

Bio-inspired Hybrid Locomotion in Mobile Robots: A Comprehensive Survey

Abdullah Maqsood¹, Humaira Afzal², Muhammad Rafiq Mufti³, Waqar Aslam⁴

^{1,3}Department of Computer Science, COMSATS Institute of Information Technology, Vehari, Pakistan.

²Department of Computer Science, Bahauddin Zakariya University, Multan, Pakistan.

⁴Department of Computer Science & Information Technology, The Islamia University of Bahawalpur, Pakistan.

ABSTRACT

Hybrid motion strategies such as combining jumping or running with flying and gliding are used in nature by numerous animals and birds for effective movements in their natural habitat. However, only, recently its importance is realized as a valuable locomotion strategy for small robots. The aim of this paper is to provide comprehensive coverage of developments in robots capable of this hybrid locomotion, i.e., a combination of aerial and terrestrial mode. Relevant works of interest in each domain are also discussed.

Keywords: Bio-inspired, robotics, ornithopter, skyhopper, hybrid locomotion.

Author's Contribution

^{1,2,3,4}Manuscript writing, Data analysis, Interpretation, Conception, Synthesis, Planning of research, Interpretation and Discussion, Data Collection

Address of Correspondence

Waqar Aslam
waqar.aslam@iub.edu.pk

Article info.

Received: Dec 16, 2017
Accepted: Oct 13, 2018
Published: June 30, 2018

Cite this article: Maqsood A, Afzal H, Mufti MR, Aslam W. Bio-inspired Hybrid Locomotion in Mobile Robots: A Comprehensive Survey. *J. Inf. commun. technol. robot. appl.* 2018; 9(2):1-12.

Funding Source: Nil
Conflict of Interest: Nil

INTRODUCTION

Navigation in rough terrain has always been a fundamental problem for mobile robots. The most obvious mode of ground locomotion in robots is the wheel, which comes with the inherent shortcoming of traversing large obstacles. The mars rovers, spirit, opportunity and sojourner have an outstanding obstacle traverse-ability to wheel size performance, thanks to their unique rocker-bogie suspension but even they cannot traverse obstacles larger than 1.5 times wheel diameter.¹ This implicit limitation of wheeled locomotion significantly reduces the capability of robots in scenarios where robot size is of greater concern. Recently, legged locomotion has shown great potential in terms of rough terrain travers-ability.^{2,3,4} However, the designs are mechanically more complex than wheels that require numerous joints, actuators, and linkages.

Nature is a great inspiration for roboticists; therefore, our focus is towards animal kingdom. Among insects and

birds, many of them use combination of aerial and terrestrial locomotion like flying/gliding in combination with jumping to move successfully in their natural environments. This can be clearly observed in case of birds like eagles and vultures jumping from high cliffs and then gliding to the next waypoint.⁵ Birds like pigeons leap from an elevation to perform a takeoff. This strategy conserves energy more heavily required either in flapping wings or running to perform a ground takeoff.⁶ as shown in Figure 1. Many birds, for example crows, sparrows and starlings use jumping,^{7,8} which enable them to perform a near vertical takeoff as depicted in Figure 2. Small birds use a combination of jumps and low altitude flying to move on an uneven ground.⁹

The particular phenomenon of getting more mileage through jumping from elevation and then gliding is more prominent in arboreal species, which are less gifted than birds for flapping flight. These include bats, Japanese

giant flying squirrels, flying snake, Draco lizard, flying frogs, etc.¹⁰⁻¹⁶ For instance, insects locusts and fleas use jumping in combination with flying to accomplish efficient movements across their natural habitat¹⁷ (see Figure 3).



Figure 1: Bird jumping from high point.

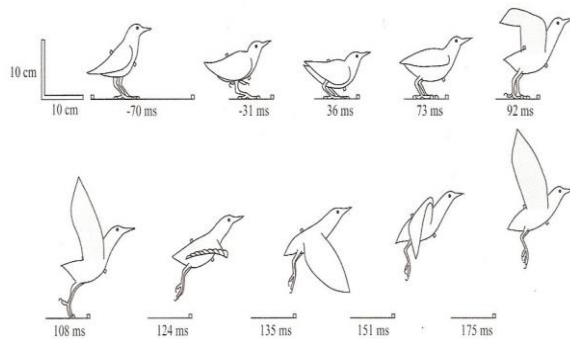


Figure 2: Near vertical take-off by some birds.

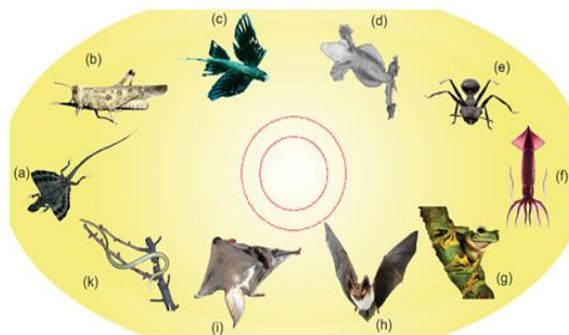


Figure 3: (a) gliding locusts, (b) locusts, (c) flying fish, (d) gliding geckoes, (e) gliding ants and spiders, (f) gliding squid, (g) gliding frogs, (h) bats, (i) gliding mammals, (k) gliding snakes.

A cursory observation of birds and animals of interest reveals that the integration of terrestrial and aerial locomotion plays a very important role in successful motion, hence critical for their survival. In our opinion, this natural spectacle presents a great research theme for

roboticists and requires a considerable attention from research community. In recent years, many miniature robots have been developed.^{18,19} Alongside considerable advances in design and control of miniature aerial vehicles (MAV), the understanding of flapping wing aerodynamics have resulted in development of robotic ornithopter platforms in particular.^{20,21} These breakthroughs have paved the way towards integration of two types of motion strategies, which can open endless future research horizons like energy efficient takeoffs, self-deployment from cluttered environments, solution to control problems, etc. The purpose of this paper is particularly to review the various research efforts on bio-inspired hybrid locomotion reported to date. We develop a general classification of existing designs such that the future designs can also be mapped to it. Moreover, the relevant work on jumping and flapping wing flying robots is discussed. Our aim is to present a holistic picture of the-state-of-the-art progress towards ideal bio-inspired hybrid robots.

The paper is structured as follows: In the next section, current robots employing bio-inspired hybrid locomotion is discussed, which can be categorized into three different classes. Section 3 gives a brief review of jumping robots. A review of relevant flying robots is discussed in Section 4. Finally, the conclusion is summarized in Section 5.

BIO-INSPIRED HYBRID ROBOT LOCOMOTION TECHNOLOGY

To the best of our knowledge, researchers have made few attempts to build a robot capable of bio-inspired hybrid locomotion. Before describing the-state-of-the-art in hybrid locomotion in detail, we first present a classification of robots such that the future designs can be mapped to them (see Figure 4).

The present prototypes can be divided into the following three categories:

- Robot locomotion with assistive gliding;
- Robot locomotion with assistive flapping;
- Flying robots with assistive ground locomotion.

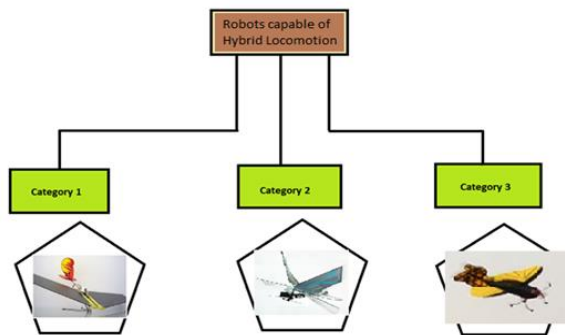


Figure 4: Taxonomy to which current and future designs can be mapped.

Robot Locomotion with Assistive Gliding

In this category, the primary mode of movement is ground locomotion, mostly jumping and is augmented by the capability of gliding after a jump. This functionality adds useful mileage to jump distance. One of such robots called Glumper was presented at University of Bath.²² As shown in Figure 5, it is an octahedral shaped 4-legs robot having weight of about 0.7 kg, which is relatively heavier than other jumping robots. Each leg comprises of a thin membrane acting as a wing while jumping. It aims at prolonged jump and reduced impact force on landing. Its octahedral structure is supported with carbon fiber reinforced plastic tubes along its edges. Four torsion springs at its knees provide the necessary force required for jumping. At the main vertices, there are pin joints between which lie a toothed belt and a compression thread. Control box winds the compression thread around a capstan and slowly pulls the vertices of the device towards one another, thus storing energy in the torsion springs. The capstan is released automatically at full compression using a series of levers. Wing-like membranes, secured between the legs are unfolded as the robot jumps. The Glumper is able to jump up to 1.17 meters but due to lack of a direction control, there is no information about its jumping performance from elevations at projected angles.

A novel robot named Ecole Polytechnique Federale de Lausanne (EPFL) jumpglider, shown in Figure 6, was reported by Kovac, which integrates 7 grams miniature jumping robot with wings.^{19,23,24} For this robot, three biological inspired wing designs, namely bat inspired, butterfly inspired and locust inspired, were considered. After feasibility evaluations, the locust inspired wing and

rigid wing designs were shortlisted for further experimentation. The empirical results showed that the rigid wings provide good performance in terms of distance covered and impact energy, owing to its simple design and consequently lesser weight. It can be self-deployed for elevated places like walls, table tops, etc. When it is deployed from a height of 2.0 meters; it is able to traverse a distance of about 4.5 meters. In short, this type of robot is very effective for jumping from heights, imitating gliding mammals that jump from elevation and glide to cover large ground, thus consume relatively less energy.

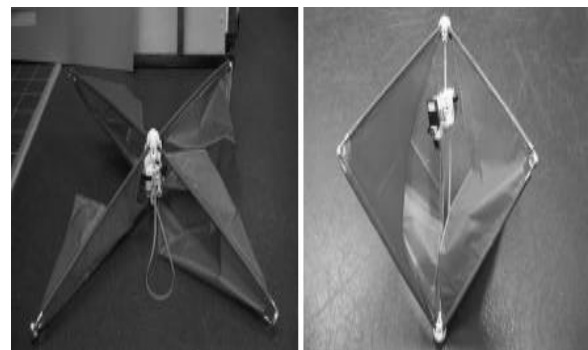


Figure 5: Glumper.



Figure 6: EPFL jumpglider.

Grillo is a bio-inspired miniature jumping robot that jumps continuously for its movement. Until now, three versions of Grillo have been developed: Grillo, Grillo-1, and Grillo-2.²⁵ It is concluded by research that wings could be utilized to prolong and stabilize the jump. Using this idea, the updated version of Grillo-1, called Grillo-2, was designed with the hope of higher and longer jumps if mechanical evolutions would allow. Recently, the latest prototype Grillo-3 has been introduced with passive wings and tails in order to increase stability during the jumping phase (see Figure 7).

Woodward of Carnegie Mellon University uses gliding in combination with jumping to prolong its jump (see Figure 8).²⁶ This robot, weighing about 100 grams, can jump up to 6 meters. Its mainframe has 2-four-bar systems, which provide the platform for both jumps and subsequent gliding. The robot design is highly coordinated, i.e. both locomotion modes share the components and this integration allows a considerable reduction in weight - a feasible design.

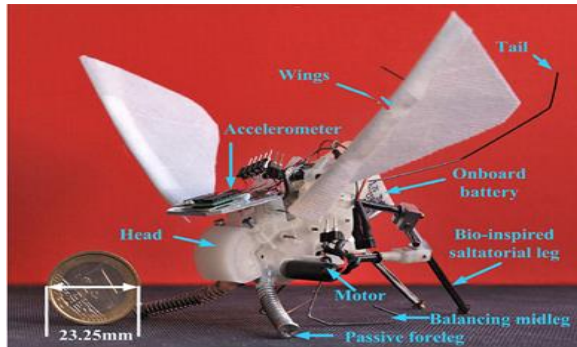


Figure 7: Grillo.

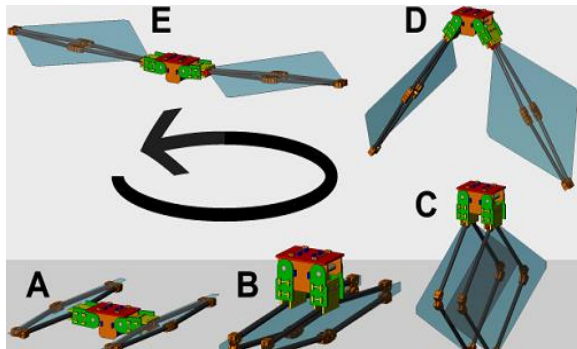


Figure 8: CMU jumping and Gliding robot.

Robot Locomotion with Assistive Flapping

Robots of this category use flapping wings to increase their ground locomotion capabilities, like speed and traverse-ability of inclined surfaces. A relevant research area can be bio-inspired takeoff from cluttered surroundings.

It was observed that adding wings to terrestrial robot Dash, resulting in DASH+Wingss, increased the locomotion capability (see Figure 9).²⁷ It was observed that the speed of DASH+Wings is double (1.29 m/s) of Dash (0.68 m/s). In addition, flapping wings have an increased the angle of ascent (from 5.60 to 16.90). DASH+Wings has opened new avenues of research in

wing assisted running, a phenomenon that considerably adds to the ground locomotion capability of birds.²⁸

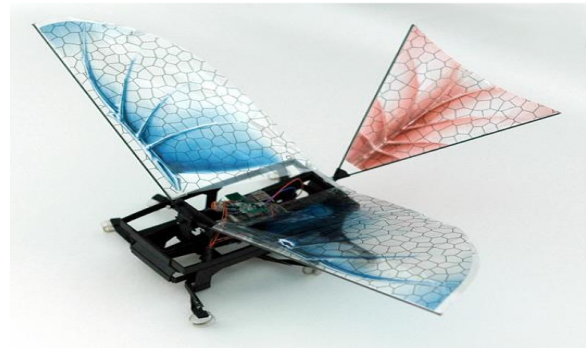


Figure 9: UCB Dash+Wings.

BOLT is a bipedal robot capable of both aerial and terrestrial locomotion in indoor environments (see Figure 10).²⁷ Weighing just 11.4 grams and a wingspan of 28 cm, it can perform ground-air transition in less than one meter. To develop the hybrid platform, wings and gearbox from a commercial Ornithopter Air Hogs V. Wing AvengerTM are combined with a custom airframe and legs. In order to reduce its weight, a single motor drives both legs and wings. The robot is equipped with an electronic package holding a 40 MHz dsPIC processor, 6-axis IMU, 1 MB flash memory and Atmel communication module. BOLT provides a handy platform to perform different experiments to exhibit the usefulness of hybrid locomotion, like efficient movement in cluttered environments and takeoff from closed places.

One of the commercial R/C hybrid robots is Skyhopper from FLYTECHTM. It can fly, walk and use its legs to move out of corners. It can also jump over obstacles and take a running takeoff from small places.

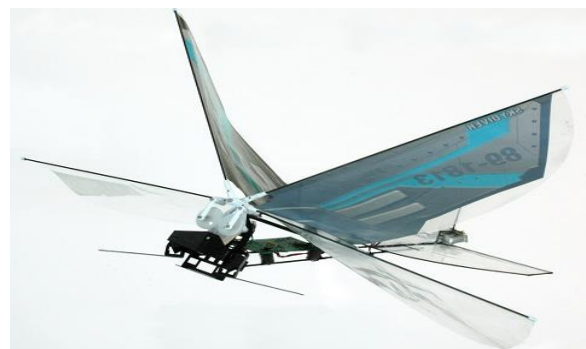


Figure 10: UCB Bolt.

Flying robots with Assistive Ground Locomotion

In these robots, ground locomotion is added in addition to the primary mode of flying to increase the mobility of the robot.

MALV is a robotic structure capable of aerial and terrestrial locomotion (see Figure 11).²⁹ Its potential usage can be the reconnaissance missions for law enforcement agencies in neighborhoods, where human deployments are very dangerous. Its dual locomotion mode will allow it to get closer to the object of interest as compared to 'aerial only' robots.



Figure 11: UFL MALV.

It integrates successfully MAV of University of Florida with wheel design of Mini-Whegs, which makes use of a novel wheel design.^{30,31} This design is sort of hybrid between wheel and legs that provides the robot with increased mobility in rough terrain. Bio-inspired flexible wing design of MALV offers maneuverability advantage over similar sized rigid wing aircrafts. MALV can be self-deployed from rooftops to perform terrestrial to aerial transformation. While on ground, it can move using its 'wheel-legs' (see Figure 12). It also has the ability to fold its wings to enter into narrow spaces.



Figure 12: UFL MALV in different phases.

Its latest version can execute autonomous navigation between (obstacle-free) waypoints by means of onboard autopilot and GPS. Moreover, this version is also equipped with camera for visual feedback.

Daler v9 robot is the latest variant of the Daler series, which is capable of three modes of locomotion: 1) walking, 2) hovering and 3) flying.³² Hovering capability allows the robot an autonomous transition from ground to flying mode. Its design is based on bio-inspired integrated and adaptive approach. Integrated design approach allows the robot to use the same set of actuators for two different forms of locomotion while adaptive design approach allows alteration in structure to suit required kind of locomotion. Movement on the ground is achieved by an adaptation of wings into whegs (wheel-legs), while wingspan is reduced by compression of carbon fiber frame thus giving more control on the ground. This robot can achieve a speed of 4 cm/s on the ground and 20 m/s in the air, traverse a maximum gap of 9 cm, climb a maximum step of 4 cm at a maximum upward slope of 7 degrees. The robot frame is covered with fabric for greater impact strength (see Figure 13).

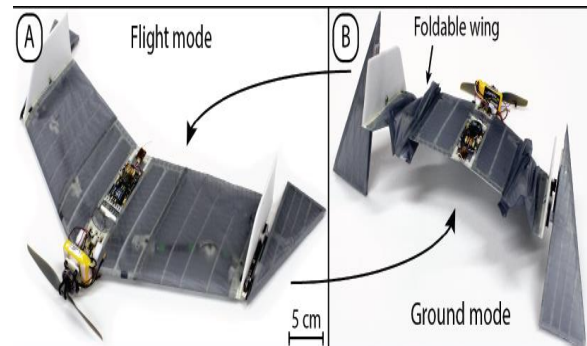


Figure 13: EPFL Daler.

A conceptual robot, shown in Figure 14, is capable of hybrid locomotion.³³ In ground mode, the robot is similar to University of Minnesota Scout robots.³⁴ Aerial mode is similar to RC helicopters where yaw is controlled by tuning the rotation speeds of rotors, whereas pitch and roll are adjusted by cyclic pitch of the lower rotor. During terrestrial mode, the rotors are wrapped against the robot's body thus results in a more compact design. The transition from ground to flight mode is initiated by extending a pair of arms hinged at the lower end of the robot. The moving arms push on the ground, lifting the

upper wheel from the ground until the robot is upright for a takeoff. The practical implementation of conceptual design is in preliminary phase.



Figure 14: University of Minnesota Hybrid robot.

JUMPING ROBOTS

For millions of years, numerous animals and insects have been using jumping to move efficiently in their natural terrain. Hence hopping and jumping together was an attractive idea for scientific community. They applied it in various scenarios, such as for an efficient transportation for celestial explorers operating in low gravity environments (moon, mars and asteroid surfaces) early on in the era of space exploration. But it was only during the last decade when this idea was applied for jumping of robots.¹⁹ Another variant of this idea was a combination of hopping with wheeled locomotion for producing rescue robots capable of jumping obstacles larger than their size.^{34,35}

Viable jumping mechanism discussed earlier for hybrid locomotion should be lightweight and at the same time should be able to provide a powerful thrust. Many big size hopping robots have been branded so far. For instance, Sandia Hopper,³⁶ Scouts from University of Minnesota,³⁴ Circular/Spherical robots for crawling and jumping³⁷ and Rescue robot³⁵ got attention, though they remained heavy to be pertinent for this type of locomotion strategy (see Figure 15). We restrict our discussion to progress in area of lightweight powerful jumping robots and their jumping mechanisms that can be potentially used with wings for research purpose.

Grillo III is a bio-inspired jumping robot with dimensions 50 mm x 25 mm x 20 mm, weight only 22 grams. It uses a 30mA lithium battery that ensures 30 minutes of jumping of maximum distance 200 mm.²⁵ To improve stability during flight/landing phases, wings and tails are added to the body. The robot's jumping has three

parts: i) levation phase ii) holding phase iii) formal jumping phase including acceleration, flight, and landing. The elevation phase includes meshing of the gears while the holding phase involves charging of springs for about 10s. After storing enough energy, a mechanism releases the spring and empowers the leg similar to the tendon-muscle system used by jumping insects like leafhoppers.

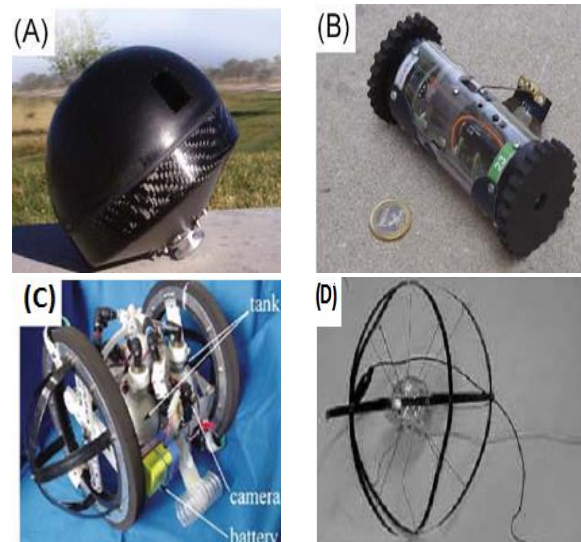


Figure 15: Large sized hopping robots.

Miniature 7 grams jumping robot shown in Figure 16A, developed at EPFL, is capable of jumping 27 times its own height. Up till now, it outperforms the existing jumping robots in terms of jump height per weight per size.^{19,38} It employs a mechanism in which a spring is energized that releases its energy instantaneously using a click mechanism. It extends the elastic element in four bar leg linkage causing robot to go airborne. The use of four-bar mechanism allows the adjustment of different parameters like takeoff angle, acceleration time, trajectory of foot tip, by changing different properties of four-bar linkage. The mechanical principle of slowly charging an elastic element and then releasing the stored energy (pause and leap) is used by small jumping insects and animals such as frogs, fleas, locusts and leafhoppers. This miniature robot provides the jump to the EPFL Jump glider discussed before. Its modified versions are able to perform repetitive and steered jumps but at the cost of jumping height (see Figure 16B).

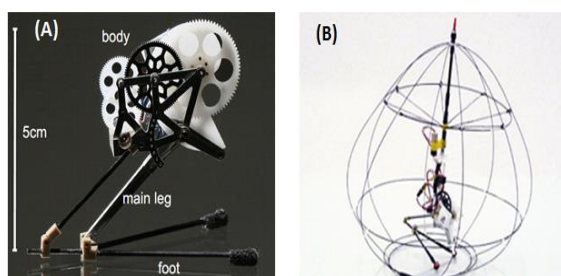


Figure 16: EPFL Hoppers.

Mini-Whegs series of robots, weighing 90-190 grams, use a novel wheel design for locomotion.^{30, 31} This design is a hybrid between wheel and legs, thus providing increased mobility in rough terrains. The jumping Mini-Whegs robot (see Figure 17) can jump to a height of 18 cm, which is about 2.5 times its height. Jumping is achieved using a four-bar parallel linkage and coil spring, which is stretched using a motor within the chassis and released automatically via an over-center mechanism that is invoked when the spring is fully extended.



Figure 17: Mini Whegs.

A hopping robot of height 8 cm can steer jump continuously to a height of 55 cm.³⁸⁻⁴¹ Two springs charged by a single motor provide the required energy for jumping (see Figure 18). These springs are part of their respective chain linkage to provide the required thrust. For reorienting after a jump, robot applies an active uprighting mechanism, enabling it to stand on two legs. As mentioned earlier, the robot is capable of self-steering, which is activated in the fallen state using gear with the same spring charging motor.

Jumping robots, called hoppers, are intended for planetary explorations.^{1,42-44} The third generation hopper is called the wheeled hopper, contrast to which the second generation hopper (see Figure 19) is purely a

jumping robot, which is capable of jumping horizontal distances of 1.8-2.0 meters and vertical heights of approximately 0.9 meters. This hopper may sound a bit erratic but due to its excellent performance and standing in lightweight jumpers, it is worth of discussion here. It employs a 6-bar linkage/spring mechanism, along with a lead screw driven compression system (see Figure 19). The primary DC motor builds compression on the leg until it is connected with a latching mechanism. When the robot is ready to hop, a small amount of additional compression causes a mating wedge on the 6-bar to release the leg latch. The robot is equipped with an active steering and self-righting mechanism. The steering mechanism controls the direction of the jump by rotating the robot around its axis. The two-stage self-righting mechanism brings the robot back to upright and stables its posture after landing. The structure of the robot is designed to accommodate an on-board camera along with other control circuitry.



Figure 18: Hopping Robot.

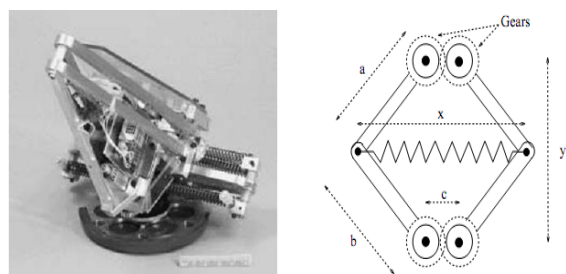


Figure 19: Second Generation Hopper.

The latest version, the wheeled hopper is provided with wheels in addition to the jumping mechanism (see Figure 20). In addition to getting air mileage by hopping, it can also perform ground locomotion using its wheels. The wheels are intended to serve two purposes: 1) to orient

the robot properly for jumping and, 2) to traverse relatively benign terrains. Except for the newly added takeoff angle adjustment mechanism that provides jump angle adjustments within the range 0° - 85° , its hopping mechanism is similar to the previously discussed second generation hopper. This robot is providing a research platform for studying autonomous goal-directed navigation using onboard sensors and a control unit.

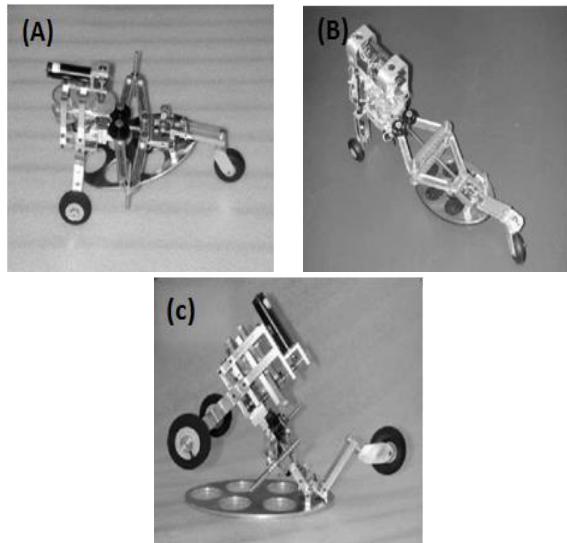


Figure 20: Wheeled Hopper.

FLYING ROBOTS

As already emphasized, flying mechanisms for hybrid robots should be lightweight so that the overall weight can be lifted up at least to some distance.⁴⁵⁻⁴⁷

Rigid wing gliders are the simplest form of flying machines and have been in business since long. The recent availability of low-energy processors and tiny sensors has enabled high optimization of the control theory, thus opening up new horizons in the autonomous operation of MAVs. Quadrotors, coaxial rotor and axial rotor platforms are most popular among researchers. Some relevant work includes ETH Zurich muFly project, Procerus coaxial platforms, Aerovironment's Black widow MAV and EPFL Blimp (see Figure 21). However, the research on miniature machines of this type is still in a primitive stage and it mainly focuses on vehicle stabilization and flight dynamics.

Bio-inspiration being the topic of this paper; we focus on bird flight features (flapping wings), which have been

consistently mysterious. For smaller size and performance in low Reynolds number regimes, the bird flight is incomparable in terms of energy efficiency, agility and maneuverability.⁴⁸ Fixed-wing aircrafts lack in hover-ability, require longer runways and give low-end agility for avoiding hurdles. Rotary-wing aircraft, such as helicopters, quadrotors, etc., have hover-ability and maneuverability, and can takeoff vertically, but they suffer from obstacle proximity effects, inefficiency and an ever lingering danger of a deadly collision leading to damaging the rotors.⁴⁹ Furthermore, a recent study reveals that optimized flapping wing motion can save up to 27% of conventional flight aerodynamic power.⁴⁸



Figure 21: a) ETH Zurich Mufly, b) AeroVironment Black Widow, c) EPFL Blimp.

Till recently flapping wing flight was engulfed in an aura of complexity. It was considered too difficult for roboticists but now things are changing. Understanding of bird flight intricacies has encouraged engineers to develop biologically inspired flapping-wing micro aerial vehicles. There is plethora of ongoing research in this field ranging from efficient wing design and improvements in aerodynamics to algorithms for autonomous flights using onboard control unit in GPS denied environments. Some highlights of the ongoing research are presented next.

Prof. Robert C Michelson is credited for designing one of the first flapping-wing robot, Entomopter, which

immediately got attention as a potential candidate for Mars exploration.⁵⁰ It could access places on Mars, which was otherwise impossible for wheeled explorers and conventional unmanned aerial vehicles (UAVs). A miniature butterfly inspired ornithopter weighing about 0.4 grams and wingspan of 140 mm, was developed in NASA. It is capable of achieving flapping frequency of 10 Hz. Using only onboard control unit in ornithopter, an autonomous goal-directed flight is also proposed.²¹ The platform is a customization of commercially available ornithopter 'Silverlit WingMaster-I Bird'. It has an electronic control unit having 40 MHz dsPIC microcontroller, 4MB memory, 3-axis accelerometer, 3-axis gyroscope, wireless transceiver, motor driver, IR camera connector and OmniVision OV7660FSL cell phone camera connector (see Figure 22).

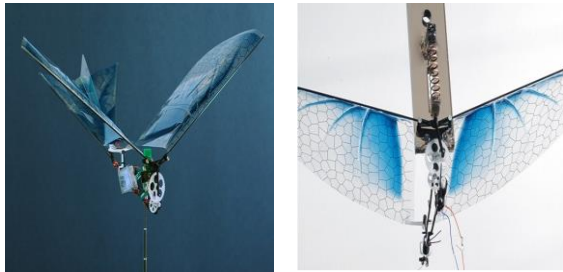


Figure 22: Research platforms using commercially available ornithopters.

The ornithopter has the ability to perform autonomous flight towards infrared (IR) emitting goal. To deal with the case of target being out of sight of IR sensor, an algorithm for dead reckoning is also designed using onboard microprocessor and IMU. The ornithopter can also accommodate a vision camera for future research on optical flow techniques for obstacle avoidance and goal directed flight. A feasibility of optical flow sensing technique for obstacle avoidance, distance regulation and moving target tracking for ornithopters is determined.⁵¹ A non-linear multibody model of ornithopter's flight dynamics is also evaluated.⁵² A design of MEMS wing frame made up of titanium with Parylene C used as membrane is proposed.⁵³

Researchers at TU Delft designed flapping wing flying robots called DelFly I, DelFly II and DelFly micro (see Figure 23a).²⁰ DelFly micro is equipped with an onboard camera for visual feedback and weighs only 3

grams. The project is aimed towards developing a small fly size ornithopter capable of autonomous navigation using onboard sensors and processors. A top down approach is followed for the construction of latest DelFly micro. In this approach, a fully functional large scale system is made and its properties studied. Research then progresses by making smaller systems while maintaining a minimum functioning limit. In this case, an onboard camera and a transmitter are minimal functioning requirements. DelFly series ornithopters are one of the few robots that are capable of extended hovering.

Hovering is one of the most fascinating abilities of small birds like hummingbirds. Producing it artificially, is however a difficult phenomenon due to the involved challenges such as stability, power to size considerations and aeroelasticity. Cornell computational synthesis laboratory presented a design capable of successful passive stable hovering.⁵⁴ The design is similar to conventional rotor driven Quadrotors with 4 pairs of 8 wings powered by 4 DC motors to provide required lift to 24 grams machine using clap and fling mechanism (see Figure 23b). The robot is able to hover for 30 seconds. One of the salient features of this design is its autonomous passive stability while hovering using a set of damping sails. Quadrotors achieve active stability through the implementation of control strategy consisting of microprocessor and IMU, thus making the system too heavy for insect scale flight.⁵⁵ Cornell extended the hovering time to 85 seconds. In 2009, AeroVironment, Inc. launched a hummingbird capable of active hovering for about 20 seconds. The research is aimed at autonomous navigation and obstacle avoidance capability using onboard microcontroller and sensors in GPS denied environments.

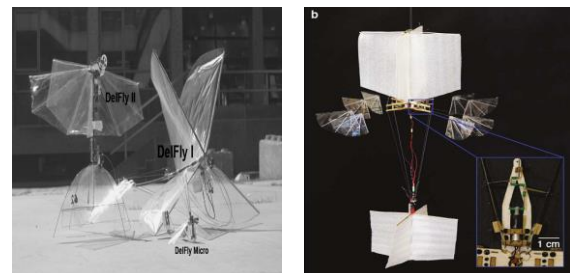


Figure 23: a) DelFly, 2) Cornell Robot.

CONCLUSION

Recent advances in robotics, ranging from intelligent control and mechanical design to swarm robotics, have opened endless application directions such as space exploration, rescue operations, etc. However, robots have to undergo drastic improvements in order to meet expectations in such real-life scenarios. Animals, birds and insects are playing the game of survival since inception of life; they have mastered the art of effective locomotion in unstructured environments. Therefore, it is of no surprise that we are continuously witnessing a paradigm shift towards bio-inspired robots. In this paper, we have reviewed the current progress on implementation of biological phenomenon. We have highlighted relevant work on bio-inspired jumping and flying used by robots to give a holistic picture on hybrid robots. Taxonomy is also presented with the aim to map most of present and future robot designs. Hybrid robot design is an area which got recent attention. The combination of jumping with flapping wings has the potential of many innovative and exciting works. The research on autonomous control and motion planning require further attention from research community.

REFERENCES

- Burdick, J., and Fiorini P., "Minimalist jumping robots for celestial exploration", *The International Journal of Robotics Research*, Volume 22, No. 7-8, pp. 653-674. 2003.
- Raibert, M., Blankespoor, K., Nelson, G., and Playter, R., "Bigdog, the rough-terrain quadruped robot", In *Proceedings of IFAC*, Volume 41, No. 2, pp. 10822-10825, 2008.
- Mishkin, A. H., Morrison, J. C., Nguyen, T. T., Stone, H.W., Cooper, B. K., and Wilcox, B. H., "Experiences with operations and autonomy of the mars pathfinder micro-rover", *IEEE, Aerospace Conference*, No. 2, pp. 337-351, 1998.
- Campbell, D., and Buehler, M., "Stair descent in the simple hexapod RHex", In *Proceedings of IEEE Robotics and Automation*, Volume 1, pp.1380-1385, 2003.
- Newman, B.G., "Soaring and gliding flight of the black vulture", *Journal of Experimental Biology*, Volume 35, No. 2, pp. 280-285, 1958.
- Heppner, F. H., and Anderson, J. G., "Leg thrust important in flight take-off in the pigeon", *Journal of Experimental Biology*, Volume 114, No. 1, pp. 285-288, 1985.
- Tucker, V.A., and Parrot, G. C., "Aerodynamics of gliding flight in a falcon and other birds", *Journal of Experimental Biology*, Volume 52, No. 2, pp. 345-367, 1970.
- Earls, K. D., "Kinematics and mechanics of ground take-off in the starling *Sturnis vulgaris* and the quail *Coturnix coturnix*", *Journal of Experimental Biology*, Volume 203, No. 4, pp. 725-739, 2000.
- Nudds, R. L., and Bryant, D. M., "The energetic cost of short flights in birds", *Journal of Experimental Biology*, Volume 203, No. 10, pp. 1561-1572, 2000.
- Lindhe-Norberg, U. M., Brooke, A.P., and Trewhella, W. J., "Soaring and non-soaring bats of the family Pteropodidae (flying foxes, *Pteropus* spp.): wing morphology and flight performance", *Journal of Experimental Biology*, Volume 203, No. 3, pp. 651-664, 2000.
- McCay, M.G. "Aerodynamic stability and maneuverability of the gliding frog *Polypedates dennysi*", *Journal of Experimental Biology*, Volume 204, No. 16, pp. 2817-2826. 2001.
- Maciá, S., Robinson, M. P., Craze, P., Dalton, R., and Thomas, J. D., "New observations on airborne jet propulsion (flight) in squid, with a review of previous reports", *Journal of molluscan studies*, Volume 70, No. 3, pp. 297-299 2004.
- Socha, J. J., O'Dempsey T., and LaBarbera M., "A 3-D kinematic analysis of gliding in a flying snake, *Chrysopelea paradise*", *Journal of Experimental Biology*, Volume 208, No. 10, pp.1817-1833, 2005.
- Meng, Hu, J., Wang, Y. Y., Wang, X., and Li, C., "A Mesozoic gliding mammal from northeastern China", *Nature*, Volume 444, No. 7121, pp. 889-893, 2006.
- Paskins, K. E., Bowyer, A., Megill, W. M., and Scheibe J. S., "Take-off and landing forces and the evolution of controlled gliding in northern flying squirrels *Glaucomys sabrinus*", *Journal of Experimental Biology*, Volume 210, No. (8), pp. 1413-1423, 2007.
- Yanoviak, S. P., Munk, Y., Kaspari, M., and Dudley, R., "Aerial maneuverability in wingless gliding ants (*Cephalotes atratus*). *Proceedings of the Royal Society of London B: Biological Sciences*, 20100170, 2010.
- Santer, R.D., Simmons, P.J., and Rind, F.C., "Gliding behaviour elicited by lateral looming stimuli in flying locusts", *Journal of Comparative Physiology A*, Volume 191, No. 1, pp. 61-73, 2005.
- Kolter, J. Z., Rodgers, M.P., and Ng, A. Y., "A control architecture for quadruped locomotion over rough terrain", *IEEE International Conference on Robotics and Automation*, pp. 811-818, 2008.
- Kovac, M., Fuchs, M., Guignard, A., Zufferey, J. C., Floreano, D., "A miniature 7g jumping robot", *IEEE International Conference on Robotics and Automation*, pp. 373-378, 2008.
- De Croon, G.C.H.E., De Clercq, K.M.E., Ruijsink, R., Remes, B., and de Wagter, C., "Design, aerodynamics, and vision-based control of the DelFly", *International Journal of Micro Air Vehicles*, Volume 1, No. 2, pp. 71-97, 2009.
- Baek, S. S., Bermudez, F. L.G., and Fearing R. S., "Flight control for target seeking by 13-gram ornithopter", *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2674-2681, 2011.

22. Armour, R., Paskins, K., Bowyer, A., Vincent, J., and Megill, W., "Jumping robots: a biomimetic solution to locomotion across rough terrain", *Bioinspiration & biomimetics*, Volume 3, No. 3, pp. 039801, 2008.
23. Kovac, M., Zufferey, J. C., and Floreano, D., "Towards a self-deploying and gliding robot", *Flying insects and robots: Springer Berlin Heidelberg*, pp. 271-284, 2009.
24. Kovac, M., Fauria, O., Zufferey, J. C., and Floreano, D., "The EPFL jumpglider: A hybrid jumping and gliding robot with rigid or folding wings", *IEEE international conference on Robotics and Biomimetics*, pp. 1503-1508, 2011.
25. Scarfogliero, U., Li, F., Chen, D., Stefanini, C., Liu, W., and Dario, P., "Jumping mini-robot as a model of scale effects on legged locomotion", *IEEE International Conference on Robotics and Biomimetics*, pp. 853-858, 2007.
26. Woodward, M. A., Sitti, M., "Design of a miniature integrated multi-modal jumping and gliding robot", *International Conference on Intelligent Robots and Systems*, pp. 556-561, 2011.
27. Peterson, K., and Fearing R. S., "Experimental dynamics of wing assisted running for a bipedal ornithopter", *International Conference on Intelligent Robots and Systems*, pp.5080-5086, 2011.
28. Bundle, M.W., and Dial, K. P., "Mechanics of wing-assisted incline running (WAIR)", *Journal of Experimental Biology*, Volume 206, No. 24, pp. 4553-4564, 2003.
29. Boria, F. J., Bachmann, R. J., Ifju, P.G., Quinn, R. D., Vaidyanathan, R., Perry, C., Wagener, J., "A sensor platform capable of aerial and terrestrial locomotion", *International Conference on Intelligent Robots and Systems*, pp. 3959-3964. 2005.
30. Lambrecht, B. G., Horschler, A. D., Quinn, R. D., "A small, insect-inspired robot that runs and jumps", *IEEE International Conference on Robotics and Automation*, pp. 1240-1245, 2005.
31. Morrey, J. M., Lambrecht, B., Horschler, A. D., Ritzmann, R. E., Quinn, R. D., "Highly mobile and robust small quadruped robots", *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 82-87, 2003.
32. Daler, L., Mintchev S., Stefanini, C., Floreano, D., "A bioinspired multi-modal flying and walking robot", *Bioinspiration & biomimetics*, Volume 10, No. 1, 016005, 2015
33. Kossett, A., Purvey, J., and Papanikolopoulos, N., "More than meets the eye: A hybrid-locomotion robot with rotary flight and wheel modes", *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 5653-5658, 2009.
34. Stoeter, S. A., Rybski, P. E., Gini, M., Papanikolopoulos, N., "Autonomous stair-hopping with scout robots", *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 721-726, 2002.
35. Tsukagoshi, H., Sasaki, M., Kitagawa, A., and Tanaka, T., "Design of a higher jumping rescue robot with the optimized pneumatic drive", *IEEE International Conference on Robotics and Automation*, pp.1276-1283, 2005.
36. Weiss, P., "Hop... hop... hopbots!: designers of small, mobile robots take cues from grasshoppers and frogs", *Science News*, Volume 159, No. 6, pp. 88-91, 2001.
37. Sugiyama, Y., Shiotsu, A., Yamanaka, M., and Hirai, S., "Circular/spherical robots for crawling and jumping", *IEEE International Conference on Robotics and Automation*, pp. 3595-3600, 2005.
38. Zhao, J., Xi, N., Gao, B., Mutka, M. W., and Xiao, L., "Development of a controllable and continuous jumping robot." *IEEE International Conference on Robotics and Automation (ICRA)*, pp. 4614-4619, 2011.
39. Zhang, Y., Zhang, L., Wang, W., Li, Y. and Zhang, Q., "Design and Implementation of a Two-Wheel and Hopping Robot With a Linkage Mechanism," *IEEE Access*, vol. 6, pp.42422-42430, 2018.
40. Saar, K.A., Giardina, F. and Iida, F., "Model-free design optimization of a hopping robot and its comparison with a human designer," *IEEE Robotics and Automation Letters*, vol. 3, no. 2, pp.1245-1251, 2018.
41. Murali, V., Nak-seung, P.H. and Verriest, E.I., "Graceful Gait Transitions for Hopping Robots on Deformable Terrain," *IEEE Annual American Control Conference (ACC)*, pp. 1299-1304, June 2018.
42. Ye, C., Wang, B., Wei, B. and Tang, B., "Modeling and Analysis of a Jumping Robot with Deforming Wheeled Mechanism," *IEEE International Conference on Mechatronics and Automation (ICMA)*, pp. 980-985, 2018.
43. Ishiyama, Y., Yamamoto, Y., Takanishi, A. and Lim, H.O., "October. Jumping Motion Control of One-legged Jumping Robot with Pneumatic Muscles," *18th IEEE International Conference on Control, Automation and Systems (ICCAS)*, pp. 225-230, 2018.
44. Hanan, U.B., Weiss, A. and Zaitsev, V., "Jumping efficiency of small creatures and its applicability in robotics," *Procedia Manufacturing*, vol. 21, pp.243-250, 2018.
45. Li, H. and Savkin, A.V., "Wireless sensor network based navigation of micro flying robots in the industrial internet of things," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 8, pp. 3524-3533, 2018.
46. Aminzadeh, A. and Atashgah, M.A., "Implementation and performance evaluation of optical flow navigation system under specific conditions for a flying robot," *IEEE Aerospace and Electronic Systems Magazine*, vol. 33, no. 11, pp.20-28, 2018.
47. [47] Somov, Y., Butyrin, S., Somova, T. and Somov, S., "Control of a Free-flying Robot at Preparation for Capturing a Passive Space Vehicle," *IFAC-PapersOnLine*, vol. 51, no. 30, pp.72-76, 2018.
48. Pesavento, U., and Wang, Z. J., "Flapping wing flight can save aerodynamic power compared to steady flight", *Physical review letters*, Volume 103, No. 11, 118102, 2009.
49. Michael, N., Mellinger, D., Lindsey, Q., Kumar, V., "The grasp multiple micro-UAV testbeds", *IEEE Robotics & Automation Magazine*, Volume 17, No. 3, pp. 56-65, 2010.

50. Tanaka, H., Hoshino, K., Matsumoto, K., and Shimoyama, I., "Flight dynamics of a butterfly-type ornithopter." International Conference on Intelligent Robots and Systems, pp. 2706-2711, 2005.
51. Bermudez, F. G., and Fearing, R., "Optical flow on a flapping wing robot." IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 5027-5032, 2009.
52. Grauer, J., and Hubbard, J., "Modeling of ornithopter flight dynamics for state estimation and control", American Control Conference, pp. 524-529, 2010.
53. Pornsin-Sirirak, T. N., Lee, S. W., Nassef, H., Grasmeyer, J., Tai, Y. C., Ho, C. M., Keennon, M., "MEMS wing technology for a battery-powered ornithopter." The 13th Annual International Conference on Micro Electro Mechanical Systems, pp. 799-804, 2000.
54. Van Breugel, F., Teoh, Z. E., and Lipson, H., "A passively stable hovering flapping micro-air vehicle." In Flying insects and robots, Springer Berlin Heidelberg, pp. 171-184, 2009.
55. Richter, C., and Lipson, H., "Untethered hovering flapping flight of a 3D-printed mechanical insect", Artificial life, Volume 17, No. 2, pp. 73-86, 2011.