V.I.S.I.O.N. - *V*ertical *I*ndependent *S*warm of *I*nteractive *O*perator A*N*ts

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***Abstract*—There are many challenges with testing algorithms with swarm robots including necessary space, cost of robots and assembly time, and ease of charging and programming. In this paper we present the design of a robot for swarm robotics education and research that is capable of driving on vertical and inverted magnetic surfaces. This includes electrical, mechanical, and software design and testing, ultimately culminating in a demonstration of ant pheromone trail behaviors. The robot system is open source, low-cost, small, easily assembled, and designed to scale well. The system has large memory and a fast processor to handle computation, complimented by quality sensors and high-bandwidth communication.**

I. Introduction

Robotics plays a pivotal role in swarm intelligence research by providing platforms upon which researchers can run experiments in the physical world as opposed to solely in computer simulations. Swarm intelligence is comprised of both natural and artificial systems with individuals that collaboratively exercise self-organization. Through many local interactions, global behaviors emerge. In nature this can be seen in something as seemingly simple as a flock of birds or a school of fish all the way to complex insect nest construction. Robots are useful for verifying models of natural swarm behaviors as well as discovering new, novel swarm behaviors.

Self-organized systems have two major aspects in common: feedback mechanisms and information exchange. To enable feedback in swarm robots, there is a need for proprioceptive and exteroceptive sensors for gathering information about the internal state as well as detect other robots and obstacles. Proprioceptive sensors typically include some form of heading detection or estimation such as an inertial-measurement unit (IMU) sensor, accelerometer, and magnetometer. On-board odometry is luxury to have on a small robot, made possible with wheel encoders, optical-sensor tracking (like computer mice), step count for stepper motor-based drive, time-based estimation. An external camera or a motion-capture system can provide accurate robot and obstacle global positioning, but is less desirable due to scaling complexity from set-up, calibration procedures, cost, and limitations on test space.

Exteroceptive sensors are necessary for identifying kin, detecting obstacles, and interacting with the environment. Cameras paired with color LEDs can be used for basic computer vision (CV) to perform color and blob detection to identify things such as other robots, nest locations, and food sources. Kin can also be identified with infrared (IR) sensors, Bluetooth (BT), and WiFi. Obstacles with a digital signature can be detected with the same methods however physical obstacles without a digital signature will require either IR sensors, ultrasonic sensors, or touch sensors. Lastly, sensors for encoding and decoding information into the environment to replicate insect pheromones opens doors for research of stigmergy algorithms.

Information exchanged between agents locally can include a range of things, whether that is orientation, distance, role, or another internal state. The distance between agents is one of the most critical pieces of information since it enables robots to localize amongst each other. Distance between neighboring robots can be calculated with IR intensity, CV and LED's, ultrasonic sensors, and Received Signal Strength Indicator (RSSI) of BT or WiFi.

There are several key characteristics of a platform designed for swarm research that operates at the scale of hundreds and thousands of robots. Foremost is the cost: with limited research funding, the cost of robots or robot parts and the cost of the man-hours required to assemble, set-up, and calibrate so many robot systems can be a large barrier to physical testing of swarm algorithms. Delivering a robot system with adequate capabilities without a prohibitive price-tag necessitates a design with minimal assembly and avoiding the need for time-consuming calibration procedures or set-up. Another design aspect that impacts how the robot scales for research is the size: larger robots will require more testing space than smaller robots let alone the additional material cost.

To develop and test with a large swarm of robots, power management and programming are two important aspects that determine how many robots can be used simultaneously. The robots should have a low-power state that enables the robots to wait and listen for experiment commands while conserving energy. Robots also need to have sufficient battery capacity given the platform's movement speed and anticipated algorithm run-time. While 1-3 hours of run-time may be sufficient for algorithms with only 10-20 agents, when you scale the group size into the hundreds and thousands the run-time needs to scale accordingly. [1] Charging the robots has to be a fast and simple process that doesn't require researchers to plug-in each individual robot. Successful options include wireless inductive charging [1], a conductive environment [2], and conductive docking stations. [] Similarly, programming should be wireless and able to be conducted in parallel so that all robots in the swarm receive the updated software at the same time. The ability to program in several languages such as C/C++, Python/ and a drag-and-drop GUI have been shown to expand the audience from academic researchers to students of various ages. [3], [4]

In this paper we present a novel solution to this problem with the introduction of a wheeled robot capable of driving on vertical and inverted horizontal magnetic surfaces such as whiteboards. This small-footprint robot will have a number of sensors and interfacing features such as wireless updating, wireless communication, light intensity and color sensing, camera and touch sensing. In addition to this, the robot will also have LED's for status as well as an ultraviolet (UV) LED for the emulation of pheromone trails. Our proposed swarm robot design offers improvements in communication speed and processing power, improved sensors, reduced cost of parts and assembly, and a solution to limited space in classrooms and research laboratories. These swarm robots will be particularly useful as a teaching aid and as a learning platform for students given the opportunity for space-saving visible demonstrations.

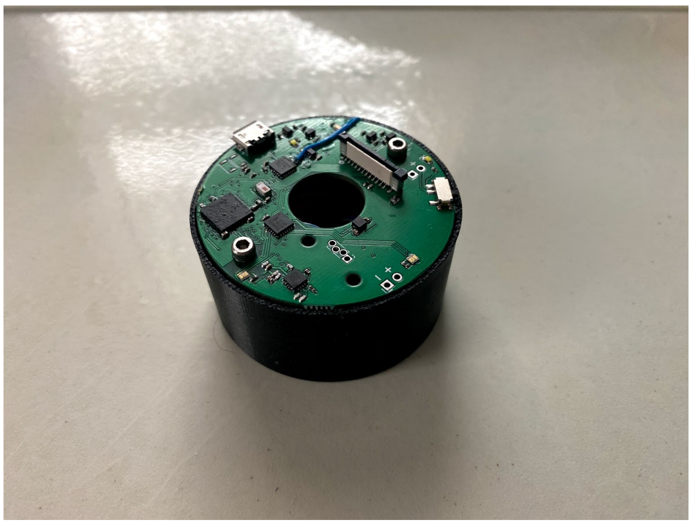

Fig. 1: Assembled Robot

II. Background

While there have been many swarm robot platforms developed to meet a variety of needs in the educational and research field, few robot platforms have been widely successful. Because there are so many areas of focus within swarm robotics that require different robot capabilities, developing a generalizable swarm robot is not a straight forward task. Consequently, almost every robot developed has had a focus to drive the design requirements.

S-bots [5] have two manipulators to enable the robots to self-assemble by connecting and disconnecting to each other and the environment. The s-bots have the ability of orienting the main body of the robot independent of the direction of the locomotion. [6] This robot platform, in conjunction with simulation, enables the study of aggregation behaviors [7], group transport [8], and pattern formation [9]. Jasmine, another robot intended for aggregation research, uses light and IR to mimic temperature and contact pheromones in bees. [10]

The Kobot, a robot designed around flocking, uses a digital compass and IR sensors for heading and sensing respectively in addition to WiFi communication. [11] The Crazyfly 2.1 Minidrone has been used for aerial swarms of up to 49 drones with a motion capture system. [12]

Several robots have been developed specifically for education, with a target in low cost, small size, and ease of use. The E-puck, an open source robot with a versatile sensor suite and simulation capability designed with customizable actuator and sensor extensions. [3] Another education robot, the R-one, is several times smaller than the E-puck at 10 mm in diameter compared to 75 mm in diameter and boasts greater run time and similar sensors for a lower cost. [4] More recently we have the Thymio II open-source robot [13] and Asebo software aimed at pairing educational robotics with Augmented Reality (AR). [14] Lastly, the Kilobot has been one of the most successful swarm robots due to the low-cost design, small-size, and scalable programming and power management [2] that enables researchers to conduct experiments with hundreds of bots. [**?**]

Several swarm robots have been designed around interacting with the environment and encoding information into the environment. TERMES [15], a stigmergy robot inspired by termite style structure construction, has the ability to collectively craft structures of foam blocks 18 times their volume without centralized control. [16] COSΦ is an adaptation of the Colias mobile robot [17] to accurately replicate insect pheromone trails in conjunction with a LCD screen and external localization camera. [18]

In [19], the authors created robots from LEGO's including an EASyMind Motorola 68332 microcontroller, IR sensors, and light-dependant resistors (LDR's). These robots used ultraviolet (UV) LED's to excite pseudo-pheromone trails on photo-luminescent paint in order to create an ant-inspired art exhibit. [19] Another attempt at modeling ant pheromone trail behavior with robots can be seen with Antbots, an E-puck with a UV LED extension for laying a trail onto a photo-luminescent surface and a camera for trail detection. This implementation was limited to only one robot for validation while the swarm aspect of the behavior was shown in Netlogo simulation. [20]

III. Methodology

A. Design

The design of the VISON robot was divided into 3 major, highly related parts. The major categories were the Mechanical design, the electronics and the software. Each category was heavily reliant on the others, as the mechanical design relied heavily on the final design of the main structure of the robot, the electronics had great input due to the physical constraints of the mechanical design as well as the requirements for motors, etc. The overall software design became heavily reliant on the micro controller used and its capabilities and its available functionalities.

1) Mechanical: In designing of the robot, to target a minimal footprint, the printed circuit boards(PCBs) were used for the main structure of the robot. The use of these PCBs in the construction of the robot allow for the use of a minimal number of 3D printed components, resulting in a very rigid system.

a) ***Locomotion:**:* For locomotion, there are two standards used in currently available swarm robots being primarily wheeled motion or motion through vibration. For this robot direct driven wheels using micro stepper motors. Stepper motors were chosen due to their ability for rough odometry tracking through the step interface used to drive them. The use of a known step amount allows the tracking of wheel rotations in 1/8 th rotations. These micro stepper motors should be able to drive the robot at approximately 50 cm/s due to their fast response time to step signals being about 100Hz. The wheels attached to the motor are 3d printed with a designed grove to fit a 5mm elastic band designed for use with braces to act as a tire, increasing the coefficient of friction of the wheels.

b) ***Vertical& inverted Motion:**:* To allow the robot to operate on vertical and inverted surfaces, the robot was designed with two 5mm N52 neodymium magnets with a combined pulling force of approximately 1.5kg. This pulling force equated to approximately 38 times the total weight of the robot. This increased attraction between the robot and the surface placed on results in increased attraction on the wheels, making it very unlikely for the robot to slip. In addition to this, the increased attraction to the surface results in the robot being able to remain stationary and un-powered for long term saving battery.

c) ***Marker Actuator:**:* To allow the robot to simply interact with the environment, each robot has a marker attached. This marker is actuated using a micro stepper motor similar to those used for locomotion. This motor raises and lowers the marker to allow it to make and break contact with the surface below.

d) ***Assembly process:**:* The assembly of the robot was made as simple as possible only requiring eight bolts, two nuts and 6 simple 3d printed parts. The motors and magnets are attached to the 3D printed base. The lower PCB is then attached to the base using four m2.5x8mm screws. The motor actuator is then attached to the 3D printed holder and attached using the final two m2.5x8mm screws. The Shell is then placed atop the lower PCB, both batteries inserted and the upper PCB is attached thought he means of pin headers and the final two m2.5x15mm screws ate inserted through the entire robot. These parts can be seen in Fig. 4

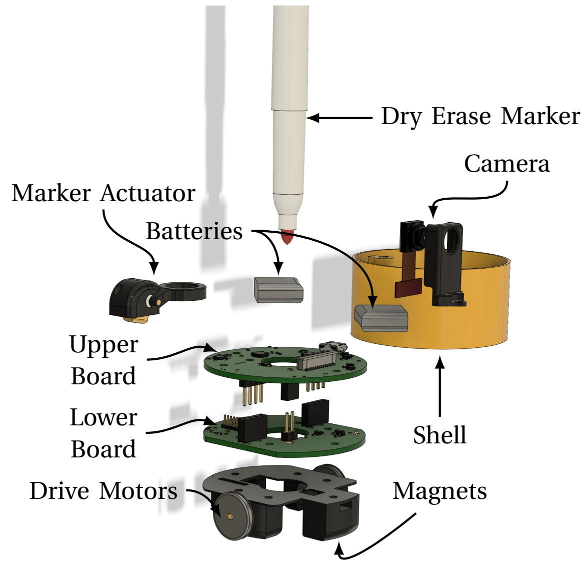

Fig. 2: Exploded View

2) Electrical: With the electronics being the bulk of the physical robot, all sensors, motor drivers and micro controllers must be combined and integrated into the designed PCBs.

a) ***Micro Controller:**:* The micro controller for the robot must have hardware i^2c, multiple GPIO and support for a camera. This limited the choices to the ESP32 and STM32 micro controllers. The ESP32 micro controller is compatible with all requirements and has hardware WiFi and Bluetooth capabilities. This provides a simple and efficient means of communication and distance approximation as well as mass programming and updating. The ESP32 is a dual core 240MHz micro controller with a dedicated Real Time Operating System to handle all tasks and processes efficiently while still providing an ultra low power sleep mode which will prove useful for long term inactivity by reducing the drain on the battery.

b) ***Sensors:**:* The VISION robots are developed with a vast series of sensors including, a pair of RGBW-Lux sensors, an Accelerometer and a variable resolution camera with up to 1600X1200 pixels. These sensors will allow for vision both in front of the robot and below looking down to the floor. The integrated RGBW-Lux sensors are spaced apart by 14mm, allowing the robot to accurately track a colored line or a line of light being emitted by a photo-luminescent surface. The Accelerometer will provide robot orientation by using the known, calibrated value of gravity to determine the angle in the X, Y axis of the robot.

c) ***Charging:**:* With the consideration of having to charge a large number of these robots simultaneously, charging pads were placed on the bottom of the robot to allow for the robot to be placed on a simple fixture that applies 5V to each robot in a bus. This 5V is then regulated to charge the two 1s batteries integrated into the robot. This charger ensures the batteries are charged accurately and safely.

*d) **Stigmergy**::* To allow these robots to effectively interact with the environment, each robot has an actuator dedicated to manipulating a marker and a UV Led to interact with the photo-luminescent surface below the robot. Both of these forms of lines will be sensed and be able to be followed by the integrated RGBW-Lux and the integrated white LED to allow different colored lines to be interpreted with different meanings or significance.

3) Software: The software structure of the robot was designed as a back-end system on which behaviours and algorithms could be written on top of with simple requests and sending of sensor an communication information. The software for this robot is written in embedded C++ using the Arduino environment for its ease of use and library support for easy distribution. The software for the robot utilizes the dual core nature of the chosen micro controller and its Real Time operating System(RTOS).

*a) **Communication**::* For communication between robots and any master controller and/or the main firmware database, WiFi is used for its high throughput and its high fidelity in RF dense environments. The use of WiFi's strength value will provide a rough distance measurement between robots, allowing them to communicate with robots selectively based on their distance.

*b) **Programming**::* Due to the nature of swarm robotics requiring a large number of these robots to be utilized, the problem of uploading a new version of firmware to such a large number of robots may become a very daunting task. To deal with this, while inactive, each robot contacts a file server, checks for a new version of the firmware available, downloads it and self updates. This allows for one file to be updated on a remote server and deployed rapidly to any number of deployed robots. In the case that an algorithm requires a unique identifier, the robots WiFi mac address is used, meaning the same firmware can be deployed without customization's for each robot.

*c) **Sensors**::* All integrated sensors and devices have had libraries written to obtain their data and processed. The sensors are then processed as needed. The RGBW-Lux sensors are used to line follow around a drawn. The disparity between the wheels are mapped to the wheels velocity. The Accelerometer is used to ensure the robot is tracking along a given trajectory in the case of exploratory driving and later processed to obtain the odometry of the robot. The camera is used to capture frames from the surrounding environment and processed in RGB and HSV color space.

All sensors have had a high level interface developed. This allows for high level algorithms to be written and tested utilizing simple getter and setter functions for all sensors and actuators. For example the orientation can be called by using *Robot.getOrientation()* function.

*d) **Odometry& Localization**::* To monitor the orientation of the robot, the accelerations in both X and Y are measured using the integrated accelerometer. This is then used to compute the orientation angle treating the accelerations as lengths in the equation: $tan^{-1}(\frac{Accel_X}{Accel_Y})$. In order to keep track of the distance the robot has traveled, the known rotational length of a single step of the micro stepper motors is used in combination with the known diameter of the wheels. The distance traveled by each wheel is traced in memory and the position in X-Y space is computed.

*e) **Tasks and Processes**::* Due to the Dual core processor being used and its integrated RTOS allows for multiple tasks to be run and computed simultaneously. All processes and computations at the low level are scheduled and distributed between both cores. Each of the sensors is read on a timed task and processed. Each task is given a priority value which determines their ability to interrupt and or block another task. This allows any high level algorithm to be run without waiting or being blocked waiting for a sensor to be read.

B. Behaviours

In parallel to developing the hardware, electronics, and software components of the robot is the development of the algorithms that govern the behaviors exhibited in the demonstration. This is completed in the ARGoS [21] multi-physics swarm robot simulator. The three critical behaviors include pheromone trail creation, pheromone trial following, and agent recruitment which is also known as tandem-running. The simulation includes 20 footbot agents augmented with the capability to modify the color of floor in the simulation. There are no obstacles, and 15 food items are distributed randomly in a small section of the map such that agents following a pheromone trail find additional food near the end of the trail.

The simulation initializes with agents scattered randomly in their nest. Agents then wander randomly, avoiding collisions with each other and the environment while searching for food or a pheromone trail. Each time the agents are near enough to each other to be avoiding a collision, they check if the agent they met is recruiting other agents to help retrieve food. If the agent they met is looking for help, they follow at a distance. If both agents are looking for help, they will randomly choose who is the follow and who is the leader. If neither agent is looking for help, they will continue their random walk searching for either food or a pheromone trail.

Once an agent finds a food source, they will return to their nest, identified via a light sensor and indicator LED's. On their path to their nest, they will deposit pheromones that decay over time for other agents to discover and follow to the food source. Agents that are randomly walking that come across a pheromone trail will follow the trail using a rudimentary line-following algorithm. The agent will remember they are following a line for several steps after losing track of a line to account for any inconsistencies in the path.

IV. Experiment

We intend on testing a swarm of VISION robots performing the behaviors developed in simulation. The robots would be placed on a whiteboard coated in photo-luminescent vinyl. We would tune the UV LED exposure rate and intensity to achieve the desired light decay rate to match ant pheromone dissipation. For simplicity, two static agents would be used to represent the nest and food source, allowing wireless communication to verify location and food pick-up/drop off.

V. Updated Timeline

A. Weekly Work

Week	Task & Work
8	-Research & Writing Background section -Robot Assembly -Robot Testing
9	-Writing introduction section -Sensor testing -Bugs found -Robot Redesigned -Consultation with Prof. Pinciroli -Two hours later... Problem Fixed
10	-Robot Testing -Simulation Development started -Firmware Started
11	-LED Testing and library written -Both color sensors tested and working -Write Pheromone Trail Creation and Tracking Behaviors

TABLE I: Weekly Work Schedule

Due to a series of issues found in the testing of the robots, the initial plan of assembling a group of robots for each of us quickly became infeasible. This led us to have a call with Prof. Pinciroli in which we discussed our plan of action. This resulted in our plan to continue development of behaviours in Argos. Briefly after this meeting, the major blocking bug was found and fixed. This then resulted in us updating Prof. Pinciroli and deciding the best plan of action would be to continue with development of the physical robot platform as well as the behaviours in Argos simultaneously. This resulted in a number of changes having to be made to our timeline which is updated in Table II

B. Updated Schedule

Week	Task & Work
12	Sensor Testing & Firmware writing, Behaviour Development in Argos
13	Firmware development, Behaviour Finalize Behavior Development in Argos, Port Behaviors to VISION Bots & Paper writing
14	Paper Writing and Presentation

TABLE II: Revised Weekly Work Schedule

A major focus in both the development of the robot firmware and the simulated behaviours is to have them well documented and easily portable to future development. For the firmware, the use of C++ classes, the robot is encapsulated withing its own class with all of its sensors and can be called by any high level algorithm developed.

VI. Results

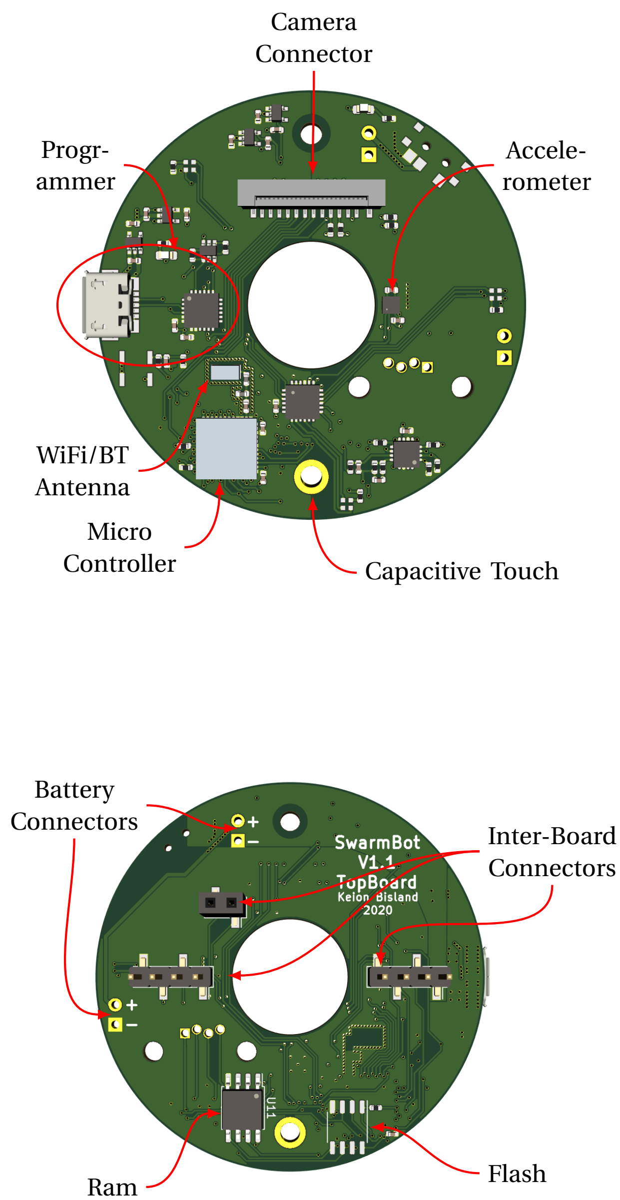

Fig. 3: Exploded View

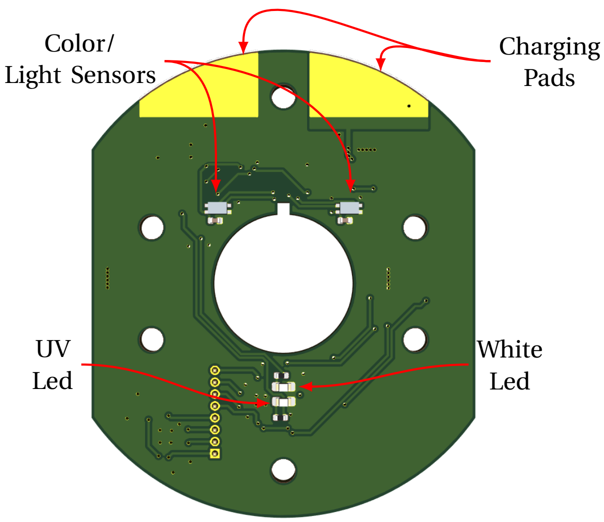

Fig. 4: Exploded View

Appendix

Robot, Year	Manip-ulator	Stigmergy	Generic Sensing	Wireless Coms.	Wireless Prog.	Parallel Prog.	Locomotion, Speed (cm/s)	Battery Life (hr)	Size (cm)	Cost ($)	Processor
VISION Bots, 2020	✗	UV LED, color / LUX	distance, camera, 9-axis IMU, bump	BT, WiFi	✓	✓	wheels, 58	30	5 dia.	28	240MHz Dual Core
Kilobot	✗	✗	distance, ambient light	IR	✓	✓	vibration, 1	3-24	3.3 dia.	14	8MHz Atmega328
Colias, 2014	✗	✗	distance, bump, bearing, range	IR	✗	✗	wheels, 35	1-3	4 dia.	41	20MHz Atmega168, 20MHz Atmega644
COSΦ, 2015 (Colias base)	✗	LCD environment, light	distance, bump, bearing, rage	IR	✗	✗	wheels, 35	1-3	4 dia.	-	20MHz Atmega168, 20MHz Atmega644
E-Puck, 2009	✗	✗	bearing, accel, microphone, camera	BT, Zigbee mesh	✓	✗	wheels, 13	1-10	7.5 dia.	600	64MHz Microchip dsPIC
Antbots, 2010 (E-Puck base)	✗	UV LEDs, camera	bearing, accel, microphone	BT, Zigbee mesh	✓	✗	wheels, 13	1-10	7.5 dia.	-	64MHz Microchip dsPIC
E-Puck2, 2018	✗	✗	distance, bearing, ToF, 9-axis IMU, microphones, camera	BT, BLE, WiFi, IR	✓	✗	wheels, 15.4	1-3	7 dia.	718	168MHz STM32F4
TERMES, 2011	✓	brick stacking, line tracking	distance, bearing, tilt, bump	BT	✗	✗	Whegs, -	-	17.5x11x10	-	16MHz ATmega1281

Source Files

https://github.com/keionbis/Vision-Robot-Electronics
https://github.com/keionbis/Vision-Robot-Firmware
https://github.com/swhiteinventor/Vision-Robot-Behaviors

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