectory and path need to be generated in advance by using CPG or other rhythm controllers. Besides, analyses of robotic controllability and observability are necessary for smooth and accurate control in the jumping process.

Control methods for keeping a jumping robot running effectively and stably can be illustrated from the aspects of hardware and algorithm.

#### 6.2.1. Hardware

In the aspect of hardware, in order to balance robot body during the flight and landing phases, several researchers tried to utilize self-stabilizing structures to design robot platforms. For example, a wheeled or a quadruped robot [11,30,91] is easier to be stabilized than a monopedal or bipedal robot which often applies SLIP as system model. Therefore, after achieving relatively excellent jumping performance, some recent researches prefer to design multi-legged robots for continuous jumps [84]. [132] designed a spined gripper mechanism in the robot foot for increasing the static friction between foot and ground to prevent the monopedal robot gliding and overturning. Nevertheless, this robot needs assistance of human to keep upright when jumping locomotion begins and finishes. Active inertial tail is also an effective method to keep robot balance in the air and for safe landing [32,39], which can also be used to control midair orientation for aerial maneuvering [37]. Bipedal miniature robot with multi locomotion of jump and glide in [50] also applied tail to guarantee robot flying stably while jumping and gliding. Aiming to make robot perform repetitive jumps and keep robot attitude stable, [139] thought that a robot who was expected to stabilize itself required uprighting and steering mechanisms, and then designed a sphere jumping robot that could passively recover after landing and orienting itself. The sketch of structure can be seen in Fig. 9. Also, Jollbot in [142] and [140] also utilized this structure to help robot keeping stable. The sphere made by metal hoop springs were suppressed to provide energy. The similar idea was also applied in [115]. Glumper in [140] was manufactured as octahedral shape that was easy to recover to the take-off state by regulating different legs (see in Fig. 10(a)). In addition, a self-righting mechanism that makes robot recover to the initial state has been applied in many jumping robots. JumpRoACH [31,43] was equipped with a pair of wings that could help robot turning its body to the state preparing for the next take-off. Angles of three legs of origami robot Tribot in [141] was regulating to shift center of mass for improving stability after landing on the ground.

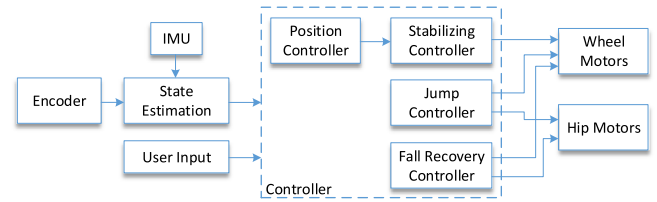


Fig. 11. Control architecture of Ascento [42].

The self-righting process can be seen in Fig. 10(b). The above ideas can solve the problem of repetitive jumps to some extent, but also could lead to relatively slow jumping frequency. In other words, the maneuverability and agility of these robots exist some deficiencies.

#### 6.2.2. Algorithm

In the aspect of algorithm, in the early stage researchers usually utilized open-loop control or simple feedback control methods. For instance, Raibert step controller [143], which aimed to realize hop and balance of a 3D one-legged machine, was decoupled into three components: forward running velocity, attitude of body and hopping height. The forward running velocity was controlled by positioning the robot foot regarding the projection of COM during flight phase, attitude of robot body was controlled by torquing the hip stance while the foot was subject to friction in place, and hopping height was controlled by adjusting thrust delivered by the leg on each hop. Controller design in [32] also adopted this idea and feedback linearization to achieve robotic stable continuous jumps.

For state/output feedback control in the stance and flight phases of vertical jumping robots, [134] proposed a control strategy for one-legged robot with hip and leg compliance by exploiting underlying passive dynamic operation for minimizing energy consumption. Based on this design, stable control and forward speed tracking of the robot was realized. During the flight phase, in order to realize forward speed controller, the authors chose to control leg angle to modulate counter-oscillation of leg and body. During the stance phase, pitch angle and hopping height were controlled by hip and leg actuators respectively. In order to control a planar one-legged hopping robot similar to [134], an equivalent piecewise-constant control method [22], which used hip torque as control input for the flight phase and axial force for the stance phase was proposed. The authors first designed a discrete-time impulsive control method which was difficult to be applied in practice, and then modified this equivalent method through analyzing and restricting hip torque solely to the flight phase. In [22] a linear state feedback method with a Hurwitz stable control gain, which was solved by building optimal quadratic and Riccati equations, was also presented for stabilizing open-loop instability of system matrix associated with forward velocity. In [42], optimal design method was also used to solve stabilizing control of two-wheeled robot Ascento. A Kalman filter was applied to estimate system states dependent on joint motor positions, then the estimated states and desired pose information were transferred to controllers. Stabilizing controller which was designed by LQR method sent torque commands to actuate the wheeled motors (Fig. 11). Inspired by human successive jump and self-upright, jump and fall recovery controller were designed as heuristic feedforward controllers which operated motion through discrete continuous phases.

PID and corresponding improved algorithms are frequently used in controller design of driving motors which are equipped on the jumping robots. In [144], to realize the synchronization of two legs for a kangaroo-inspired bipedal jumping robot, the

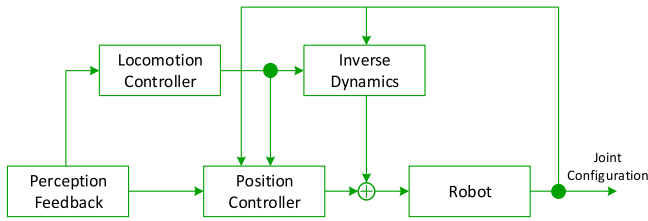


Fig. 12. The control structure to perform the planned motions of HyQ [112].

deviation error between two legs (each leg was actuated by DC motors controlled by PID controllers) was minimized by a PI control method. In [145], a cascade position PID controller was devised for hindlimbs of frog-hopper actuated by pneumatic muscle, whose parameters were tuned by RBF neural network. In [112], a locomotion controller built by a low-gain PD controller and an inverse dynamic calculation procedure was used to execute robotic planned motions. The control structure is shown in Fig. 12.

CPG is an important method in synchronous control of multi-legged robots [146–148] and also has broad applications in bio-inspired jumping robots [99,103,149]. CPG can be considered as an exclusive neural network including a group of neurons, which can coordinately generate rhythmic signals such as kinematics, force, torques and muscle lengths without sensory feedback, while sensory feedback is needed to shape the CPG signals [146]. Several theories and applications of CPG in jumping robots have been developed due to the property of multi-leg coordinated movement in multi-legged jumping robots. For instance, in [102], the authors designed a CPG controller which was inspired by a two-level CPG model for a biped robot in unpredictable environment. The interneurons in two-level CPG model were modeled to generate motion rhythm and pattern promptly for motion sequence control, and the motoneurons were modeled to control output forces of joint drivers based on real-time feedback information. The authors in [103] designed a CPG network framework based on bi-articular muscles to realize a jump behavior of a cat-inspired quadruped skeleton robot with a waist joint. In [99], CPG network was utilized to generate jumping motion trajectory (see in Fig. 13). The posture and compliance controllers in the designed humanoid robot were defined to control hopping motion. These generation and control were built as evolutionary optimization problems to realize optimal jumping motion with maximum flight time and stable hopping. [112] used a CPG network with four nonlinear oscillators to generate synchronously position references according to the desired gait for quadruped robot HyQ. Though CPG control model has been generally applied in mobile robots, it also exists several disadvantages [150]. The oscillation mechanism of CPG is unknown, therefore, it is hard to design CPG network structure according to desired signals. Current research seldom considers how to adjust network structure to optimize performance theoretically, but usually tries to use trial and error, experience or learning (usually genetic algorithm, swarm intelligence, reinforcement learning, etc. [151,152]) to tune parameters. Due to the complex structure of CPG network, a lot of computation for parameter tuning is needed. Thus it may be have difficulties to be applied to embedding system or miniature robots. In addition, the inherent relationships of physical and control parameters in network framework are needed to study further.

Advanced control algorithms such as sliding mode control, robust control, adaptive control, fuzzy control, computational intelligence and so on gradually begin to be used in motion control, attitude regulation and trajectory optimization of jumping

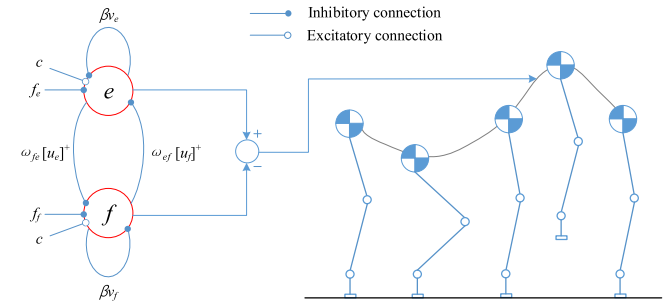


Fig. 13. Hopping trajectory generation by CPG of humanoid robot in [99].

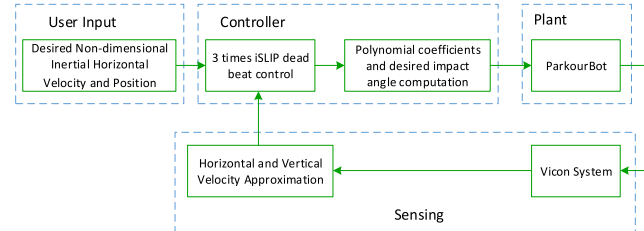


Fig. 14. Polynomial energy insertion control system in [156].

robots [37,153–159]. Sliding mode control was applied to regulate the robot body angle to keep constant under the unknown system state in [37]. In order to unify the dynamic equations of the stance and flight phase formulated by float basis method, a reaching law in sliding mode control was designed in task space, which could make state trajectory starting from anywhere move towards the switching surface and exponentially converge system tracking error to zero in [154]. An off-line optimization procedure in [153] was proposed to determine the hopping gaits in advance for different hopping distances and heights. Robust backstepping control method was adopted to stabilize a robot system with two actuated arms, which was a non-SLIP model based on second-order nonholonomic mechanical system in [155]. Based on an instantaneous-SLIP model named *ParkourBot*, optimal parameters analysis method of swing leg retraction was provided in [160] during the stance phase, and polynomial energy insertion method proposed in [156] during the flight phase when jumping robot was moving on a planar unknown rough-terrain environment. The overall control system of the flight time was shown in Fig. 14. Desired velocity and height of robot relative to the impacted ground was input by user. The controller was only driven when the robot had a positive vertical velocity and had not already sent a command during this cycle. The inverse dynamics of the iSLIP was computed three times according to desired values and sensing feedback. The desired energy parabolic coefficients and desired angle would be found by using the above framework. P controller whose parameter was regulated by fuzzy system was used to control knee and ankle motors, and to perform soft contact allowing the displacement of the COM of a humanoid robot while jumping vertically in [157]. In order to generate periodic inertial actuation for a bouncing robot, an adaptive control scheme shown in Fig. 15 was presented in [159]. The adaptive position control of the spinners' rotation angles was to apply inertial actuation to robotic main mass. A tracking controller based on feedback linearization was used to track the adaptive reference spinners' position angle.

In summary, control strategies play an important role during the whole jumping phases. But due to the limitations of the mechanical performances, there is little work on path planning or autonomous movement for purely jumping robots. The majority

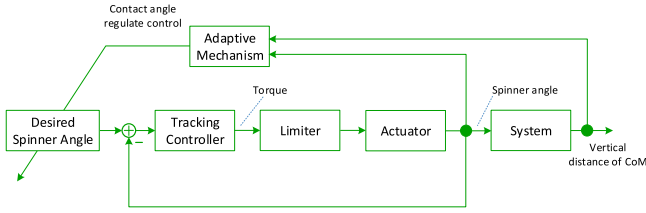


Fig. 15. Adaptive control system framework in [159].

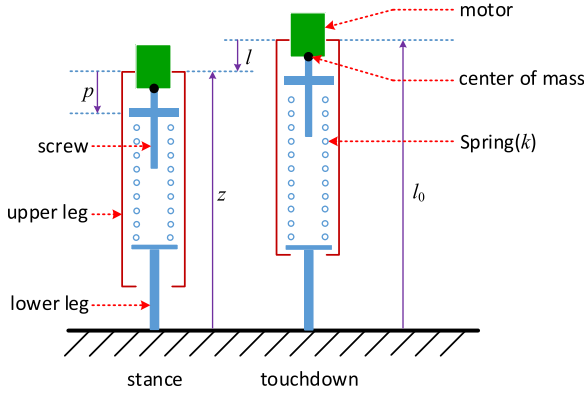


Fig. 16. A simple model of vertical hopper [162].

of researches on path planning prefer to design multiple locomotion robots with jump and other agile motions. Many relative studies remain in the stage of simulation [161].

### 6.3. Stability and stabilization

In the above we have introduced some problems of stability about bio-inspired jumping robots from the aspects of hardware and algorithm. Here we will emphasize stability and stabilization by theoretic analysis. For clarity and without loss of generality, the specific model proposed in [108] and [162] is taken as an example to illustrate this problem.

The authors in [162] built a vertical jumping robot model (a simple diagram is shown in Fig. 16. Besides, the meanings of symbols in this section are different from Fig. 6 and Section 3) including the stance and flight phases which were judged by the leg deflection  $l$ . If  $l < 0$ , the hopper was in the stance phase, and else in the flight phase. The dynamics and the desired behavior of this model were known and could be described by  $l$  and its higher derivatives. The objective of controller design was to make the designed limit cycle in phase plane  $(l, \dot{l})$  (see in Fig. 17) globally attractive. Screw torque  $\tau = rk(p-l)$  was chosen as control output, and according to [108], where  $k$  is spring stiffness coefficient,  $r$  is lead of screw. The control of body height was only considered for the stance phase since it had no effect on the flight phase. The simplified dynamic equation of stance phase could be written as

$$\ddot{l}(t) = -cl(t) - g \quad (3)$$

where  $g$  is acceleration of gravity,  $c = k/m$ ,  $m$  is mass of the hopper, and with initial condition  $l(0) = 0$ ,  $\dot{l}(0) = \dot{l}_{des} < 0$ .

Then the elliptic phase trajectory was

$$\left(l + \frac{g}{c}\right)^2 + \frac{\dot{l}^2}{c} = R^2 \quad (4)$$

where  $R^2 \triangleq (g/c)^2 + \dot{l}_{des}^2/c$ .

The control law  $\tau$  also needed a correction factor to correct if the desired velocity  $\dot{l}_{des}$  and the touchdown velocity  $\dot{l}$  did not

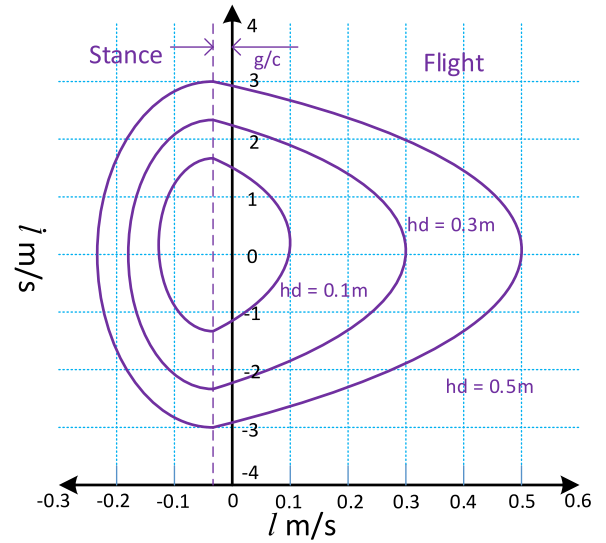


Fig. 17. The desired limit cycle of each desired hopping height [162].

match. The tangent vector to the limit cycle at any point  $(l, \dot{l})$  in the phase plane was defined as  $[\dot{l}, -cl - g]^T$ . The correction of the tangent vector would be decided by the cycle where a point was located. If the point belonged to a larger cycle the tangent vector could be corrected by adding a correction term  $\delta(l, \dot{l})$  on its vertical component. If the trajectory had a trend to close the desired orbit in Fig. 17, the correction term  $\delta(l, \dot{l})$  would decrease and its form would be as follows:

$$\delta(l, \dot{l}) = \beta \dot{l} \left[ \left(l + \frac{g}{c}\right)^2 + \frac{\dot{l}^2}{c} - R^2 \right] \quad (5)$$

where  $\beta > 0$ . The tangent vector  $[\dot{l}, -cl - g + \delta(l, \dot{l})]^T$  of the corrected trajectory could be used to reconstruct the motion along the desired trajectory

$$\begin{aligned} \dot{l} &= -cl - g + \delta(l, \dot{l}) \\ &= -cl - g + \beta \dot{l} \left[ \left(l + \frac{g}{c}\right)^2 + \frac{\dot{l}^2}{c} - R^2 \right] \end{aligned} \quad (6)$$

Here a typical nonlinear system stabilization method of vertical monopodal jumping robots was given by designing a correction factor via limit cycle analysis [108,162]. The correction term could rotate direction of the tangent vector to the desired cycle no matter what the current cycle was larger or smaller than the desired cycle. The damping term  $-R^2 + (l + g/c)^2 + \dot{l}^2/c$  of the controlled system would converge to the desired limit cycle. Also, the authors used Lyapunov function based on the distance from the limit cycle to prove that the desired limit cycle was a globally asymptotically stable attractor of (6). Lasalle's stability theorem was used to show the desired limit cycle was a positive limit set of the closed-loop dynamics. That could be asymptotically stable with a domain of attraction in the whole real plane [162].

In addition to the above illustrations, for the stability problems of robotic models there are many other different stabilization methods can be applied, which can be seen in [19,37,135,153–157,163] etc. To sum up, stabilization and controllability analyses are difficult to be studied due to the structural instability of SLIP in jumping robots. The theoretic results are usually hard to be applied to the actual robotic platforms. For multi-legged jumping robots, though the landing stability is better than SLIP, the overall robotic analysis that the each leg must be considered is much more complex. Thus, there is little stability analysis aiming to these robots, and we will no longer give a typical analytical process of these robots.



## 7. Discussion

Due to the requirements of maneuverability, agility and adaptability of mobile robots in unstructured environment, and practical tasks about freight transportation, patient care, interstellar exploration, disaster relief and rescue, researchers try to design jumping and multiple locomotion robots through imitating animal's actions. There is no doubt that rapid and unprecedented development has been achieved in bio-inspired jumping robots since 1980s. However, we must envisage the fact that there remains a lot of difficulties to be solved in jumping robots. In this section, we will illustrate them and present several meaningful future prospects of bio-inspired jumping robots.

### 7.1. Existing problems

#### 7.1.1. Modeling

In order to overcome the complexity of jumping locomotion, the general model of jumping robot is usually divided into three phases, namely, the stance phase, the flight phase and the landing phase. But in this switch system complex environment with multiple disturbances is not usually considered. Furthermore, the target of designing a jumping robot is to make it pass over tough terrain or obstacle. It not only considers the body's anti-disturbance, robustness, but also copes with unstructured surroundings and obtains self-adaptability. In addition, modeling of SLIP-based jumping robot is developed greatly, but robot model with the structure of open-chain and closed-chain multi-linkage, which is intricate and coupled, is relatively fewer than SLIP. The modeling problem of jumping robot with this structure is necessary because it is helpful to realize robotic autonomous mobile ability and apply them in the practical scene.

#### 7.1.2. Control method

Control is a key step to stabilize robotic jumping locomotion. Nowadays, open-loop control and simple feedback control are still primary strategies applied in jumping robot control. However, in most instances the simple control methods cannot guarantee the control stability, smoothness, accuracy and robustness about attitude and landing control, trajectory optimization, self-righting or motor smooth output. The reasons that advanced control methods have not been widely utilized can be summarized as follow: First, advanced control methods are usually model-based, and they may be not adoptable if the accurate mathematical models cannot be obtained. Second, for the regular control task such as DC motor speed regulation in jumping robot, advanced control methods are not necessarily better than conventional methods. Third, advanced control methods need a lot of computation. But the majority of jumping robots are miniature, the computing resources installed on the robot platform may be insufficient to support complex control methods, especially intelligent methods. Thus a contradiction between requirements of high performance and low computational complexity hampers the applications of advanced control methods (intelligent methods especially) in jumping robots control.

#### 7.1.3. Materials

Both robotic body preparation and actuator design need to be supported by material science. In robotic body preparation, different properties of materials need to cope with different requirements according to different jumping performances. For example, miniature jumping robot needs light and firm materials to fabricate robot body in order to make robot jump higher and farther, and it often does not consider the landing state so that it should be strong enough for avoiding damage. In actuator design, a sort of materials with characteristics of small volume, light mass and

high energy density will be ideal to manufacture robotic actuator. SMA which has been applied in robot design [91,115] has excellent performance which has been involved in the above, but high dissipation energy in process of deformation annoys researchers and could be solved by developing more new materials.

#### 7.1.4. Mechanical structure design and vibration prevention

How to reasonably configure different components at the robot platform also needs to be optimized. A robot with bio-inspired multi-legged structure often possesses multiple types of locomotion, thus efficient utilization of components becomes a significant issue for reducing robot volume and mass. We have illustrated the component sharing method in [38] which realizes jumping and gliding locomotion with light mass. But the majority of researches are not considered this problem in robot design. We deem that it is of importance to achieve autonomous motion of jumping robots.

Mechanical vibration has effects on motor regulation, gear meshing, and further on jumping trajectory and mechanical durability. Also, it is also an important element to restrict the robot size. Vibration prevention needs a comprehensive solution that requires the cooperation of reasonable mechanical structure, lightweight material, excellent control method and other helpful techniques. Recently, soft jumping robot has made several progresses. By placing soft materials in the bottom of robot, the robot can land softly and the vibration is reduced greatly. More schemes to solve vibration problem should be developed in the future.

#### 7.1.5. Energy storage

High energy density contributes to higher jumping height and farther jumping distances. General energy storage modes have their own advantages and disadvantages, which we have introduced in Section 4. Energy storage without high energy density is hardly to meet all the performance requests in jumping robots. In order to improve energy density, method of multiple energy storage devices providing energy synchronously begins to be applied in certain jumping robot designs. Also, how to use new materials and shapes to obtain new energy storage is a still popular research subject.

#### 7.1.6. Miniaturization and multi-function

Miniature robots account for a sizeable proportion in jumping robots. Miniaturization is helpful to obtain more excellent jumping performances, reduce mechanical vibration and simplify structure. However, to realize the original design targets mentioned above, the jumping robots need to be addressed other locomotion modes such as glide, run, walk or roll. Also, a miniature robot is hard to integrate system framework due to insufficient space. In robot design these two aspects should be considered solemnly and present a comprised scheme should be presented according to the practical requirements.

#### 7.1.7. Actuator

In the design of miniature robots, actuator usually affects structure design and trajectory smoothness, etc. Mechanical vibration and shocking are often generated by actuators as well. Due to the light weight of miniature robot, mechanical vibration generated by electric motor may aggravate abrasion of gearing and damage working life of robot components. Hydraulic and pneumatic actuators with high compliance are hard to be fabricated as micro motors which have complex manufacturing processes and high costs.

### 7.1.8. Trajectory and path optimization

Trajectory planning is related to jumping performances such as height, distance and angle, and jumping effects such as stability and safety. For the sake of completing a jumping action, jumping performance, take-off angle, energy expenditure and restrict condition of robot, as well as roughness and concave-convexity of terrain should be considered comprehensively. For example, if a jumping robot wants to jump onto a table, height of table, distance between robot and edge of table should be measured and computed. Then it needs to be judged out whether the extreme jumping ability can help the robot jumping onto the table. Finally, if it can, provide an appropriate take-off angle and how much energy required should be determined for the whole jumping process. Some researchers designed trajectory optimization methods for specific jumping task. But seldom can realize the overall closed-loop jumping process including measuring environment, judging feasibility, computing take-off angle and required energy, and executing action. The computing process usually needs excessive resource that only can be provided by laptop or desktop. This restriction impedes development of miniature jumping robots with abilities of real-time trajectory planning and better control performances.

The realization of path planning requires continuous motion ability (continuous jumps or multiple locomotion modes) and accurate landing of the jumping robot. However, the majority of current jumping robots cannot satisfy these performances. There is few research about path planning of jumping robots. [161] presented a ballistic motion planning approach that linked two positions between obstacle surfaces using jump motion, but it still stayed in the stage of graphics and simulation verification.

### 7.2. Future prospects

Until now, bio-inspired jumping robots have been designing and manufacturing in the laboratory for academia. There are very few robot platforms that are tested and applied in outdoor unknown complex environment. Taking the previous and current research situations into consideration, we discuss and present several possible future developments on bio-inspired jumping robots.

As a type of autonomous mobile robot, the greatest advantages of jumping robot is that it can leap across obstacles or pass through complex terrain via high energy density. Therefore, path planning based on jumping locomotion in unknown and unstructured environment is of importance for realizing rescue, patient, exploration or other difficult tasks that need the ability of obstacle surmounting.

The majority of researches on jumping robots are trying to design a miniature robot for using energy and power with higher efficiency and avoiding mechanical vibrations. Precision processing and manufacturing technique such as micro electro-mechanical systems (MEMS) are general applied in instrumentation, antenna, semi-conductor and integrated circuit design [164–166]. They may be used to decrease body size or optimize mechanical structure of miniature robots. For instance, MEMS sensors (such as MEMS accelerometer, optical, force or position sensors) or motors can be integrated in a small space and the mechanism can be designed more compactly. Of course, the cost of MEMS is much expensive and it may be not suitable to be applied in most actual scenes. But it is necessary to use these techniques to globally or locally improve structure and framework for jumping robots.

Energy efficiency optimization should be improved further for higher and farther jumps. Friction and resistance in robotic joints, springs, motors, in the air or on the ground considerably decrease energy efficiency and are harmful to basic jumping performances and endurance. It is especially serious in jumping robots with

the property of high energy density. In general, increasing stored energy and reducing energy dissipation are the two ways of energy optimization. For example, *JumpRoACH* [31] tried to combine linear spring and torsional spring to increase the total stored energy. The energy of combination (2.31J) exceeded both linear spring (1.38J) and torsional spring (1.98J). *MultiMo-Bat* [38] optimized spring design (used 8 light springs to replace single spring) through stress and strain analysis to improve energy density. S. Ghassemi [167] tried to design a bipedal robot attached a helium filled ball for reducing robot weight, and similar methods may be referred to improve energy efficiency by decreasing gravitational potential energy. Therefore, the optimization process should be considered both in mechanical design and dynamical models. The utilization of precision components also contributes to increase energy efficiency.

Application of advanced control methods (such as adaptive control, model predictive control, fuzzy control, evolutionary computation, etc.) needs to be paid attention in the subsequent development of jumping robots. Researchers are making every effort to meet the requirement of basic performances (such as jumping height and weight). At the same time, they have begun to consider how to realize smooth landing, optimize jumping trajectory and so on. In terms of landing control, there are few researches that can help robot landing smoothly and stably. Though [168] had tried to analyze stable landing problem of a planar bipedal jumping robot in theory, subsequent studies are still very few. Therefore, advanced control algorithms should be used to strengthen the performance of landing stability and improve other possible control objects we involved above. In addition, high-precision localization and navigation of jumping robots may be realized by introducing advanced control methods to assist the mixed sensor information.

Artificial intelligence technology has been widely applied in manipulators and mobile robots since 2000s. For mobile robots, it can help robots perceiving and understanding surroundings, and further realizing autonomous motion behaviors [167,169,170], navigation and path planning [171–175]. Nowadays, with regard to bio-inspired jumping robots, the emerging intelligent methods [176,177] such as reinforcement learning, deep learning, meta learning, brain-inspired intelligence, etc. can contribute to realize controller design, trajectory optimization with better performance, and localization and navigation in unstructured environments. For instance, Y. Chen [178] designed a convex recurrent neural network to capture temporal behavior of dynamical systems. The optimal controller obtaining by solving a convex model predictive control problem was verified in simulated robotic environment. In terms of intelligent perception and inference, intelligent techniques can help jumping robots learning new environments autonomously and interacting with other agents. Also, it can improve the adaptability and robustness of jumping robots in the wild surroundings, and obtain better control effects.

Multiple locomotion modes for a robot is often used to increase autonomous mobile ability. For a jumping robot with walk, roll or climb, it can conserve energy to increase endurance time and obtain more agile movement. But this design would make the robotic structure more complicated, and in the most cases it needs to add many components that is not good for decreasing weight and size. In Section 2 we review the kinematic flexibility of jumping creatures. This ability of animals can also be applied in jumping robot design to make it adapt to more types of terrains and decrease energy consumption.

Using soft material to design jumping robot is also a popular research. The flexibility, elasticity and ductility of soft material are suitable for human-machine interaction in complex surroundings. In robotics, soft material is usually studied to make soft

actuator, flexible manipulator, rehabilitation robots or crawling robots [179–181]. We also have illustrated several soft jumping robots and suggest that their advantages are helpful for reducing vibration from mechanical collisions and shocking from collisions between robot and ground while landing. In addition, soft, and elastic material can be used to design actuator and energy storage with higher performance applied in jumping robots. Deformability in soft material may be able to make robot better bend to unstructured environment.

Finally, we will discuss the practical applications of jumping robot. We have been mentioned that jumping robots may be applied in patient care, freight transportation, disaster relief, wild rescue and so on. In addition to these extremely complicated scenes, some other applications in simplified or indoor scenes have been noticed and attract quite a number of researches to focus on. For example, a certain number of miniature jumping robots can be used to build a multiple robotic system to carry out tasks in the way of swarm. As an autonomous robot with agility and obstacle avoidance, jumping robot also has potential applications in sensor networks or internet of things (IoT) [123,182–184]. Besides, jumping robots may be manufactured as service robots and applied to home accompany or entertainment.

## 8. Conclusion

As a common motion type of animals with high agility and maneuverability, jump and its excellent motion properties attract robotic researchers all over the world. In this paper, we comprehensively review the development of biologically inspired jumping robots. First we discuss the jumping mechanism of animals and take frogs, locusts and kangaroos as typical examples to indicate it. The limb muscles, power generation, coordination ability, motion behavior, and effects of hindlimbs and forelimbs of these jumping animals are studied to illustrate the possible enlightenments for bio-inspired jumping robots. Then the two main models of SLIP and open and closed-chain linkage structures are concluded. In order to show the dynamical analysis of jumping robot, an example of SLIP using Lagrangian dynamics is introduced. Next, we discuss several key technologies from the perspective of engineering implementation including actuators, energy storages, sensors, and materials which are very important to jumping robots and analyze the shortcomings in the current designs and methods. The problem of control and stability is investigated emphatically through the applications of controller design and giving an example to analyze a vertical jumping SLIP system stability via phase plane method. Finally we present several existing problems, try to give possible solutions, and analyze reasonable and potential development trends of bio-inspired jumping robots.

After rapid development in the past 30 years, bio-inspired jumping robots become gradually developed and have great potentials in broad application scenes. Of course there are still many technical problems which need to be solved, the researches on bio-inspired jumping robots require the further development to achieve better motion performances.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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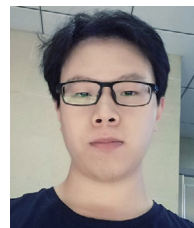


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