Hop, Lean, Balance, & Spin:
New modes of locomotion for small agile robots

Chris Schmidt-Wetekam, Andrew Cavender, Nick Morozovsky, David Zhang, and Thomas Bewley

Coordinated Robotics Lab; Dept of MAE; University of California, San Diego

Robots are already deployed in a wide variety of socially-relevant applications. Articulated robotic arms weld, solder, and fasten components precisely on assembly lines all over the world, and have been extended to retrieve and deploy satellites from space shuttles, to perform delicate life-saving surgeries, and to defuse Improvised Explosive Devices (IEDs) in conflict zones. Mobile robots [including UAVs, UGVs, USVs, and UUVs; that is, Unmanned Aerial, Ground, Surface (i.e., floating), and Underwater Vehicles, respectively] explore dangerous, remote, and inaccessible areas, automate repetitive tasks such as security patrol, cleaning, and harvesting, and monitor/forecast the movement of hurricanes, volcanic ash, oil, and sewage in the environment. Over the years, both articulated robotic arms and mobile robots themselves have become quite sophisticated, and are today a multi-billion dollar industry that is growing rapidly.

The UCSD Coordinated Robotics Lab is developing new paradigms for agility and coordination for mobile robots, enabling small, relatively simple robotic vehicles to move robustly in complex environments, and to work together to solve a host of involved tasks. The research involved leverages sophisticated 3D dynamic models and feedback control theories, and reflects a tight synthesis of mechanical design and control design, as the latter is not an effective surrogate for the former in the development of high-performance vehicles.

Remote-controlled treaded UGVs and autonomous UAVs date back at least to the Goliath and the V-1 “Buzz Bomb”, respectively, of WWII Germany. Modern US military incarnations of such vehicles include iRobot's PackBot and Foster-Miller's Talon, both fielded for IED disposal, and General Atomics’ Predator and Northrop Grumman’s Global Hawk, fielded for both long-range surveillance and ordinance delivery.

A transformative idea

The genesis of the UCSD Coordinated Robotics Lab was the final exam for a master’s level dynamics and control class offered by the PI at UCSD in 2003. This exam introduced the idea of a multimodal UGV that can self-transform between traditional (low-profile) horizontal roving, vertical roving (similar to a Segway), and pogo-stick-like hopping (Figure 1). Unlike conventional UGVs, which are typically dynamically stable over almost their entire range of motion, the proposed vehicle design supplants static stability with feedback control, like in a modern jet fighter, to improve maneuverability and efficiency at significantly reduced weight.

The vehicle proposed has two large main wheels at the bottom of a single leg, and a small omniwheel at the top. It steers when roving by differential actuation of the main wheels, and rights itself by aggressively torquing the main wheels backwards. The vehicle hops by releasing the energy of a pretensioned spring within the leg while upright. When airborne, it uses its two main wheels (and two smaller wheels mounted orthogonally between them) as “reaction wheels” - torquing these wheels in one direction generates an equal-and-opposite reaction torque on the vehicle, which can be leveraged to control the orientation of the vehicle.

When roving vertically, the proposed vehicle can also perform an energetic running single hop, enabling it to jump a significant horizontal distance. Upon landing, the vehicle recompresses its spring to soften the landing and to recover a substantial fraction of the energy of the hop, returning immediately to upright roving mode, ready to hop again. Such a capability enables the proposed vehicle to jump quickly over a complex burning obstacle, a situation in which speed is essential to ensure survival of the vehicle. While rolling is the energetically efficient way to travel, and is thus to be used whenever possible with such a design, hopping provides agility when the mission calls for it.

Soon after our initial explorations in implementing this idea in hardware, we realized that creative use of advanced 3D dynamics and feedback control theory could lead to a host of novel designs for practical UGVs with enhanced capabilities, and our lab stepped in to explore the possibilities. Note that all of the advanced vehicle designs and multimodal functionality discussed herein, as well as several of the key enabling components, are *patent pending*; much more is being investigated behind the scenes in our lab today, and will be revealed in the future.

Hopping and Leaning

We first investigated a simple pogo-stick-like vehicle, dubbed iHop v.1 (Figure 2), using a small rack-and-pinion mechanism mounted on the center of the leg to add energy to each bounce. This naïve initial prototype could stabilize a continuous hopping motion, but not robustly; the linear bearings used to guide the leg motion proved to be particularly difficult to keep aligned. However, we learned a lot from this prototype about the iHop design space, and leveraged this knowledge heavily when we went back to the drawing board on iHop v.2 in 2006.

Akin to the original cartoon, iHop v.2 (Figure 3) has two main wheels on the bottom, and a small omniwheel at the top of a movable leg. Inside the robot body, an internal reaction wheel is mounted orthogonal to the two main wheels. When airborne, iHop v.2 torques against the two main wheels to reorient itself fore/aft, and against the internal reaction wheel to reorient left/right. This design facilitates all of the maneuvers indicated in the original cartoon (Figure 1). However, left/right stabilization of iHop v.2 proved to be somewhat difficult with this design, due to the high moment of inertia in this direction; as a result, the third reaction wheel was occasionally spun up to high rpm in testing.

Perhaps the most significant design feature of iHop v.2 is its dual four-bar linkage mechanism. This innovative mechanism facilitates:
(1) precise linear motion of the leg (via just eight rotary joints);
(2) locking of the leg in the retracted position during roving (and release of this lock to initiate hopping); and
(3) a continuously-variable transmission of torque from the drive motor during the hopping motion of the vehicle, supplying high torque when it is needed (at low speeds), and high speed when it is needed (at low torques).

Note also that an elastomer spring, mounted between a post at the top of the leg and a bracket at the bottom of a long lead screw, stores energy during hopping, converting the kinetic energy of the vehicle upon landing into compressed spring energy, and then back into kinetic energy again as the vehicle begins the next hop. A small motor which drives the lead screw may be used to accumulate spring energy gradually; this spring energy may then be released suddenly, on command, to perform a single energetic hop.

We next focused our attention on the problem of stair climbing with a multimodal vehicle of this configuration. While stair climbing can be accomplished via hopping, there is no need to use such an energetically expensive, difficult-to-stabilize “dyno” maneuver to achieve it when the same result can be accomplished with a simpler, more reliable, quasi-static maneuver. We thus developed the iLean concept and prototypes (Figure 4). This vehicle overcomes stairs by balancing on its toe while its body (with the main wheels attached) ascends from the bottom to the top of the leg. It then “leans” the body onto the next step, transferring its center of mass over the step, and finally torques the wheels appropriately to upright the lightweight leg (with the opposite end of the leg now pointed up). The design is symmetric, so this motion can be repeated to climb the next step, etc. Note that iLean has only two wheels. When roving, the wheels are parallel; when climbing, iLean must cant the wheels inward to a roughly perpendicular orientation in order to stabilize the vehicle in both the fore/aft and the left/right directions. Such canting is the most difficult maneuver to perform reliably with this design.

Back to the drawing board one more time in 2008, iHop v.3 (Figure 5) fused the iHop v.2 and iLean concepts, retaining the remarkable capabilities of each while being simpler, lighter, and more robust. A key feature of iHop v.3 is the elimination of the large internal reaction wheel used in iHop v.2 for left/right stabilization, without requiring the delicate canting of the main wheels as implemented by iLean. Instead, iHop v.3 stabilizes itself in the left/right direction simply by shifting the mass of the two main wheels from side to side, akin to the balancing motion of a tightrope walker. This redesign of iHop thus converts its significant lateral moment of inertia from a liability into an asset that is leveraged to stabilize the vehicle.

Remarkably, the multifunctional wheels of iHop v.3 have *six* distinct useful functions:
(a) driving (when roving and the wheels are operated in conjunction);
(b) steering (when roving and the wheels are operated in opposition);
(c) uprighting from horizontal (by aggressively torquing the wheels in the correct direction);
(d) balancing in the fore-aft direction (when hopping) via reaction-wheel stabilization;
(e) balancing in the left-right direction (when hopping) via antisymmetric movement of the wheels as counterweights; and
(f) recovering the energy of the hopping motion via symmetric movement of the wheels as counterweights, causing periodic storage and release of energy from the elastomer springs.

This multifunctionality is facilitated by the truly remarkable linkage mechanism implemented in iHop v.3. In addition to the three essential features of the dual four-bar linkage mechanism of iHop v.2 mentioned previously, this new linkage mechanism facilitates both a controllable, antisymmetric, left/right rotation of the entire wheel/arm assembly which does *not* deflect the springs, as well as a controllable, symmetric, up/down motion of the left and right arms which *does* deflect the springs, thus efficiently facilitating both (e) and (f) as described above.

Note that the two main wheels of iHop v.3 must have significant mass to act effectively as reaction wheels. Rather than adding dead weight, incorporating the batteries and wheel motors on the wheels themselves significantly reduces the overall mass of the vehicle. Note also that the (heavy) main arm motors of iHop v.3 are also fundamentally multifunctional: via creative use of a lightweight latching mechanism on the motor housings, they produce completely different effects when driven clockwise or counterclockwise, driving the hopping motion when actuated in one direction, and pretensioning the spring when actuated in the other.

Balancing

Encouraged by the promise of the multifunctional mechanisms incorporated in iHop, we also explored what could be done to extend the functionality of a traditional treaded vehicle. The result of this investigation, dubbed Switchblade (Figure 6), is a treaded vehicle that can balance on its front tread sprockets, on its back tread sprockets, or on a contact point on its treads anywhere in-between; that is, it can stabilize both a wheelie and a stoppie, and can balance on the edge of a step. Furthermore, it can transition smoothly between these various modes. Switchblade accomplishes this remarkable range of motion by independently rotating the tread assemblies with respect to the chassis, in addition to driving the treads themselves, in a carefully controlled fashion. In short, this allows the vehicle to dynamically adjust the position of its center of mass as necessary. This motion is facilitated by an advanced yet robust hip joint (Figure 6), with all necessary motors contained securely inside the body of the vehicle itself.

With the tread assemblies unfolded away from its body, Switchblade, which is normally a low-profile vehicle only 5” tall, can balance upright on its treaded “toes” in order to stand up to 25” high, thus greatly extending its reach and the field of view of its onboard cameras. This standing configuration also allows Switchblade to overcome obstacles that would otherwise be completely insurmountable by a traditional treaded vehicle of its nominal size. For example, Switchblade can approach a stair in this upright stance, then shift its center of mass to balance on the edge of the first step. It can then smear up the first step while remaining balanced on its edge, then transition to execute the same motion to overcome the second step, etc. Clever use of feedback control in this manner enables a vehicle of this design to overcome stairs that would otherwise require a traditional treaded vehicle three times its length. Switchblade is also capable of both crossing chasms nearly as wide as the vehicle is long, and using the front-mounted pivot of the chassis to actively dampen vibrations when driving quickly over rough terrain.

Spinning

In the 1999 remake of *The Avengers*, John Steed and Emma Peel walk across the Thames enclosed in large plastic spheres (now available commercially from Waterwalkerz, Ltd). Though hamster balls have been popular pet novelties for decades, the Rhino character from Disney’s 2008 animation *Bolt* brought the idea back to the silver screen. There have been several internally-driven spherebots designed in recent years around this basic hamster-ball concept. Though engaging, all such vehicles suffer from a *fundamental performance limitation*: they can accelerate only as fast as a certain fraction of the acceleration due to gravity, as dictated by basic geometric arguments (related to the possible positions of the center of mass within the sphere).

iceCube (Figure 7) takes the idea of spherebots to the next level, and is distinguished from all other spherebots we are aware of in that its center of mass is always at the center of the sphere. Rather than moving the center of mass, iceCube builds up angular momentum in four carefully-configured, internal gimbaled flywheels (known in such applications as Control Moment Gyros, or CMGs), then, when necessary, reorients these spinning flywheels to impart, quickly, large coordinated reaction torques on the sphere in order to spin it in the desired direction. This approach bypasses the fundamental performance limitation associated with the hamster-ball concept, and is limited only by the friction between the sphere and the ground, which can be enhanced by endowing the sphere with a rough surface. Note also that iceCube can be made lighter than water to make an amphibious vehicle that can “swim” simply by spinning, and can also be made with small pressure bladders to accurately control its buoyancy, thereby enabling it to float (and maneuver) just below the water’s surface for stealth amphibious operations.

Fun

It is tempting to use personifications to describe robotic systems; these temptations are especially strong for a vehicle endowed with feedback, which often bestows the vehicle with a certain life-like responsiveness, and makes the vehicle particularly engaging as a toy. We have thus explored the miniaturization and simplification of our original iHop concept to form a (non-hopping) self-righting Segway dubbed iFling (Figure 8) that can pick up and throw ping-pong balls (or swack them around, using the leg as a hockey stick). Due to the very careful attention paid during its design, picking up a ball is in fact quite easy with this vehicle: simply roll over a ball to wedge it between its carefully-sculpted body and one of its rotating wheels, which then lifts the ball into a cage. Throwing a ball is also quite effective, and is achieved in a precise and energetic lacrosse/jai-alai fashion. Again, this design is particularly novel and inexpensive because it is inherently multimodal, and its two motors are used for multiple distinct functions: specifically, driving, steering, uprighting, picking up balls, and throwing balls.

Discussion

Crossing disciplinary boundaries. Robotics is one of the most demanding and interdisciplinary areas of mechanical engineering, as a successful designer must balance and fuse many disparate pieces of technology, expertise, and theory in order to realize any new vehicle concept in an optimal fashion. One of the key challenges is to find the appropriate blend of commercial off-the-shelf (COTS) technology and software (the sophistication of which, today, is quite remarkable) with custom-designed vehicle configurations, electronic circuits (designed with minimum footprint and power drain), and maximally effective and robust control strategies.

Design/Build/Test/Repeat. Our approach to robotic system design is fundamentally iterative, as the multifarious challenges associated with any new design concept cannot generally be anticipated before the first prototype is built. As a result, investigations of this sort would be impossible without modern CAD programs, which are instrumental in making the iterative design process efficient, and computer-controlled shop equipment (laser cutters, mills, and 3D printers), which fundamentally reduce the labor involved in the construction of new prototypes.

Reaction wheels versus CMGs. Archimedes once said "Give me a place to stand and a lever long enough, and I will move the earth." As Archimedes needed a fulcrum, so also does a balancing, hopping, or orbiting vehicle need an inertial mass to torque against in order to reorient itself. This is the purpose of reaction wheels, whose use is relatively straightforward: torque a reaction wheel, and the vehicle experiences an equal-and-opposite reaction torque. The resulting motion of the reaction wheel itself can later be bled back off, either with reaction control thrusters, or merely when the vehicle comes back in contact with the ground. Though simple, the instantaneous torque available when using a reaction wheel is limited to that provided by the motor used to drive it. The torque associated with a CMG, on the other hand, is akin to that experienced in the high-school science experiment in which one sits in a swivel chair holding a heavy spinning bicycle wheel: by gently reorienting this spinning wheel, a relatively large reaction torque is applied immediately to the subject in an orthogonal direction, and the chair swivels. Though more complex, the instantaneous torque available when using CMGs is not limited by that of the motor used to drive the gyros, and can thus lead to more agile designs. Note that both reaction wheels and CMGs are used extensively in the satellite industry.

Modeling and control. If we have, or can develop, an accurate dynamic model of the system under consideration (which is certainly the case), then it is generally to our advantage to use it; thus, all of the vehicles described in this article are coordinated leveraging control strategies designed around (or at least tuned based on) such models. Note that accurate dynamic modeling of such systems is doable, though not necessarily easy; in particular, iceCube has a rich range of possible motions that must be handled carefully and with a singularity-free state description. Offline and online identification of model parameters is also sometimes necessary in such problems. Finally, the substantial body of existing linear control theory provides a flexible set of tools that go a long way towards the effective control of robotic systems, which are typically fraught with complex trigonometric nonlinearities. Richard Bellman is said to have once compared one who designs linear controls for nonlinear systems with one whom, "having lost his watch in a dark alley, is searching for it under a lamp post." Erudite comments of this sort are often taken far too seriously, as all differentiable systems are linear when considered as small perturbations about a nominal position or trajectory. As just one example, consider the double-pendulum swing-up and stabilization problem: though dominantly nonlinear, our lab has solved this reference problem (apparently, for the first time) using a straightforward combination of Model Predictive Control (MPC) trajectory planning (via successive linearizations about candidate trajectories) and Linear Quadratic Gaussian (LQG) stabilization (Figure 9).

The future. The current pace of innovation in the development of new modes of locomotion for mobile robotic systems is ferocious, and (based on the number of relatively unexplored paradigms still under investigation) shows little sign of slowing down. Current work in this area leverages significant emerging advances with several critical component technologies, including microprocessors, batteries, sensors, imaging systems, and wireless communications; the time is thus ripe for a revolution in the capabilities of systems which leverage these advances. In short, the innovations to emerge in the next decade are fully expected to completely reshape this field.

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