A Review of Self-Righting Techniques for Terrestrial Animals

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Abstract

We present a review of literature covering different techniques used by land animals and humans for ensuring appropriate body orientation after landing in the event of desired jumps or accidental falls. It appears that at least five different families of strategies emerge: modification of angular momentum prior to leaving the ground, body reorientation through limb motion, twisting with no initial angular momentum, *a posteriori* self-righting, and aerodynamic stabilization. This last family of strategies is particularity suited for robots explicitly designed for flying but is out of the scope of this review.

Fig. 1a) Cross-country motorcyclist performing pitch attitude correction by throttling or braking the wheels (Pouzols et al. 2006)

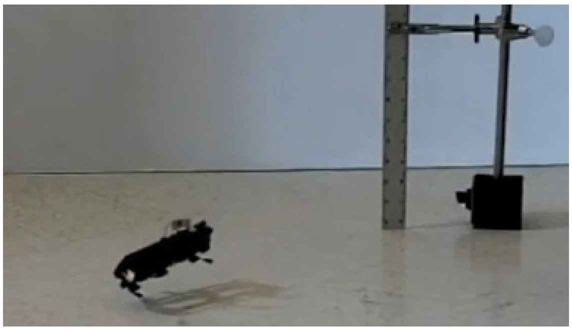

Fig. 1b) The DASH roach-like hexapedal robot bouncing after having survived a fall from a large height (Birkmeyer et al. 2009)

1. Motivation

Vehicles and robots meant for terrestrial operation may be able to maintain a given orientation relative to the horizon while on the surface, but their ability to do so while in mid-air is generally limited compared to that of flying machines. For example, cross-country motorcyclists commonly thrust or brake their wheels in order to correct their pitch angle during a ballistic phase, but cannot easily control their roll angle (Fig. 1a). Also, some robots are designed to resist falls, and it becomes necessary for them to ensure that they land with an orientation favorable for continuing operation (Fig. 1b). In fact, for ground robots meant for high-speed movement on uncertain terrain, ballistic phases can occur frequently, and it becomes crucial to provide the robots with self-righting capabilities in order to ensure smooth landing, protect their payloads and maintain maneuverability. This is also the case for robots falling from a height regardless of their initial velocity, and for robots voluntarily jumping over an obstacle, or seeking balance from an unstable posture. Terrestrial animals are confronted with the same problems, and have evolved a series of features or behaviors enabling them to recover from a fall.

2. Review

In a scenario in which self-righting maneuvers are to be required, from one to four successive phases can be identified, depending on the severity of the destabilization to compensate for. These phases are presented in chronological order.

2.1 Modification of angular momentum prior to leaving the ground

If an animal is aware that it is about to fall or to enter a ballistic phase, be it voluntarily or not, it can use the last instants of contact with the surface to shape its trajectory and angular velocity by taking support on the ground. Frogs are an example of animal to be particularity adapted for taking advantage of this fact for jumping. Their long, strongly articulated and muscular hind limbs enable them to control their linear and angular momenta for an extended period of time during take-off, while their strongly compliant hind feet maintain prolonged contact with the ground during that time (Wang et al. 2008). This contact phase is of particular importance in that it represents the last opportunity to advantageously modify the subject's initial linear and angular momenta; while the animal's center of gravity will follow a parabolic trajectory, its total angular momentum will remain constant throughout the ballistic phase.

By carefully coordinating limb motion during takeoff, it has been shown that the aerial tumbling performance of gymnasts can be optimized (King & Yeadon 2004). King and Yeadon devised a five-segment planar model calibrated to elite gymnasts, and performed various optimizations on its joint torque activation timings, while retaining the approach linear and angular momenta measured during an actual performance. They successfully showed that under these initial conditions, substantial improvements in tumbling performance could be achieved. Moreover, performance loss caused by variations of the approach linear and angular velocities could be compensated for by performing similar optimizations on the model's joint torque activation timings (King & Yeadon 2003).

2.2 Body reorientation through limb motion

During a ballistic phase, a common means for modifying body orientation is to initiate the angular motion of certain limbs. The conservation of angular momentum dictates that the ratio of angular velocities generated between the thrown limb and the rest of the body will be inversely proportional to the ratio of their moments of inertia about the axis of rotation. Moreover, performing such a motion while still on the ground increases the effect since the floor reaction forces can contribute to amplifying the desired movement (Frohlich 1979).

Beyond exploiting the contra-rotation effect generated by displacing limbs, it is possible to initiate twisting motions if the subject is tumbling and has an initial amount of angular momentum. Considering the subject's initial angular velocity vector and inertia tensor, modifying components in the latter by moving limbs necessarily implies a reorientation of the angular momentum vector (Decatoire 2002). This is well known by gymnasts who can throw an arm while tumbling to initiate a twist, then throw the other arm to terminate the movement. It has been established that this aerial effect on twisting surpasses the contribution to the movement that could be brought by initiating the motion on the ground (Yeadon 1993).

2.3 Twisting with no initial angular momentum

In the case where a twisting motion is to be initiated when no initial angular momentum is available, a maneuver sometimes referred to as the “cat twist” can be performed. One method for achieving this maneuver involves two phases: firstly, the moment of inertia of the anterior half of the body is decreased relatively to the posterior half by retracting the front limbs and extending the hind limbs. Then by bending and twisting the spine, the front half of the body rotates by a relatively greater angle than the back half. Secondly, the opposite maneuver is performed, by extending the front limbs, retracting the back limbs, then twisting (Marey 1894).

Another maneuver for performing a “cat twist” can be described as a single continuous motion without varying the moments of inertia of the anterior and posterior body halves: by bending the two body halves toward one another around what could be schematized by an universal joint, then by twisting the joint, the subject reorients itself without modifying its total angular momentum. The front and back body halves rotate with partial angular momentum vectors whose sum is canceled by that of the global rotation of the whole body (Frohlich 1979). Mechanical prototypes demonstrating this schematized description have been demonstrated to be able to complete the maneuver (Galli 1995). In a much similar fashion, geckos have been shown to self-right by orienting their massive tails perpendicularly to their spine, and by swiveling them in a circular trajectory, causing the opposite rotation of their bodies (Jusufi et al. 2008).

2.4 *A posteriori* self-righting

During a landing phase and after at least one limb is in contact with the ground, the subject can attempt to correct its orientation using the renewed support, but may fail. While creatures with relatively long limbs can right themselves easily from any final orientation, this can be more complicated for other creatures unable to reach a supporting surface. In the event that they land on their backs, some species of beetles (such as *Eucnemidae*) are known to arc their body, storing elastic energy, before explosively releasing it in a jump aimed at self-righting. Others species, such as the *Histeridae*, open their elytra (the hardened protection of their hindwings) into flight position against the ground, then explosively shut them, resulting once again in a self-righting jump (Frantsevich 2004).

Turtles also have notorious difficulties to self-right if turned upside down. However, certain species, for example *Geochelone elegans*, have evolved shells with a highly domed shape, enabling them to self-right almost passively under the influence of gravity, and by departing from local minima in potential energy induced by irregularities in the shape of their shells by gesticulating (Domokos & Várkonyi 2008**.** In fact, strong similarities were observed between the shape of their shells and a recently discovered three-dimensional homogeneous body, the Gömböc, whose property is to have just one stable and one unstable point of equilibrium (Várkonyi & Domokos 2006).

3. Conclusion

It has been shown that terrestrial animals have evolved a number of features and behaviors enabling them to come back to their feet in the event of falls and jumps. When possible, preemptive action is taken on the ground; then, depending on the severity of the ballistic phase, orientation can be recovered through limb motion, or through a full-fledged twisting maneuver. If all else fails, ground-based recovery techniques can be used. The animals living today are the result of billions of years of natural selection, and should be considered as an invaluable source of inspiration for the development of tomorrow's robots and machines.

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