To generate power for the whole system, including sufficient voltage for leg actuation, we must make full use of all possible p-n junctions due to the limited die area. As seen in Fig. 12.1.3, a triple-well CMOS process includes p-n diodes at N+ to P-well, P-well to deep-N-well, and deep-N-well to P-sub junctions. By connecting P-well to P-sub and N+ to deep-N-well, a p-n junction is used for voltage generation across P-sub (12.1.3, top, right). A unit solar cell has similar connections but shorts P-sub to deep-N-well instead (Fig. 12.1.3, top, left). A pair of legs require a peak-to-peak voltage swing >0.6V to actuate, while the open-circuit voltage (without load) of a CMOS p-n diode is <0.5V, even under >100k lux light. However, given the triple-well process, we float P-sub and stack the positive and negative solar cells, generating >0.6V across VSG and VSS (Fig. 12.1.3). For the circuits on the die, all PMOS devices are in N-wells that are connected to VSS, and all NMOS are in P-wells that are connected to VDD, with their deep-N-wells isolated from P-sub by connecting them to VDD. Figure 12.1.3 shows the measured VDD − VSS (no load) under different light intensities. Note that because the robot operates in a fully untethered way, there is no ground and P-sub is biased at VDD/2. To actuate the legs, VDD − VSS is applied between a pair of front and rear legs (Fig. 12.1.3, mid, right). This configuration generates >0.5V and <−0.5V on each leg, relative to the solution potential, which is sufficient to achieve curvatures. Leg actuation is controlled using counters triggered by clk_system, and the period, phase, and pulse width of the leg actuation signals are configured with a resolution of one clk_system period.

The proposed micro-robot is guided by a customized processor with 11-bit instructions (Fig. 12.1.4). The processor takes input data from the optical receiver as well as the temperature and electric-field sensors and generates the actuation signals of the four legs (which includes uplink communication through waving) as outputs. Configuration instructions are encoded in a minimal instruction set (Fig. 12.1.3, top, right). Memory mapped address space is used to transmit a program and the micro-robot is shown to switch to attention mode when activated by a 60k lux light source. The proposed CMOS design employs 210μm × 340μm × 50μm CMOS die that integrates all the electronic functions necessary for a micro-robot, including bidirectional communication, sensing, processing, energy harvesting, and actuation. We also demonstrate integration of our circuits with electrochemical actuators and show leg movement when activated by a 60k lux light source. The proposed CMOS design employs p-n junctions to create two opposite-polarity solar cells and generate >0.6V to power the circuits and legs. The design implements ultra-low power ring-oscillator-based temperature sensors and electric field sensors (for neighbor proximity detection) to allow the robot to respond to external stimuli. An optical receiver (RX) is designed based on the architecture in [9] and uses an integrated CMOS solar cell as a light-sensing element. A custom processor with 11-bit instructions and high-level robot specific functions minimizes code size and power consumption. Each die is pre-assigned one of ten IDs, which are used as an address by the RX, allowing units in a robot swarm to be programmed with different programs and enabling robot collaboration. Uplink uses a visual cue approach (leg-waving), which maintains monolithic integration and low-power, in contrast to the use of stacked micro-LEDs [4,6] or a higher-power backscatter-based data uplink [7]. Finally, prior micro-systems typically use older technologies (e.g. 180nm [4]) that offer ultra-low leakage power but could not meet the logic area constraint for our micro-robot. Instead, we use a customized 55nm process with increased Vth’s that meets both the stringent leakage and area objectives.

Figure 12.1.1 shows the robot in [8] with electrochemical actuators and two fabricated p-n junctions, next to a biological microorganism (paramecium). The curvatures of these actuators change when they are biased relative to the surrounding aqueous electrolyte [8]. This robot, however, is passive, requiring laser light to be alternately directed to the front/rear p-n junctions to actuate the legs and induce motion. In contrast, the proposed robot function that greatly reduce code size, including move (with the direction and number of steps determined by configuration values), temperature sense, electrical sense, and wave. As an example, Fig. 12.1.4 (bottom) shows the temperature sense “TS” instruction format. The program demonstrated in measurements has 22 instructions, including 18 conventional instructions. A general purpose 32-bit low power processor, such as an ARM Cortex-M0, would instead require 34 instructions of 32 bit each, or 4× the memory footprint.

The proposed CMOS micro-robot die was fabricated in 55nm triple-well DCC process provided by United Semiconductor Japan, occupying an area of 210μm × 340μm. To reduce robot weight the CMOS die was thinned to 50μm. We worked with the foundry to fabricate transistors with higher Vth, reducing leakage by ~9× compared to the standard option, and allowing both power and area constraints to be met. Figure 12.1.5 presents measured waveforms showing unthethered programming and operation. The chip was fully powered by 60k lux ambient light, and two oscilloscope probes (10MO | 12pF) were connected solely to record the voltages between the front legs (V_FL, V_FR) and VSS. The waveforms show that the micro-robot initially enters a default mode while it continues to check whether a passcode is being sent. An extra light source was then used to transmit a program and the micro-robot is shown to switch to attention mode and the program when it matches its chip ID. The program activates the front-right leg to turn left, then activates legs to move forward 5 steps and takes a temperature measurement. If the temperature exceeds a pre-defined threshold, it will stop and wave its front-right leg to uplink the measured temperature code using Manchester encoding.

We also successfully deposited two legs on a test die with identical harvesting and drive circuits (Fig. 12.1.5, bot, left). When activated with light (60k lux), leg actuation was observed, demonstrating the ability of the proposed circuits to initiate actuation. Figure 12.1.6 summarizes the performance and features of the proposed micro-robot design and compares it to prior state-of-the-art ultra-small microsystems. The proposed design offers lower leakage and power density compared to chip designs that use, for example, wireless sensing, processing, communication, and actuation [1-8]. Figure 12.1.7 shows the chip micrograph of an array of micro-robot designs and a zoom-in of an individual system.

References:
Figure 12.1.1: Proposed micro-robot that consists of a CMOS die and electrochemical actuators; vision of groups of micro-robots assembling chiplets.

Figure 12.1.2: Layout and floorplan of the proposed CMOS system; high-level diagram of the proposed design; operation states of the proposed micro-robot that supports both default mode and untethered programming.

Figure 12.1.3: Cross section of the well structures for positive solar cell unit, negative solar cell unit, and an inverter in the proposed design; programmable leg actuation and voltage waveforms.

Figure 12.1.4: Customized processor in the proposed CMOS system; datapaths of two instructions (“TS Rs, 1, F” and “WAV 0, F”) for temperature sensing and leg-waving (uplink); customized 11-bit instructions.

Figure 12.1.5: Measured waveforms of front-left and front-right legs during untethered programming; two legs deposited on a test die and measured curvature of the leg during untethered testing (fully powered by light).

Figure 12.1.6: Comparison with the prior state-of-the-art microsystems.
Figure 12.1.7: Chip micrograph of the micro-robot design array and zoom-in of an individual CMOS system.

Additional References: