

BIOLOGY-INSPIRED INTELLIGENCE IN THE DESIGN, CONTROL, AND POWER SYSTEMS OF INSECT-SIZED FLYING ROBOTS

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ABSTRACT

A technology grand challenge for micro-systems that weigh far below a gram is giving them mobility and autonomy. We posit that creating intelligent, self-contained system so will require a confluence of biological inspiration, a formalized co-design process for all of their elements ranging from controllers to power sources to sensors, and a fabrication process that allows for rapid design iteration.

KEYWORDS

Microrobotics, flying insect robotics, biology-inspired robotics, autonomous systems

This paper is about a technology grand challenge for micro-sized systems that are well below a gram: making them mobile and autonomous. Yet the potential is enormous. Unlike their larger autonomous robotic brethren, micro-robots can operate in more confined spaces, in close proximity to humans without safety hazard, and potentially operate persistently using sources of energy readily available in the environment, such as light, heat, or radiofrequency sources, that are too minute for larger robots. Despite these advantages and countless emerging applications in agriculture, industrial inspection, and even low-launch cost space missions, such systems have not yet been realized. Sub-gram robots have not shown any significant degree of autonomy, that is, ability to sense and respond intelligently to the environment [1].

Lack of autonomy in small devices can largely be attributed to two key causes. The first is simply the challenge to miniaturize the mass and power consumption of the sensor suite. And the second is the need to re-consider many of the technologies that have been successful in larger robotic systems in light of the changed physics associated with small scale. As scale reduces, the dominant effect of many important physical processes changes, leading to so-called “phase transitions” in which a substantially different technological approach suddenly becomes viable as the size scale of the system reduces.

The solutions entail three key technical competencies.

The first is the ability to look closely at and analyze the solutions used by biology. Biology is, as a rule, not beholden to preconceptions of how the world ought to work; instead, it is able, through evolution, to perform a more exhaustive exploration of the solution space than a human might consider. That said, it is important to also observe biology with a keen eye, because many of its characteristics are driven by considerations that are distinct from those of the micro-roboticist. Almost all materials used in biology must be solution-processed in water, restricting the materials set. To date, at least, it is hard to imagine a need for sexual reproduction in robots. And communication by nerve cells is much slower than electrical conductors. Biology could never have realized a jet engine, a microprocessor, or even a wheel, for that matter. Nevertheless, it still far exceeds man-made systems in many important areas, most notably in self-assembly, evolution and learning, and dynamic and robust motor control. It is these latter elements that serve as the most important inspiration for current roboticists.

The second is an ability, to a larger extent than has been necessary on larger robots, for a process to co-design the robotic

system to balance conflicting needs in all of its facets, from mechanical design, to choice of sensors, to control system, to energy storage and collection. These considerations of course are primarily driven by the task the robot is to pursue. Only by doing so can we hope to achieve the mechanical and sensor efficiency that will be needed for tiny autonomous systems to operate for a significant fraction of the time.

And the third is a manufacturing process to create the mechanical and electrical systems of the microrobot. It must be relatively fast, to allow for what inevitably turns out to be many physical iterations of mechanical and electrical systems. And the ability to incorporate a range of materials including high-performance composites, can be an advantage.

A discussion of some recent advances in the area of flying microrobots follows, including some by the Autonomous Insect Robotics Laboratory at the University of Washington that I direct.

The first comes in the area of manufacturing: early architects of robotic insects recognized that scaling physics did not favor electromagnetic motors. This led to a focus on creating a flexure-based manufacturing method known as Smart Composite Microstructures (SCM) [2] and the use of muscle-like reciprocating actuators powered by electrostatic forces that scale down more favorably in terms of efficiency and power density than magnetic coils [3]. In biology, a phase transition can be observed in the flight apparatus of small flying animals: the very smallest, including flies, bees, and hummingbirds, flap continuously rather than gliding. This can be attributed to the increasing relative effect of viscosity as scale reduces, which eventually results in a very low glide ratio and therefore inefficient gliding flight [4]. The confluence of flexure-based manufacturing, electrostatic actuation, and flapping-wing flight led to the first lift > weight on a sub-gram flying device [5] and subsequent controlled flight [6].

The sensor systems of micro-robotic aircraft are also beholden to scaling physics. One aspect we observe in small flying animals such as the fruit fly is a reliance on a multiplicity of sensors, each of which is by itself limited, but when used in conjunction can provide for high performance. In forward flight, fruit flies have a very low-latency sense of their airspeed, but it is corrupted by the ubiquitous presence of air currents, which confound any ability to measure ground speed. They additionally carry large compound eyes that, by observing how the visual scenery moves by, that is, using “optic flow,” can provide a more or less absolute estimate of ground speed, but with significant added “noise” uncertainty. Flies’ solution is simply to add together the effects of these two feedback terms; the result is a flight control system that is both high bandwidth and able to compensate for wind disturbances [7]. We have recently begun to realize a flight control architecture inspired this finding that is able to operate on the conceptual mass and power budget for a controller even as the robot scales down to on the order of 10 mg [8].

The last element is how to weigh different considerations in the co-design of complete systems. Recent theoretical work has begun to realize a framework that can place these considerations together into a finite set of “realizations” of different controller, actuator, and sensor types so that pareto fronts of equal competence can be identified [9]. These can be used to, for

example, identify optimal choices from a commercial perspective.

The unifying theme is a notion of biology-inspired “intelligence” in the design of all of the interconnected elements of the microrobotic system. It is remarkable how biology, through evolution, is able to simultaneously and in concert adapt the entire system, from its mechanics, sensing, and control in a way that improves its functional fitness. We as microroboticists can only hope to some day begin to do the same.

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