Mechanism and Machine Theory 44 (2009) 513–526

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

A biologically inspired micro-vehicle capable of aerial and terrestrial locomotion ☆

Richard J. Bachmann [a], Frank J. Boria [b], Ravi Vaidyanathan [c,d,*], Peter G. Ifju [b], Roger D. Quinn [e]

[a] BioRobots, LLC Cleveland, 3030 E. 63rd St., Suite 313, Cleveland, OH 44127, USA
[b] University of Florida, Mechanical and Aerospace Engineering, 231 MAE-A, Gainesville, FL 32611-6250, USA
[c] University of Bristol, Mechanical Engineering, Queens Building, University Walk, Bristol BS8 1TH, United Kingdom
[d] Naval Postgraduate School, Systems Engineering, Monterey, CA 93943, USA
[e] Case Western Reserve University, Mechanical and Aerospace Engineering, 10900 Euclid Ave., Cleveland, OH 44106-7222, USA

ARTICLE INFO

Article history:
Received 4 November 2007
Received in revised form 27 August 2008
Accepted 28 August 2008
Available online 8 October 2008

Keywords:
Micro air vehicles
Crawling robots
Multi-modal mobility
Micro robots
Biologically inspired robotics

ABSTRACT

This paper reports the design, fabrication, and field testing of a small (30.5 cm wingspan) robot capable of aerial and terrestrial locomotion. The micro air-land vehicle (MALV) flies using a chord-wise, undercambered, bat-like compliant wing and walks over rough terrain using passively compliant wheel-leg running gear. MALV successfully performs transitions from flight to walking and in some situations, from walking to flight. The lightweight (~100 g) carbon fiber vehicle can fly, land, and crawl with a sensor payload exceeding 20% its own mass.

1. Introduction

Advances in fabrication, sensors, electronics, and power storage have made possible the development of a wide range of small robotic vehicles capable of either aerial or terrestrial locomotion. Furthermore, insights into animal locomotion principles and mechanisms have significantly improved the mobility and stability of these vehicles. For example, the utility and importance of passively compliant wings for fixed wing micro air vehicles (MAVs) has been demonstrated for aircraft with wingspans as small as 10 cm [1]. Likewise, highly mobile ground vehicles using compliant legs have been constructed as short as 9 cm that can run rapidly over obstacles in excess of their own height [2].

This paper describes the design, fabrication, and testing of a novel small vehicle (dubbed the micro air-land vehicle (MALV)) that is capable of *both* aerial and terrestrial locomotion. Robot morphology is inspired by neuromechanics in animal locomotion, integrating passive compliance in both its wings, joints, and legs, such that it may fly, land, walk on the ground, climb over obstacles, and (in some circumstances) take to the air again all while transmitting sensor (video) feedback. Experimental testing of the vehicle has been conducted in actual field conditions for the operations of surveillance, explosive detection,

---

☆ This work was supported in part by the US Department of Defense under Contracts FA8651-04-C-0234 and FA8651-05-C-0097 and the US Special Operations Command-Naval Postgraduate School (USSOCOM-NPS) Field Experimentation Cooperative Program.

* Corresponding author. Address: University of Bristol, Mechanical Engineering, Room 2.50, Queens Building, University Walk, Bristol BS8 1TH, United Kingdom. Tel.: +44 7970 330 814.

E-mail addresses: r.j.bachmann@bio-robots.com (R.J. Bachmann), frankboria@gmail.com (F.J. Boria), rxv@case.edu (R. Vaidyanathan), ifju@ufl.edu (P.G. Ifju), rdq@case.edu (R.D. Quinn).

0094-114X/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mechmachtheory.2008.08.008

search/rescue, and remote inspection. In the longer term, the design architecture and locomotion mechanisms are expected to lead to a family of vehicles of varying size, sensor payload, and range that may be configured for a wide range of applications.

1.1. Overview and design approach

In a biological organism, execution of a desired motion (e.g. locomotion) arises from the interaction of active (higher-level) control centers with passive (lower-level) properties of the sensorimotor system, including the intrinsic mechanical response of the body. Animal "neuromechanical" systems successfully reject a range of disturbances that could otherwise induce instability or deformation of planned trajectories [3]. The first response to minimize such effects, in particular for higher frequency disturbances such as maintaining posture over varying terrestrial substrates and unexpected gusts in flight, is provided by the mechanical properties of the organism. In legged locomotion, for example, compliance (i.e. springs and dampers) plays a fundamental role in joints and structures that stabilize the body in an intrinsic fashion and thus greatly simplify higher-level control [4,5]. Reproduction of the dynamic properties of muscle and the intrinsic response of the entire mechanical system [6] has been a serious impediment to the successful realization of animal-like robot mobility over a variety of substrates and through different mediums. It is these intrinsic properties of the musculoskeletal system which augment neural stabilization of the body of an organism.

Although biological inspiration offers a wealth of promise for robot mobility, many constituent technologies are not at a state of maturity where they may be effectively implemented for small autonomous robots. Existing power, actuation, materials, and other robotic technologies have not developed to the point where animal-like neuromechanics may be directly integrated into robotic systems. Given this challenge, the majority of biologically inspired legged and flying robots have been confined to laboratory or limited field demonstrations. A method to surmount this, known as abstracted biological inspiration [7], focuses principally on the delivery of critical performance characteristics to the engineering system. Abstracted biological inspiration attempts to abstract salient biological principles and implement them using available technologies. This approach founded the basis of the design methodology aimed at delivering capabilities of flight locomotion, crawling locomotion, and transitions between the two to MALV.

1.1.1. Organization of paper

The remainder of this section describes past work in flying and crawling micro robots, respectively, in addition to some of the small body of research in robots with multimodal mobility. Section 2 delineates the biologically inspired structures for flight and walking used on MALV. Section 3 details design process and vehicle fabrication, while Section 4 presents performance characteristics of the robot. Section 5 enumerates the conclusions of the research and envisioned future work.

1.2. Micro ground vehicles

Among the breadth of factors presently inhibiting the real-world deployment of terrestrial micro robots, we have repeatedly encountered two in our own research. First, the relative size of real-world obstacles (e.g. stairs, gravel, terrain fluctuations, etc.) makes movement difficult for small robots. For example, the RHex platform (∼50 cm length), is the shortest robot to our knowledge that can climb standard stairs [8]. Second, power source miniaturization has not kept pace with other critical equipment such as actuation, sensing, and computation.

A wide array of vehicles has been constructed that attest to the difficulty of designing field-deployable terrestrial mobile micro robots, in particular with respect to the issues of obstacle clearance and power source miniaturization. For example, Khepera robots have a 5 cm wheelbase, onboard power, and an array of sensors [9]. Although they are widely used by group behavior researchers, their 1.4 cm diameter wheels restrict them to operation on very smooth, flat surfaces. Millibots [10] use tracks, but it is not clear that they offer significant advantages since it is difficult to implement a modern track suspension at this small scale. A small hexapod has been developed by Fukui et al. [11] which runs in a tripod gait using piezoelectric actuators. However, small joint excursions also limit the vehicle to relatively flat surfaces. Birch et al. [12] developed a 7.5 cm long hexapod inspired by the cricket and actuated by McKibben artificial muscles. Though capable of waking using 2 bars of air pressure it has not yet carried its own power supply. Sprawlita [13] is a 16 cm long hexapod which uses a combination of servomotors and air cylinders. Sprawlita attains a top speed of 4.5 body lengths per second, which is fast compared to existing robots of similar size. However, an operating air pressure of 6 bars makes it unlikely that the robot will become autonomous in its current form.

Abstracted biological inspiration has spawned a group of highly mobile robots, called Whegs™ [14] and Mini-Whegs™ [15]. Using a single drive motor, the 9 cm long Mini-Whegs™ robot has run at 10 body lengths per second, and can easily run over 3.5 cm tall obstacles – higher than its body. The more recently developed iSprawl [16] also uses single motor propulsion and benefits from abstracted biological principles. It has run even faster, 15 body lengths per second, although its obstacle climbing ability is more restricted because of the relatively small range of motion of its feet.

1.3. Micro air vehicles (MAVs)

The majority of research to develop practical non-rotatary-winged MAVs can be broadly categorized into three fundamental approaches. The first and most widely used is to configure the airframe as a lifting body or flying wing using propel-