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The Case for Insect-Scale RoboArch

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This poster will introduce architects to the emerging field of insect-scale robotics, highlight some of the unique challenges when working at this scale, and present a call to action for developing the infrastructure required to explore this space.

1. Insect-Scale Robotics

In the last decade, there has been growing interest in miniaturizing robots, down to the insect scale. Insect-scale robots hold the potential to revolutionize applications such as reconnaissance, search-and-rescue, and environmental monitoring. An important characteristic of miniaturization of any device is the effect of physical scaling laws. Our everyday experiences inform our *macro-intuition* of the world, but this intuition begins to break down at the centimeter-scale. When designing insect-scale robots, roboticists must instead rely on *micro-intuition* [8]. Consequently, there has been an increasing number of demonstrations of different insect-scale robots that vary in their shape, size, manufacturing, and actuation strategy, as shown in Figure 1 [**?**, 1, 4, 6, 7, 9, 12–14, 22, 27]. Each insect-scale robot platform has its own unique set of actuation, sensing, and control challenges.

An example of the role of physical scaling in the physical design of the robot is seen with insect-scale aerial robots. At larger-scales, fixed-wing aerial robots can achieve lift-to-drag ratios exceeding 100. Scaling down in size sees an increased influence of viscous effects which leads to lower lift-to-drag ratios. At the insect scale, fixed-wing aerodynamics becomes impractical due to energy losses from drag at speeds required to maintain sufficient lift for flying. Similarly, rotary aerial vehicles experience challenges when scaling down in size [11, 26]. Electromagnetic motors see degraded performance at reduced sizes and begin to require substantial gearing to achieve a desired propeller velocity, which is difficult to manufacture [11,26]. Instead, insect-scale aerial robots see the use of custom made piezoelectric [13, 24, 25], electrohydrodynamic [6], and dielectric elastomer actuators [12]. The use of custom actuators requires that new controllers, as well as custom power electronics and actuator driving circuits.

Scaling also affects the rates at which robot control loops must run. For example, when scaling down one of the smallest and fastest insect-scale crawling robots, HAMR-VI (picture 4 shown in 1), from a body length of 45.1 mm and body mass of 1.41 g to a body length of 22.5 mm and body mass of 0.32 g, the stride frequency for maximal locomotion performance jumps from 65 Hz to 200 Hz. Consequently, the control loop needs to be approximately 3$\times$ faster [10]. The required increase of the control loop update rate is fairly common across insect-scale robots, due to their "faster dynamics" at smaller scales. Flapping-wing aerial insect-scale robots, such as the Harvard RoboBee [13], need control loop update rates up to 250 Hz [5, 11, 17, 21].

Lastly, there is the size-grain hypothesis [15], which states that as terrestrial organisms are scaled down in size, planar environments become relatively more rough. This necessitates nuanced mechanical design for terrestrial-insect scale robots such that they can clear "featured" surfaces, either via clever actuator and limb designs [22], or via jumping []. Either approach also requires nuanced design in sensing, control, and planning algorithms that are aware of the context of the size-grain hypothesis.

The effects of these physical scaling laws can be seen in the various different insect-scale robots shown in Figure 1. Going in numbered order: 1. the Harvard RoboBee uses piezoelectric actuators powered by a photovoltaic array to fly, 2. the University of Washington RobyFly uses piezoelectric actuators and is powered via pointing an external laser at it, 3. a flapping wing robot that uses dielectric elastomer actuators and may be composed into larger multi-robot systems, 4. HAMR-VI and HAMR-Jr, crawling robots that use piezoelectric actuators, 5. a crawling robot that uses magnetic actuation and can switch between different gait configurations, 6. a crawling robot that uses a catalytic artificial muscle actuator, 7. four variations of JUMPA robots that use coiled artificial muscle actuators, 8. a terrestrial robot capable of hopping and jumping using combustion-driven actuators, 9. an aerial ionocraft robot that uses electro-hydrodynamic actuators, 10. Gamma bot, which utilizes surface tension and piezoelectric actuators to skim across water surfaces, 11. a variation of the Harvard RoboBee capable of being submersed in water, breaking the water air barrier, and flying, and 12. an origami robot that uses electromagnetic actuators to change its shape and to control its fall after being dropped by a drone.

In addition to the challenge of physical scaling due to miniaturization, there is also the challenge of stringent size, weight, and power (SWaP) constraints that become more and more pronounced as systems scale down. The size and maximum weight of the robot make end-to-end system integration difficult. Microcontrollers, sensor suites, and power supplies must all be carefully chosen or built such that they meet the payload capacity of the robot. The limitation of state-of-the-art batteries is apparent when comparing specific energy output of the best centimeter-scale Li-ion batteries, 1.8 MJ/kg, to that of metabolized fat by insects, 38 MJ/kg [27]. Because of this, most insect-scale robots are demonstrated when tethered to a power source. The Harvard RoboBee famously demonstrated untethered flight in [13], but required a modified design that includes a photovoltaic array receiving energy from a light source of about 3 Suns.

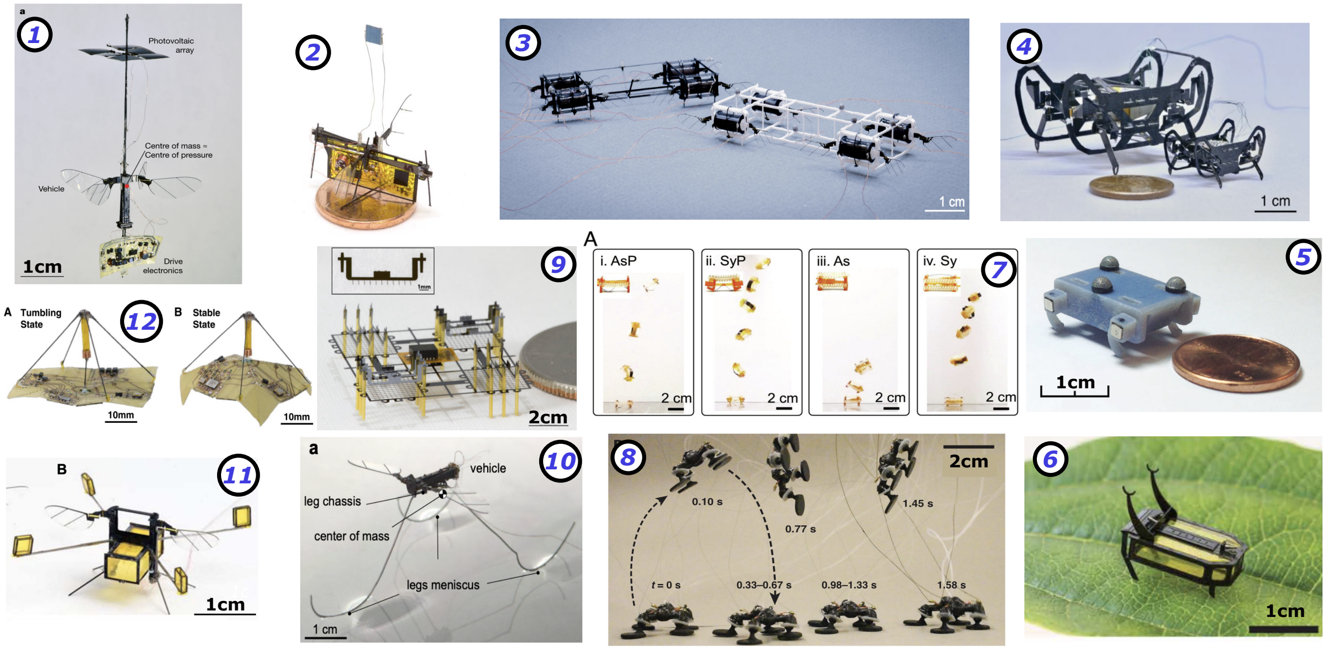

Figure 1: The Diversity of Insect-Scale Robots – Challenges and constraints imposed by physical scaling laws have resulted in a diverse collection of robots that vary in shape, size, and locomotion strategy.

2. Insect-Scale RoboArch

Recently, roboticists have shifted toward end-to-end system integration for insect-scale robots, equipping them with custom actuators, sensor suites, power supplies, and commercially available ARM Cortex-M microcontrollers. The unique challenges and constraints faced by insect-scale robots makes them an ideal area for exploration within RoboArch. To date, untethered functionality of these robots has been limited. Specialized hardware may improve the energy and latency in perception, control, and planning algorithms, helping these robots meet real-time constraints and extend operational time. Custom hardware might also enable more complex algorithms, unlocking new capabilities and applications. To support hardware-software co-design, baseline evaluations of insect-scale robotics algorithms and benchmark suites on target hardware are essential.

Because roboticists are moving towards end-to-end system integration and demonstration of insect-scale robots, there is a need to evaluate latency and energy consumption of workloads on potential hardware. In lieu of measuring on real hardware, they employ FLOP counting [24, 25] to estimate latency and subsequently power consumption. Recent work [20] has shown that this flop counting method applied to an optimized SVD kernel for 8×3 and 256×3 matrices, undercounts the true latency and energy consumption, having a relative error up to 80% of relative cycle error, and up to 85% relative energy error. Computation on the 256×3 matrices saw a $13\times$ increase in measured cycles, compared to an $25\times$ increase in estimated cycles. On the other hand, computer architects utilize microarchitectural simulators [16, 23] to model their computer system and evaluate performance. From initial testing using a lightly modified configuration of the in-order minor cpu model in gem5, we have found that the absolute cycle counts for the same kernel in [20] overestimate, with a relative error of 49,723% and 9,053% respectively, and the latency increase when performing SVD on a 256×3 matrix compared to an 8×3 matrix, is a factor of $24\times$.

Researchers have started building benchmark suites and evaluation frameworks for hardware/software co-design for robotic, but the published work has limitations for insect-scale systems. Existing benchmark suites [2, 3, 18] , often choose algorithms and implementations requiring more compute resources insect-scale systems offer. And while device I/O has limited impact on the performance of larger processors, accessing memory-mapped peripherals and sensors on a microcontroller appropriate for insect-scale robots can consume a noticeable percentage of memory bus bandwidth, an interaction typically overlooked. Additionally, they often assume the presence of an operating system and robotic software framework such as ROS. The RoSe evaluation framework [19] makes an important contribution of closing the loop on simulation by integrating robot environment simulation with custom hardware simulation. However, it lacks support for simulating Cortex-M microcontrollers and also builds on software frameworks not typically found on robots of this size.

3. Call to Action

The field of insect-scale robotics holds significant promise for software/harware co-design. We look forward to participating in this workshop as a call-to-action and hopefully inspiring the RoboArch community to develop appropriate benchmark suites and hardware evaluation frameworks suitable for insect-scale robotics.

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