Control of Swarm Robotics Systems Using Computer Vision and Solar Panels

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***Abstract*—Control and communication is a critical part of maintaining robot swarms. Typically in most robot swarms, a Radio Frequency (RF) mesh network is used to transmit data. However, these transceivers can quickly increase the cost and complexity of swarms as the number of robots increases. We demonstrate the feasibility of using computer and AruCo tags in conjunction with small solar panels for swarm robot control and communication. This results in a highly scalable swarm and provides a simple, robust communication protocol. In addition, some potential future work is described as well as the expandability and limitations of this method.**

***Index Terms*—Swarm Robots, Computer Vision, Solar Panels, Parallel Communication, Low-Cost**

I. Introduction

TRADITIONALLY, most robots use a type of radio frequency (RF) network to communicate data between the robot and the host controller. This provides a robust and fast communication protocol. However, RF communications suffer from significant power drain and are poorly scalable to large swarms [1]. Because of this, it is beneficial, particularly for large swarms, to explore alternative communication methods that consume less power and scale easily.

Improved swarm robotic systems are of interest because due to current excessive costs of swarm robots, unnecessarily complex and non-scalable communication methods. One of the most prevalent swarm robot systems is the ”Kilobot” developed by Harvard University [2]. Unfortunately this system communicates to only one robot at a time using infrared communication. Although this has been used to create large robot swarms it is unnecessarily complex. Additionally the goal of the ”Kilobot” project was to design a robot that was extremely low cost which is necessary for large swarms in an educational setting, the actual cost per unit is approximately $100 USD, which is far to expensive to be practical.

Several methods have been explored for avoiding the drawbacks associated with RF networks. Researchers have used infrared light, sound, and even pheromones to communicate between robots and a host controller (if applicable) [3], [4]. Many of these systems offer solutions to the problems of RF transceivers, but also create problems of their own such as the speed of data transfer, signal integrity, and power draw.

In an effort to reduce complexity and cost of robots in the swarm, a system of solar panels, Augmented Reality (AR) tags[3], and an overhead projector and camera have been deployed as a replacement for RF transceivers. By offloading the computing requirements and removing the need for an RF mesh network, it makes it simple and cost effective to add additional robots to the swarm. In addition, it removes the RF transceiver power draw. The AR codes on the robots are monitored using the overhead camera to determine the position and orientation of the individual robots. The robots then receive commands by varying the intensity of light on the solar panel to emulate a logic level of 0 for dark or a logic level of 1 for bright white light.

Though this approach provides a cost efficient way to implement robot swarms, it isn’t without its drawbacks. Because the solar panels are also used for charging, the robot cannot receive commands from the mainframe computer during a charging cycle. In addition, the communication rate is limited to the refresh rate of the projector. Lastly, this system is susceptible to interference due to outside light.

II. Methods

The main focus for this research was on the use of solar panels for communication with swarm robots. In addition to this goal, several supporting components also needed to be developed. First, a chassis was needed to carry the solar panel and AR tag as well as provide reliable motion. Beyond this, a structure was created to hold a projector and camera above the swarm area. Finally, a charging area was created to charge the on board batteries via the solar panels.

A. Robot

Because most of the techniques this project explores are unconventional, a simple off the shelf swarm robot kit does not suffice. These kits do not contain unnecessary parts and aren’t easily modified to accept custom components. Thus, the group designed and constructed a swarm robot specific to our purpose.

The robot needed to be small enough such that swarms of a dozen or more in a laboratory setting are practical. Additionally, each robot must be low-cost and easy to manufacture.

The design for this robot includes a laser-cut acrylic chassis to which all components are mounted. Continuous rotation servo motors comprise the robot’s differential drive while a chassis mounted ball caster provides a third contact point. A single cell lithium battery is mounted atop the chassis between the wheels. A .5W solar panel sits atop the battery. This acts as the bot’s charging source and its data receiver (described in further detail below). A signal filter, battery charger, and microcontroller are mounted on the electronics board beneath

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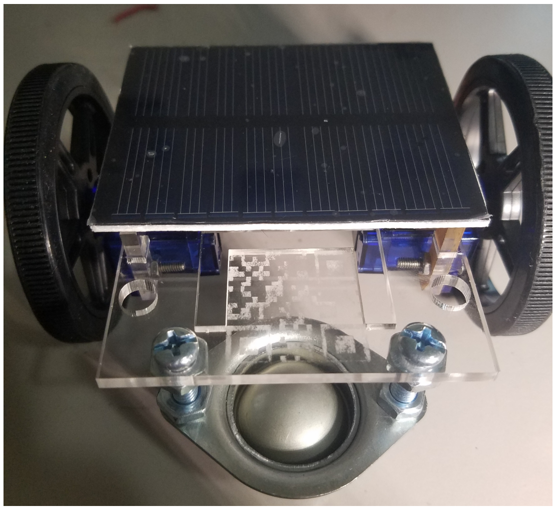


Fig. 1. Chassis disassembled and with motor brackets installed.

the bot. The AR tag identifying the robot is placed atop the robot, in front of the solar panel so it can be seen by the overhead camera. A 5mm LED mounted to the right of the AR tag allows the robot to transmit its state.

The following methods were used to keep the design low cost and easy to manufacture:

- Solar panel doubles as info receiver and charging source.
- Servo brackets are cut from center of chassis minimize
- Chassis is able to tessellate a plane; a single sheet of material can be cut into robots with near zero waste
- Electronics all off-the-shelf

The design methods used resulted in a bot with the following specifications:

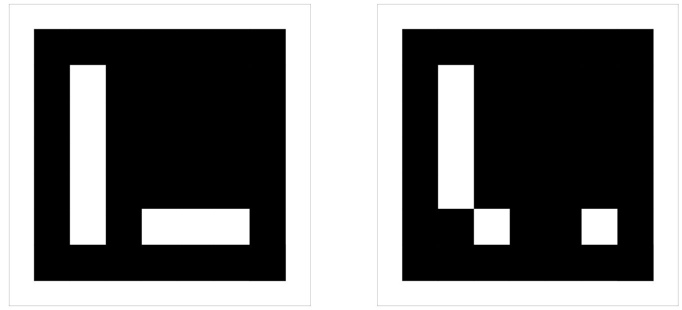
1) Cost: $60/bot
2) Footprint: 6.5 in^2
3) Microcontroller: 8MHz ATTiny85, 5 pin GPIO, 3.3V
4) Battery: 3.7V 300mAh Lipo battery

B. *Robot Monitoring*

In order to send commands to individual robots, it is necessary to understand the robot's position and orientation. To determine robot position, each robot is equipped with a 1.25 inch AR tag with a unique identifier. An example of two AR tags is given in Figure 2. These tags contain both a unique identifier and orientation.

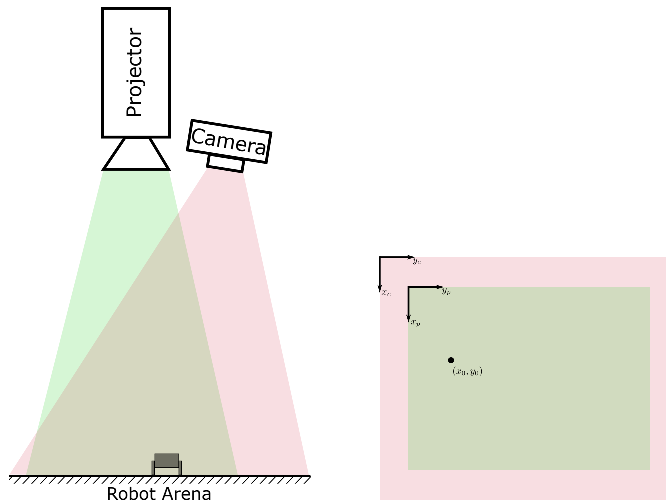
A Logitech C270 webcam was placed over the robot arena and used to determine each robot's position and orientation. The frames from the camera are passed to a computer running OpenCV [5]. This computer then determines the location of each tag, its orientation, and its unique identifier. Once this information is determined, the desired signal can be sent to only a specific location in the robot arena.

Because the camera and the projector do not have the same field of view, a homography mapping was used to ensure the robot locations corresponded to the appropriate projector pixel location. The homography matrix is determined using the OpenCV function "FindHomography". A graphic of this mapping is shown in Figure 3.



(a) ID 1 (b) ID 2

Fig. 2. Two sample AR tags with ID markers 1 and 2 for use on the robots. The origin is at the bottom left corner with positive X and Y in the right and up directions respectively.



(a) Overhead projector and camera (b) Camera and projector reference frames

Fig. 3. Camera and projector layout along with their associated reference frames. The relationship between them is determined with a homography matrix.

The homography transformation allows the signals to be projected only to the solar panel location. This allows for individual robot communication and prevents the projected image from interfering with the AR tag detection. In addition, it ensures that the message is in the correct location regardless of discrepancies between to field of view.

C. *Data Transmission*

1) Computer to robot [6]: Once an individual robot's pose is known, the overhead projector can send data only to the specific location corresponding to that robot's solar panel. This not only allows each robot to receive individualized commands, it also allows all communication to be done in parallel.

To send data to a specific robot, an overhead projector displays a white or dark circle centered on that bot's solar panel to create a voltage difference on the panels output. This change in intensity is small, and the digital inputs of the microcontroller are not able to discern the small ΔV of the unconditioned panel voltage. In order for the robot to interpret

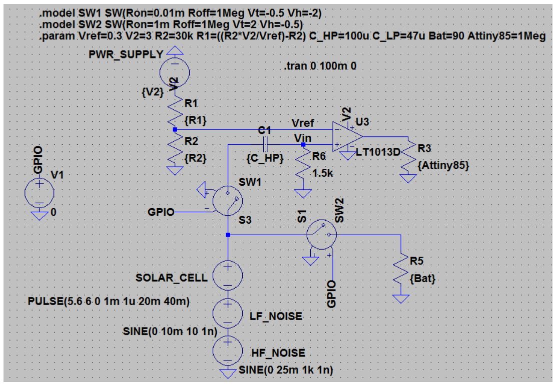


Fig. 4. Schematics of the solar panel circuit for filtering and charging (Two switches have been used to represent a relay).

this signal, an inline filter is used to ensure a logic level output to the microcontroller.

The LT1013 is used to build a comparator circuit. To ensure the filter output is independent of the light intensity of the surroundings, a simple RC high pass filter is included before the signal goes to the LT1013. When a white square is "written" to the solar panel, the voltage on its output increases. This change propagates through to the comparator, and if the filtered signal goes above the reference value, the amplifier saturates the output at V+. The other scenario (signal is smaller than reference) sets the output at V-. For our purpose, V+ is set at 3V and V- is ground, allowing the digital inputs of the microcontroller to read the message the projector is sending.

2) Robot to computer: The robot is able to communicate with the computer via an RGB LED located on the robot chassis adjacent to its identifying AR tag. The color of this LED indicates the robots status, according to the following list:

- Red: Low battery
- Green: Idle
- Blue: Lost
- Yellow: Doing Action
- Orange: Charging
- Purple: Asleep

The LED pulses on for 3 seconds every 30 seconds to keep power use low. The overhead camera is able to identify the color of this LED to determine a robots status and thus its next move.

D. Charging

As swarms grow in size, they become unwieldy to charge manually. A swarm of a dozen means a dozen batteries to charge often. This problem only grows with the swarm size. To solve this the group designed robots that are able to charge themselves.

The charging solution developed by the team utilizes solar panels on each robot that are charged by an artificial light source that is independent from the light used to communicate with the robot.

.5W solar panels are chosen to power the robots. As the light intensity indoors is significantly lower than light intensity outdoors ($\approx 1\frac{kW}{m^2}$), it is necessary to provide a powerful artificial light source the robots will seek when they are low on energy.

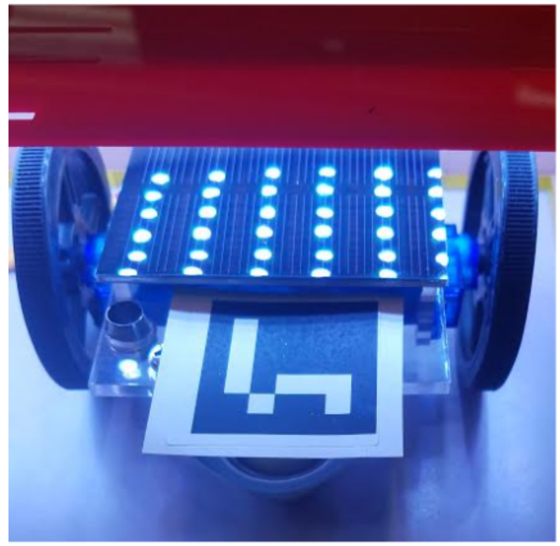


Fig. 5. A robot undergoing charging.

A box with a roof covered with high power LEDs was developed to allow the robots to charge wirelessly. The LED intensity is controlled by the computer to only enable the charger when a robot is present.

This structure, colloquially referred to by the group as "the oven", consists of 126 LEDs arranged in strips on a plate. This plate is elevated 3" off the ground to allow the robots room to sit underneath while charging while still maintaining a close distance between panel and LED to achieve high power transfer.

Whenever a robot indicates it has low battery, the master controller will direct it to the oven. Once the robot is confirmed to be fully under the power LEDs, the master controller enables the oven to full power. The theoretical maximum power transfer can be found by accounting for the various efficiencies within the system:

$$P_{battery} = N_L \cdot p_L \cdot \frac{A_{panel}}{A_{oven}} \cdot \eta_{LED} \cdot \eta_{panel} \cdot \eta_{charger} = .1W$$

As can be seen, the design choices only utilize 20% of the total capacity of the solar panel.

The net charging time at this rate can be found (assuming the battery was empty):

$$t = \frac{c_{battery}}{P_{battery}} = \frac{3.7V \cdot .3A \cdot 3600s}{.1W} \approx 11h$$

Future work includes higher density LEDs to utilize the full power output of the panel.

E. Arena

The "Arena" is the bounded area in which the robots move and charge. The arena is approximately one meter square and prevents robots from moving past the field of view of the camera and projector. The arena was assembled from

Fig. 6. The system setup.

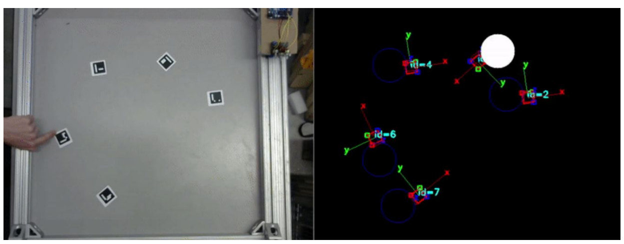


Fig. 7. Sample AR tag detection frame. ID numbers and pose are shown on the tag. The white (or black) circle indicates the solar panel area.

reconfigurable extruded aluminum (8020) to allow for simple additions and to also provide a rigid frame for mounting the projector and camera. Further development of this swarm robot system could include building a larger arena to accommodate more robots.

III. Results

A. AR tag recognition

AR tag recognition was successful and tested with up to 10 tags in the frame. These tags returned a vector of their position and orientation in the camera frame. This was then used to offset a circle in the direction of the solar panel for data transmission (Figure 7).

In the examples shown, a random white or black circle is projected in the location of the solar panel.

Once the camera was detecting the images reliably, we attempted to apply a homography transformation to the output projector image. This process was completed by projecting a checkerboard pattern to the robot arena and mapping the checkerboard corner locations to camera coordinates. The output 3x3 homography matrix was then applied to projector image to map the pixels in the output frame to the corresponding projector location.

Though the transformation was calculated, the code written would not accurately apply the homography matrix. Instead of applying the matrix to all pixels in the projected image, only the first pixel in the image received a homography transform. The cause of this is likely related to the scaling parameters used for the creation of the homography matrix and those used for the AR tag detection. The first pixel was likely being scaled to cover the entire output image and the remaining values were projected off screen.

B. Data Transmission

One way parallel communication via light is demonstrated. The team successfully implemented a solar panel and filter combination as a data receiver capable of interfacing with a 3.3V microcontroller. Future work on the system includes higher frequency transmission and full utilization of the parallel communication abilities of the projector system.

C. Charging

The system demonstrated by the team shows that the solar panel can be a capable charging system for swarm robots. While the system implemented resulted in a low charging rate, key improvements in both the panel and the LED ”oven” could result in improvements of up to an order of magnitude in the charging rate.

IV. Conclusion

The methods used in this project proved to be quite successful in terms of a proof of concept for a swarm robot system. Overall, this project provided successful demonstration of

1) Swarm tracking using AR tags
2) Data transmission using Solar Panels
3) Wireless charging for swarms
4) Cost reduction of robots

Though a full system model was not created, each subsystem was able to individually complete the appropriate actions. Future work to be done on this project involves optimizing the individual components in order to maximize the potential of our system and integrating the components together into full working model. Opportunities for improvement include:

1) Faster charging (higher power leds)
2) Lower cost robot (custom PCB)
3) Correctly applied homography matrix
4) Communication protocol development

The ultimate goal for this will be to integrate all components together to create a full working model. In addition, the future goal will be to develop a framework for sending messages to a given robot using a simple library. Finally, the team hopes to extend the swarm to several dozen swarm bots for research in swarm behavior and swarm systems.

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