Battery-free Computer Vision on Insect-scale Microrobots







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Why use Battery-free and Mobile Microrobots?

Goal: Battery-free robots [1,2] with on-device computer vision can reduce e-waste [3] and have the potential to operate indefinitely. This could allow for more sustainable mobile, autonomous sensing devices for industrial, environmental & disaster recovery applications.

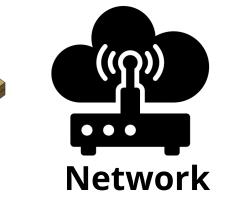










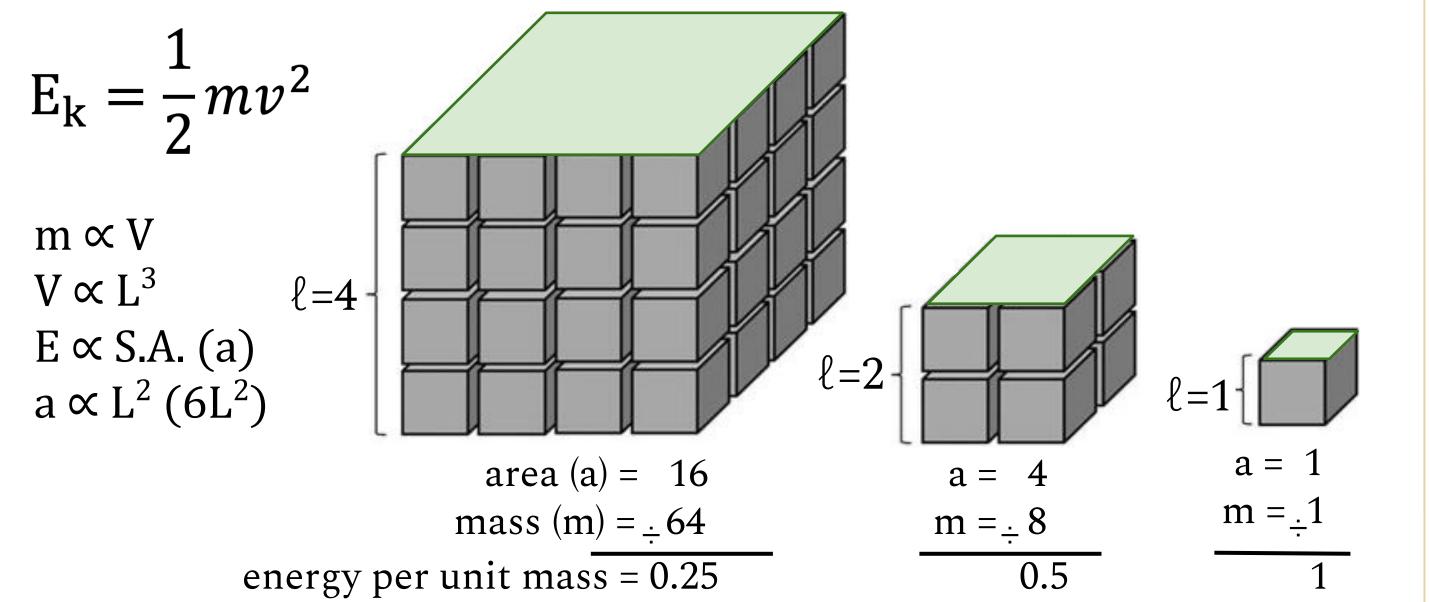






Benefits of Microrobot Swarms:

- Small robots can reach confined areas [4]
- In swarms small robots can offer a more scalable, versatile, and robust sensing network
- Small computing systems can leverage energy harvesting techniques to run indefinitely



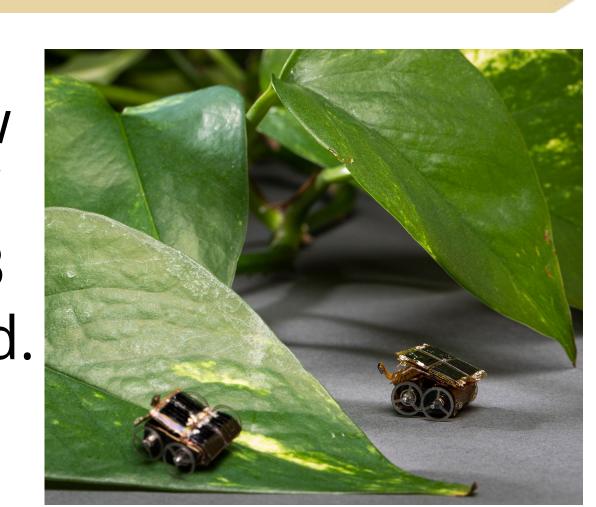
Millimeter- scale Robots	Battery Free Mobility	Power Autonomy (untethered)	Control Autonomy & Sensing	Communication Link, Range	Mass (g)	Min. Power While Moving (µW)
Kilobot	-	✓	✓	Infrared LED & Photodiode, (0.1 m)	36	12,000
HAMR-F	-	✓	✓	802.15.4, (5 m)	2.79	423,000
RoACH	-	✓	-	IRDA Infrared, (1 m)	2.4	440,000
Soft Millirobot Carried-on	√	_ *	-	NFC (0.09 m)	>0.05*	203*
Alice	-	✓	-	RF 433 MHz, (10 m)	5	4,000
Bipedal eBiobot	✓	_ *	-	NFC (0.09 m)	>5*	-
Laser-powered Microrobot	✓	✓	-	-	0.1	2,500
MilliMobile	1	/	/	BLE (200 m)	1.09	50

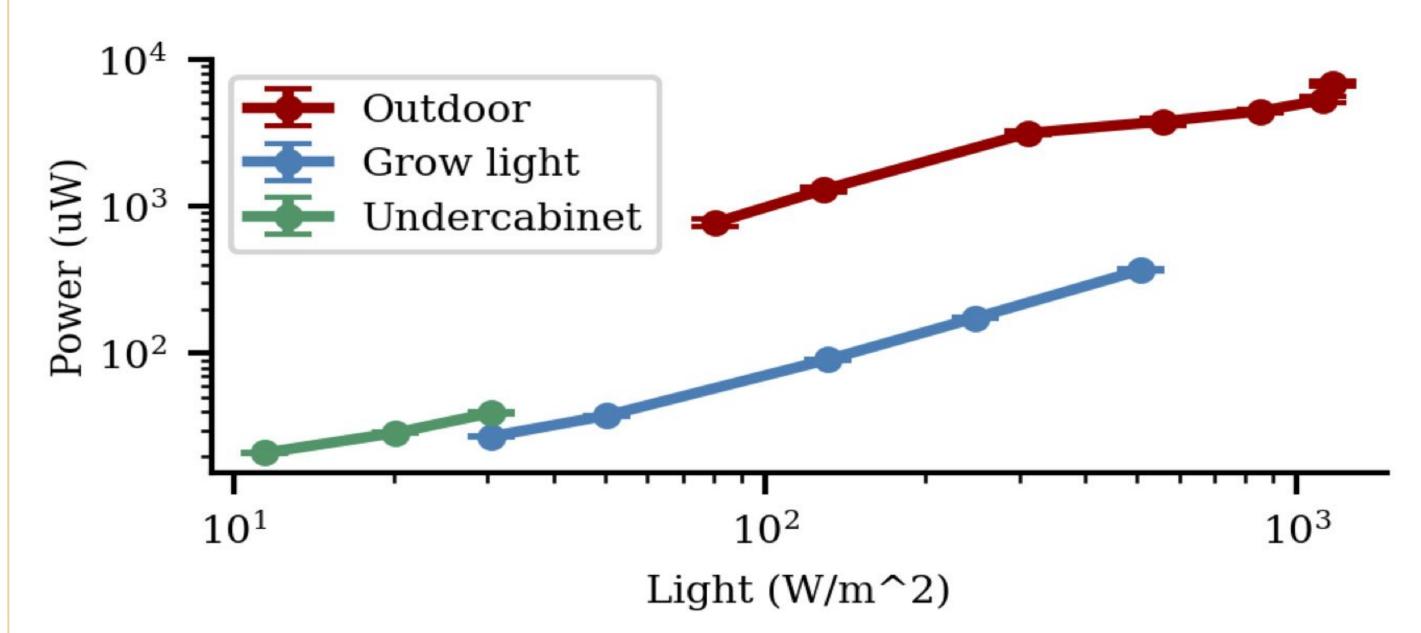
Challenges of Microrobot Swarms:

- Microrobot swarms have very limited power, payload, and compute constraints
- Previous work has explored under-actuated and low-mobility designs without intelligence
- Full Cartesian autonomy for object tracking at insect-scale remains unexplored

MilliMobile Platform

Intermittent computing and locomotion techniques allow MilliMobile to run on µWs of solar or RF power, with 1 MB Flash & 256 KB RAM onboard. The capacitor-driven max speed is 5.5 mm/s indoors.





Outdoors there's mWs of harvestable energy.

Proposed Model Architecture

- Utilizes TensorFlow Lite for Microcontrollers for lightweight neural networks
- MilliMobileNet model appeared equipped for efficient on-device image classification [5,6]

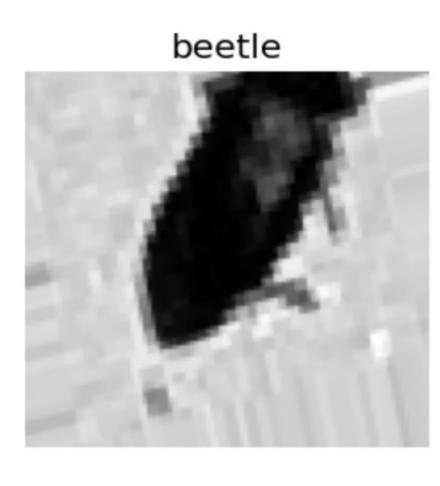
	ML Model	Parameter Range
	Fomo (Edge Impulse)	100K – 1M
]	TFLite Person Detection	250K – 1M
	SqueezeNet (Tiny variant)	500K – 1M
	MobileNetV2 (Quantized)	350K – 3.5M
-	ShuffleNetV2 (Quantized)	1.4M – 3.5M
	Tiny-YOLO	1M – 5M
-	EfficientNet-Lite0	4.7M
ResNet-18 (Tiny variant)		1.8M – 11.7M
-	MilliMobileNet	11.7K

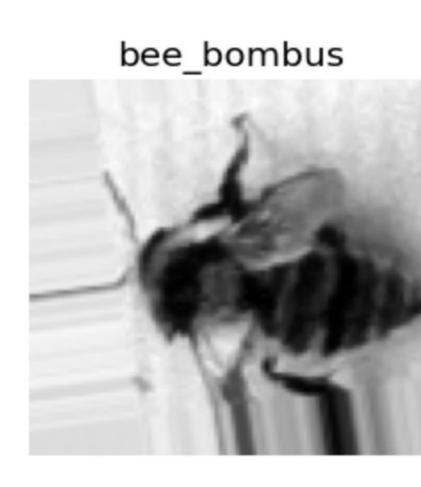
Camera Module	Resolution	Active Power	Standby Power	Additional Notes
HM01B0	320×240 (QVGA)	1.1 mW	8.4 μW	Ultra-low power; ideal for always-on applications.
OV7670	640×480 (VGA)	60 mW	< 34 µW	Popular for embedded systems; cost-effective.
OV7675	640×480 (VGA)	98 mW	60 μW	Enhanced sensitivity; suitable for low-light conditions.
OV2640	1600×1200 (UXGA)	125 mW	780 µW	Higher resolution; includes on-chip JPEG encoder.

Preliminary Model Results

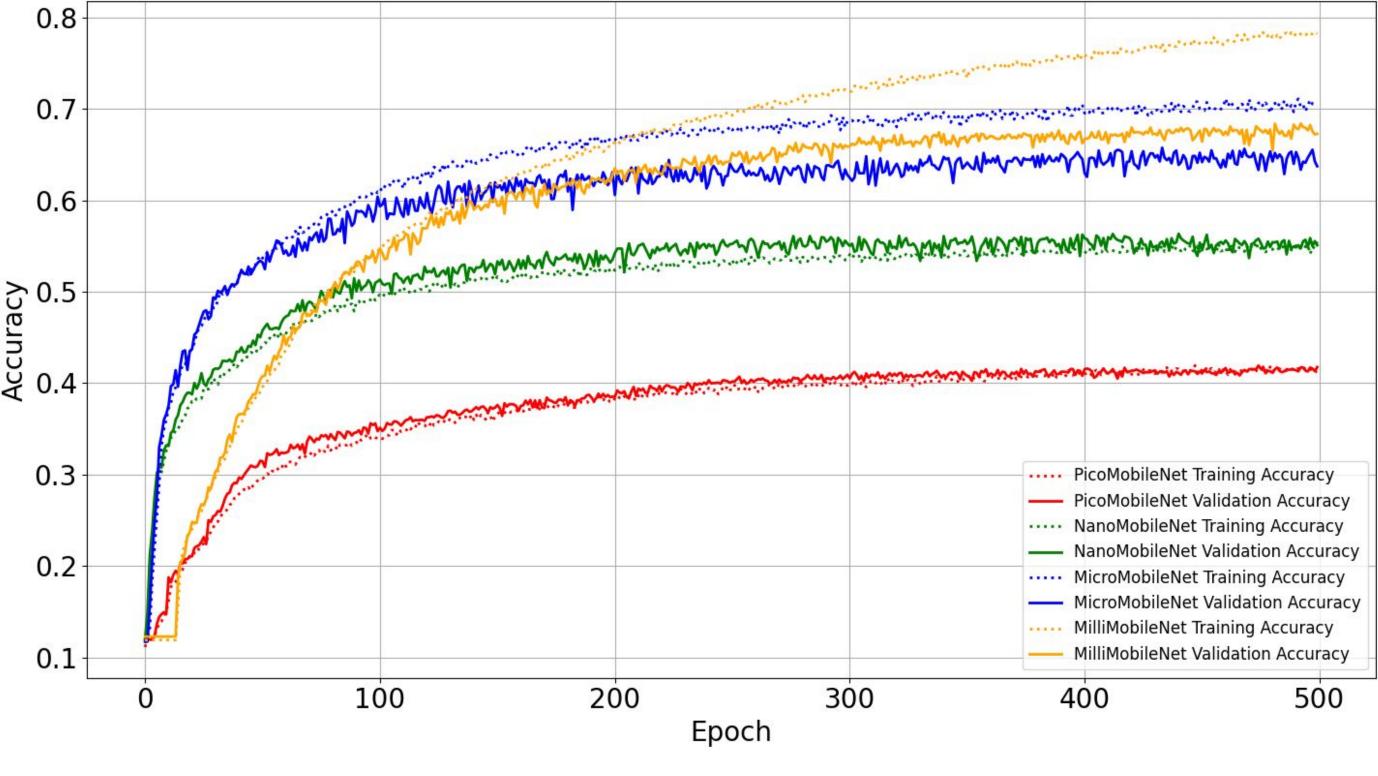
Dataset: Zenodo Insect Classification V2 [7] scaled to 96×96 px and grayed to meet the MilliMobile's memory constraint. Power constraints are scaled by the duty cycle of the MCU.



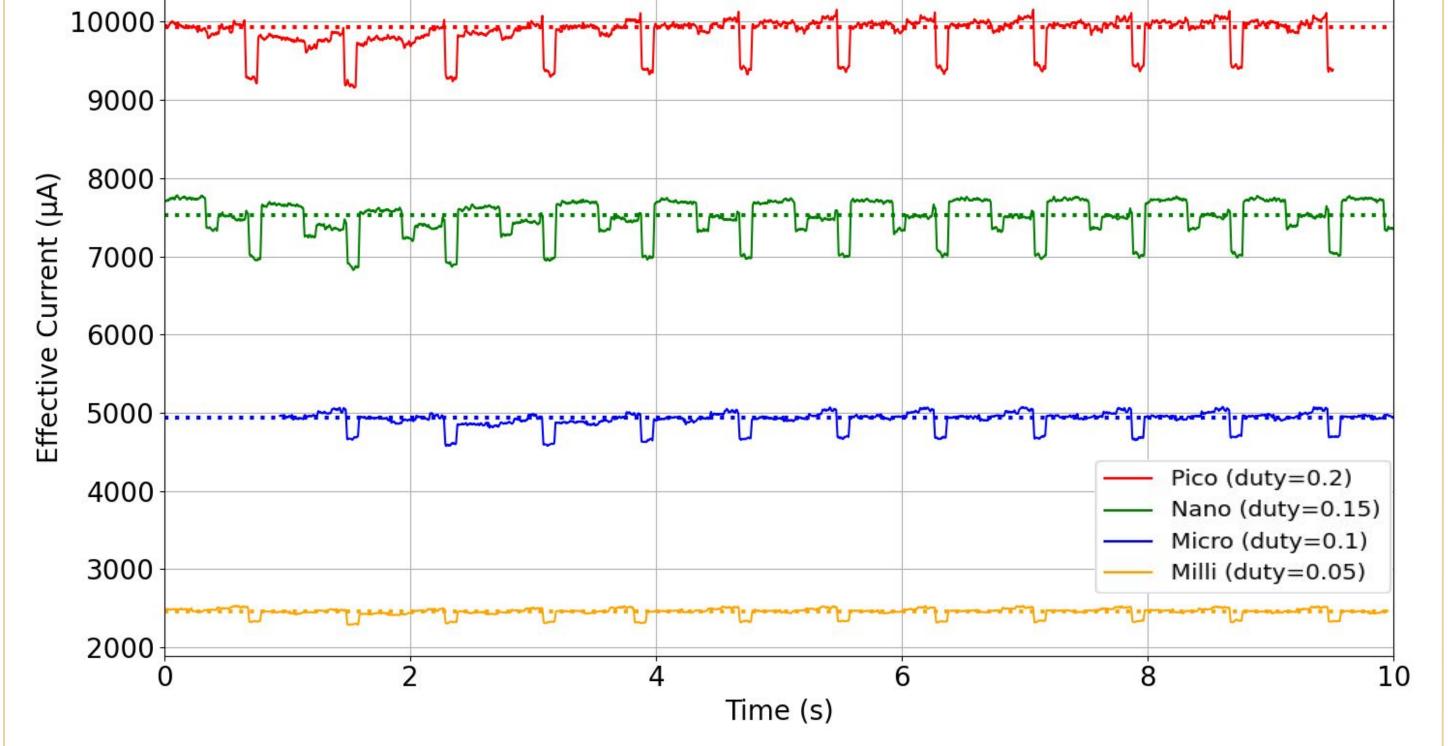




MilliMobileNet outperforms smaller models after parameter tuning and 500 epochs of training.

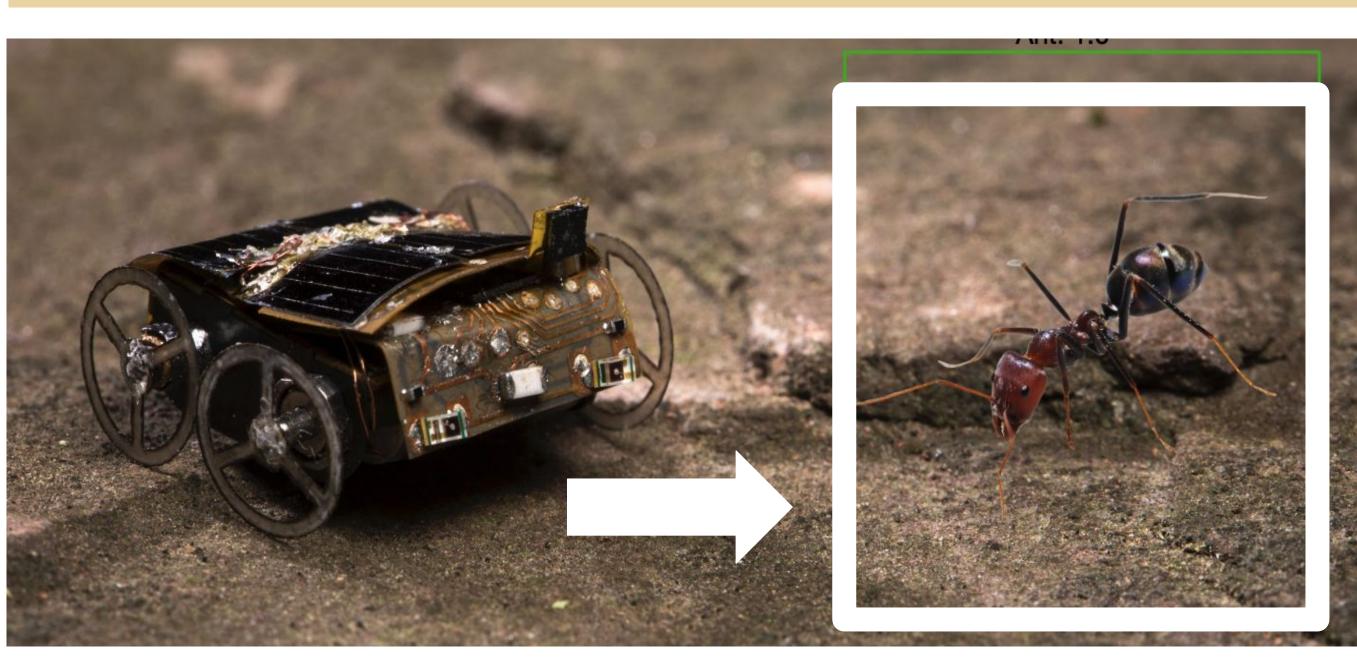


Power consumption was relatively constant, independent of the number of insect classes. Further tuning of model will focus on accuracy.



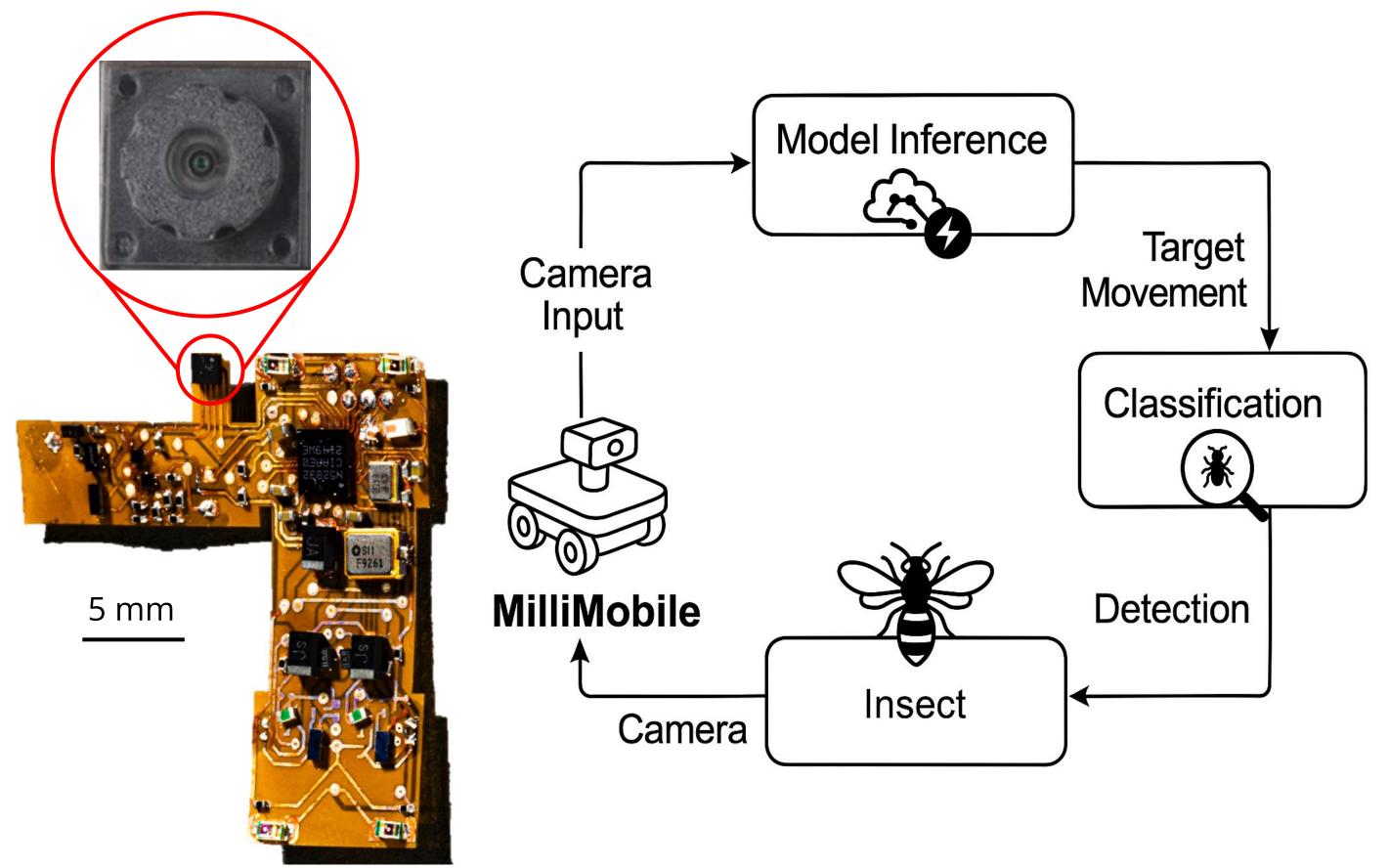
Experiments implemented on Arduino hardware show available harvested power as a major constraint, resulting in low duty cycles on the MCU.

Next Steps



Conceptual photograph of full system integration.

- Reduce hardware power consumption
- Finalize satisfactory model accuracy and max duty cycle given onboard power limitations
- Integrate model onboard, enabling autonomous insect tracking [8]



References

- 1. Kyle Johnson, Vicente Arroyos, et al. 2023. MilliMobile: An Autonomous Battery-free Wireless Microrobot.
- 2. Vikram Iyer, et al. 2020. Wireless steerable vision for live insects and insect-scale robots
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- 8. Zhitao Yu, et al. TinySense: A Lighter Weight and More Powerefficient Avionics System for Flying Insect-scale Robots.