BIO-INSPIRED DESIGN, FALL 2012

PascoBot

Ant-Inspired Autonomous Contamination Mapping

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Design Summary

Desert ants, *Cataglyphis*, have the remarkable ability to take a perfectly straight path home after wandering far from the nest during hours of foraging. This is important because they must return home quickly in order to avoid burning in the intense heat of the desert. In the bleak, featureless landscape of the desert, these creatures behave almost as if they had an internal compass pointing home, but how do they do it? They do in fact have a type of biological compass, but instead of using a magnetic reference point, they follow a vector of polarized UV light which points directly to the origin point of the journey. This “homing” vector is integrated from solar data that is gradually collected over the outward-bound journey, via a hard-coded neural template. This highly efficient yet simple behavior can be emulated by engineers to make inexpensive yet effective forms of artificial intelligence.

Modern disaster response efforts still struggle to perform data collection and analysis at hazardous material contamination sites without risking human health or incurring great equipment expenses in the process. Sample-collecting robots used in such scenarios are not only extremely expensive (on the order of tens or hundreds of thousands of dollars), but also large, heavy, and relatively clumsy due to their rigid locomotion mechanisms. Robots which perform complicated tasks require high-capacity processors and cooling systems, which contribute to size and expense. Our designers realized that these types of “advanced” robots suffer from their own versatility. PascoBot diverges from this traditional robot model and instead follows a minimalist design philosophy. Its designers conceived the smallest, simplest possible device to accomplish a basic, time-critical task. They recognized an opportunity to apply the computationally cheap, simple, and reliable navigation behavior used by desert ants.

PascoBot is a system comprised of many identical devices which “swarm” the area being investigated. PascoBot mimics the ant's simplicity, disposability, and most of all, its celestial tracking abilities. The PascoBots are dispersed over the contaminated area in a way that minimizes human proximity to the area (i.e., they are launched from a significant distance and passively scattered) while eliminating the need for long-range signaling capacity or advanced GPS scanners. After landing, the PascoBot enters return mode and uses solar cue to fly back to the base. All the while, its sensors are actively scanning the area and sampling data. The advantage of this system is not only its computational efficiency, but also the inherent speed and mapping potential of contamination variation over a large area.

Solution Description

Desert ants are one of the few organisms capable of surviving in the harsh environmental conditions of deserts in both Africa and California. Due to the frequent absence of consistent environmental landmarks and frequently shifting sands, the ants are unable to utilize traditional navigation techniques. Instead, the ants have developed a unique navigation system which provides them with the ability to return to the nest, even in the absence of landmarks, as shown in **Figure 1**.

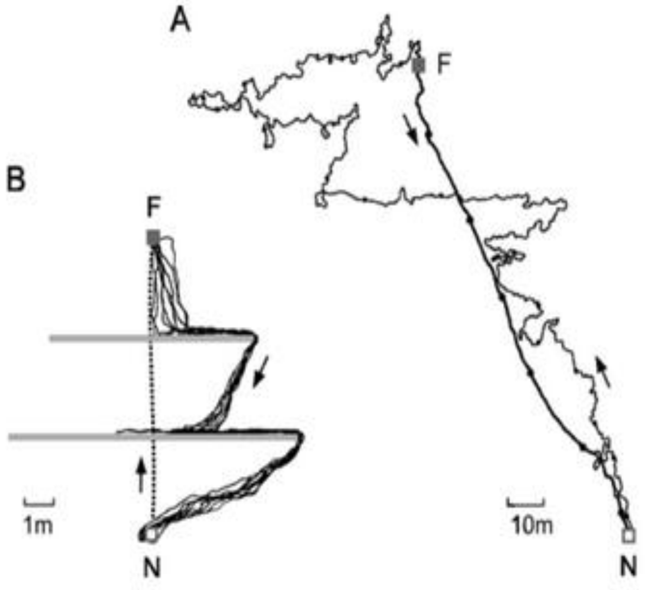

Fig. 2A, B Path integration (vector navigation) in *Cataglyphis fortis*. **A** An ant's tortuous outward (foraging) and straight homeward path recorded in a featureless salt pan. **B** Straight outward paths indicated by the *dotted line*and multi-leg homeward paths caused by experimental barriers *(grey bars)*, which the ant could pass on its way out (from *N* to *F*) but not on its way in. Nine successive runs of one ant. *F* feeding site, *N* nest. **A** from Wehner and Wehner (1990), **B** from D. Andel and R. Wehner (unpublished observations)

Figure 1. Path Integration (Wehner, 2003).

Navigation is accomplished using polarized UV light of approximately 350 nanometers wavelength to generate directional cues. "Hard coded" UV receptor cells, found along the dorsal rim of the eye coupled with a small processing region in the ant's brain, process this data while expending minimal energy. Before the ant leaves the nest, it obtains an initial polarization reading, establishing this reading as the baseline for the ant to return to. From there it begins to forage, and analyzers, found in the eye, generate a direction field. This data is fed through a small number of polarization-sensitive neurons which relate the data to distinct e-vectors which are updated as the ant turns. These inputs are then hypothesized to be sent to a series of "compass neurons" calibrated to fire at a given degree of rotation allowing the ant to "see" the most direct vector between its given position and the nest. While there are many receptor cells along the eye, there are only approximately three integrators feeding to an unknown number of compass neurons (Wehner 2003).

The superiority of the system lies in the simplicity of required calculations. For most animals, navigation requires collection, separation, and processing of data before meaningful information can be obtained, and navigation can occur. The ants' neural network circumvents this issue by utilizing the fixed geometry of the ant's eye to break down complex polarized light inputs into simple vectors. Then, following the process described above, the ant performs simple processing which can be understood as:

$$Homing\ Vector < magnitude, angle > =$$

$$< 0{,}180° > - \frac{\int_0^{Exploration\ \ Time} Orientation\ away\ from\ sun\ for\ Part\ A}{Exploration}$$

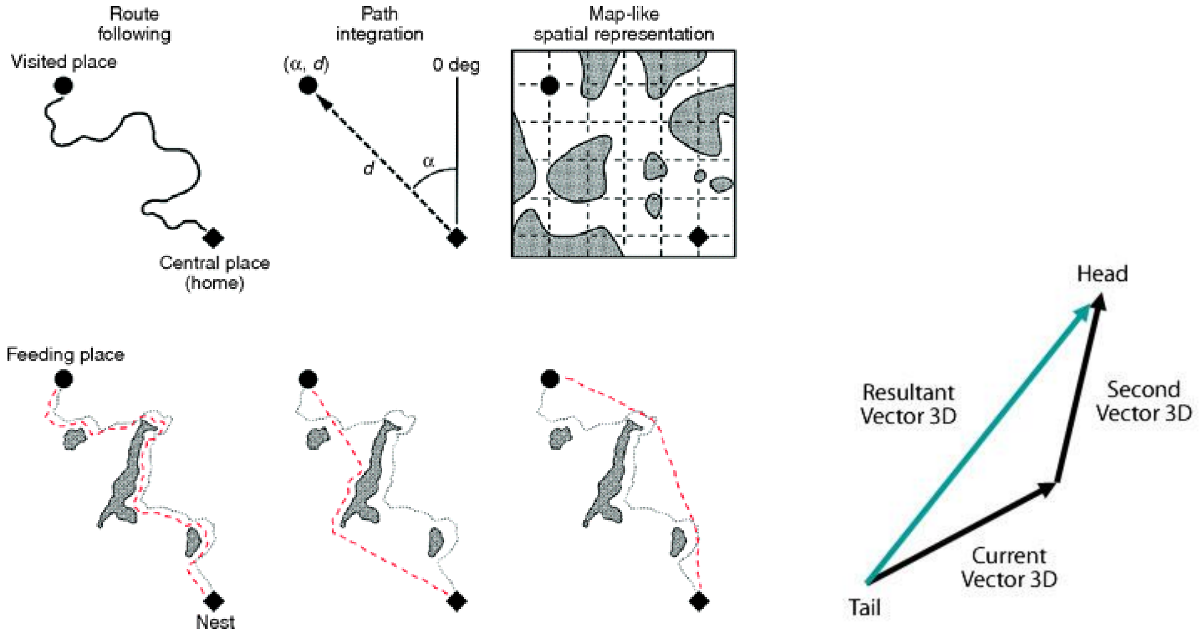

Figure 2. Path Integration

This calculation, which includes distance and angle information, is performed throughout the ant's explorative journey allowing it to simply follow the vector back to the nest when it is has completed foraging (Hölldobler & Wilson, 1990). While this compiled data allows the ant to estimate the approximate location of the nest, compounded errors along the journey lead to errors in exact nest location. To account for this, upon reaching the theoretical nest location, the ant will begin to utilize the Bayesian target search model to locate the nest entrance using concentric circles (Vickerstaff & Merkle, 2012).

Problem Description

The problem is not to discover novel sources of environmental hazards, but to rapidly survey the variation of contamination levels over a hazardous area. At the current time, autonomous and radio-controlled robotic technologies for disaster response are expensive, besides being large and unwieldy (Blown Up iRobot PackBots Get Resurrected In Iraq, 2009). In addition, existing solutions usually suffer from limited or unstable means of locomotion, often making them unreliable or ineffective in debris-filled disaster zones. While improvements in these technologies are in development and will likely make such designs much more affordable and reliable in the future, their uses are currently limited. One way of looking at these problems is that they are problems of design philosophy, in that a single, consolidated automaton performing all desired tasks may not always be best suited to a given situation. It is readily conceivable, especially upon observing the behavior of swarm insects, that a large number of small, low-cost robots could effectively replace a single, large robot, especially in cases where there is no particular need to carry out a mechanical action - e.g. lifting, pushing, twisting, etc. Sensing, a function that can be carried out by an autonomous device, presents a significant problem that often requires none of these mechanical actions. Therefore, the use of distributed, small-automaton sensing has potential as a major improvement over current large robots with sensing components.

A specific example of a sensing problem where robots are used is in the detection and mapping of hazardous radiation and chemicals in the wake of accidents and disasters (Greenemeier, 2011). In the immediate aftermath of a nuclear site disaster, for example, the collective response agencies must begin immediately to characterize the location of radiation sources, in order to minimize human exposure to them and to ensure their disposal. While a number of airborne technologies exist to survey and broadly map radiation in an emergency scenario (US Department of Energy), U.S. government response plans still incorporate the use of handheld radiation detectors to identify the location of smaller-scale sources and ensure comprehensive cleanup (US Department of Energy). Because these devices are held by human response workers, these workers are subject to the effects of the radiation the sources emit. It would therefore be of great benefit to radiation response efforts to eliminate or minimize the need for such handheld devices. Current robots designed for radiation detection do exist for this purpose, though as mentioned previously, they are large, slow and expensive. In most cases, they are also remote controlled, meaning that they require a skilled operator with full knowledge of the device's capabilities (Guizzo E. , 2011).

Overall, the activity of chemical and radiation source sensing reveals the potential for improvements in automation, mobility, cost effectiveness, and reliability, and provides a motivation for combining these improvements into a single system. Even more specifically, the challenge of making a small, cheap robot an automaton is a difficult one. Many current self-navigating robot designs rely on complicated sensor packages, or else have limited navigational ability (iRobot's New SUGV Robot Can Drive Itself with 3D Laser Vision, 2010). Their navigation functions are too expensive in terms of hardware or computation to make them practical at a small scale. The ability to downsize navigation equipment and use it cheaply and without expending excessive energy opens the door to small, self-navigating robots suited to the purposes described above, and no doubt to many more as well. This technology could also be simply repurposed for non-hazardous situations where interested ecologists can rapidly survey for other environmental factors, like moisture content.

Analogy

Desert ants accomplish foraging with two separate control schemas, a randomized search and a directed return, but use only one method of locomotion for both phases. Our design separates the exploration and retrieval in terms of behavior and locomotion in order to optimize each process for our specific domain.

The current problem centers on making efficient, quick, and reliable measurements of an area to quickly understand threat levels without risking human health and safety. Desert ants randomly forage for food while constantly taking note of an environmental constant (the Sun), enabling them to maintain a "home vector" that points to the nest. This measurement is hardcoded in its biology via a neural template, so no complex algorithms or comprehension are needed on the part of the ants. The beauty of the ants' mechanism is in its ability to reduce exposure time to the extreme heat of the desert and cut total foraging time, thus reducing energy expenditure. By mimicking the ants' cheap and fast navigation techniques and behaviors, we can quickly and effectively deploy a system to collect large amount of information about an area in a relatively short amount of time, without risking safety or large sums of money. The system may not be as capable as highly specialized and expensive robots in terms of versatility, but would serve well as a first response survey for a large area, due to its scalability in terms of numbers which comes from each individual unit being almost disposable, yet capable of being reused several times. Deploying hundreds of cheap robots would cover more ground than two or three expensive robots.

Deserts ants are, however, not a perfect analogy for the design problem of detecting radiation in disaster areas. Detecting concentrations of radiation is a difficult task due to the danger of radiation exposure. It requires sensors or components that can detect how many alpha-particles/beta-particles/photons/etc. are in the area. Although ants can see polarized sunlight with their ocelli, they are not able to detect radiation. They can form low-resolution images of its surroundings, and keep track of its location by registering patterns of polarized light in the sky. In disaster situations, collecting information as fast as possible is very important. Having real-time data is crucial, and requires expensive communications equipment on the people or robots that are surveying in the field. In contrast, the ant-inspired system has no way of obtaining the information from any single unit until the unit has returned safely to the base. Similarly, desert ants have no mechanism to contact the nest until they return home. This aspect of our design prevents the researchers from understanding the situation until several minutes after deployment when most of the ants have returned home. Ants can quickly cover a wide area, and return home with valuable information much more quickly than robots or humans could cover the same area. However robots and humans can provide real-time data, which may be more beneficial in targeted surveys of a specific location that demands information. If, for some reason, none or very few of the units return to the base, the entire effort is wasted because the information is impossible to retrieve. However, the redundancy of the design makes this occurrence very unlikely.

Design

Mechanistic Explanation

Some challenges associated with the environment of a contamination site include difficult terrain, mechanical corrosion from chemicals, or potential damage to electronic equipment due to high levels of radiation. These challenges factor into high expense for autonomous devices deployed at the disaster site to collect samples. Typical surveying robots can cost several hundreds of thousands of dollars. To circumvent this problem, the designers of PascoBot envisioned a system of hundreds or even thousands of cheap, tiny sensors which could be rapidly dispersed over a large contaminated area, and then autonomously find their way back to deliver spatialized data to researchers awaiting in safe zones. The speed of the survey would enable the robots to return before their electronics could be corrupted. Their individual inexpensiveness means that no great loss is incurred if a small percentage of the fleet is lost or destroyed.

PascoBot is a biologically inspired, behavioral system for quickly scanning a broad region for contaminants. The system's goal is to perform a rapid survey of potentially contaminated areas that could be too dangerous for sending in humans, and need to be surveyed faster than larger robots could manage. The more quickly information can be gathered and analyzed about the environmental contamination, the more safely and effectively it can be addressed. Each PascoBot unit is a small, inexpensive sensing robot which uses the sun's polarization and a very simple algorithm to determine its direction and distance home. Groups of PascoBots operate as first-response tools in the environment of a recent radiological or chemical disaster. Part of the beauty of the Pascobots' design is that they reduce their cost, and heaviness by eliminating communication structures between units. Instead they only communicate passively with the active collector base. Structurally, a PascoBot unit contains the following components and sensors:

- A self-stabilized flying machine based-upon existing hardware
    - Accelerometer
    - Gyroscopic sensors
- UV photo-sensing diodes with directionally polarized filters (for navigation)
- Bottom mounted IR sensors (short-range navigation at home base)
- Specific Environmental Sensor (Radiation, Volatile Organic Compounds, etc.)
- Inexpensive Microcontroller (about $2.50 each)
- Inductor for passing information from microcontroller to RFID-reader

The system includes two additional devices that supplement the function of the flying autonomous sensors. A rapid delivery rocket is the disposable launch vehicle which carries a "team" of PascoBots into affected areas. A homing cradle provides a corrective, short-range navigational beacon which collects individual robots and synthesizes full contamination maps based off their data. The roles of these two components will be further discussed below.

A mapping device utilizing a few, simple environmental cues can be much smaller and cheaper than current robotic technologies which are either individually remotely controlled by skilled operators or use advanced cameras and processors for self-navigation. This behavior rather than a physical mechanism is the novel function which we would like to implement within existing inexpensive robotics. Since our design team hopes to use an existing physical blueprint or small flying robot, the physical mechanisms of flight will not be discussed here in detail, but an example of one such device, modeled by researchers at the University of Maryland from Samara seed physics, is shown in **Figure 2**. The remote-control mechanism in these existing devices will be replaced in PascoBot's design with a basic microprocessor which can perform the simple navigation algorithm without any human input. The PascoBot conceptualization is shown in **Figures 3 and 4**. Its behavior-based navigation function can be decomposed into two sub-functions, launch and retrieval.

Figure 3. Small Winged Robot (Salton, 2009).

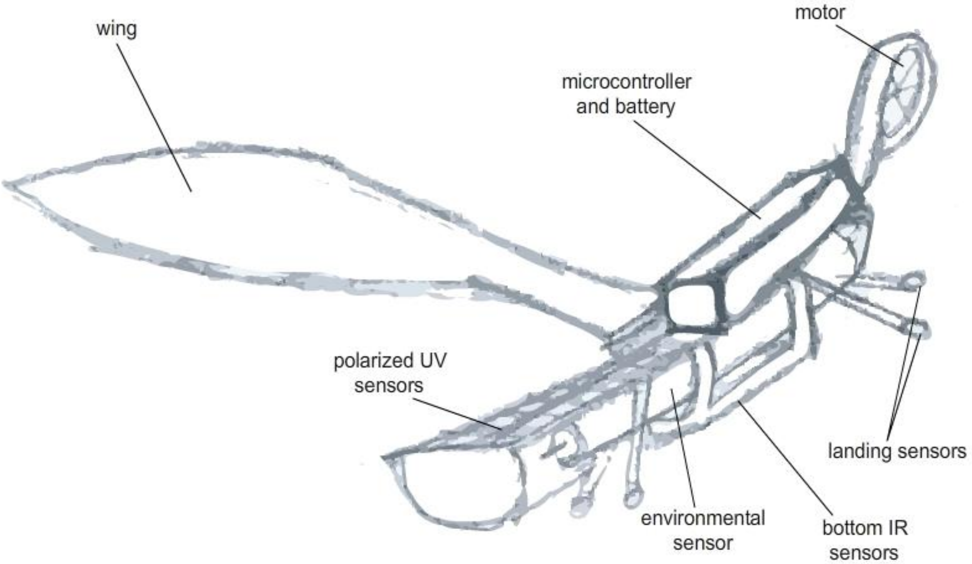

Figure 4. PascoBot Detail

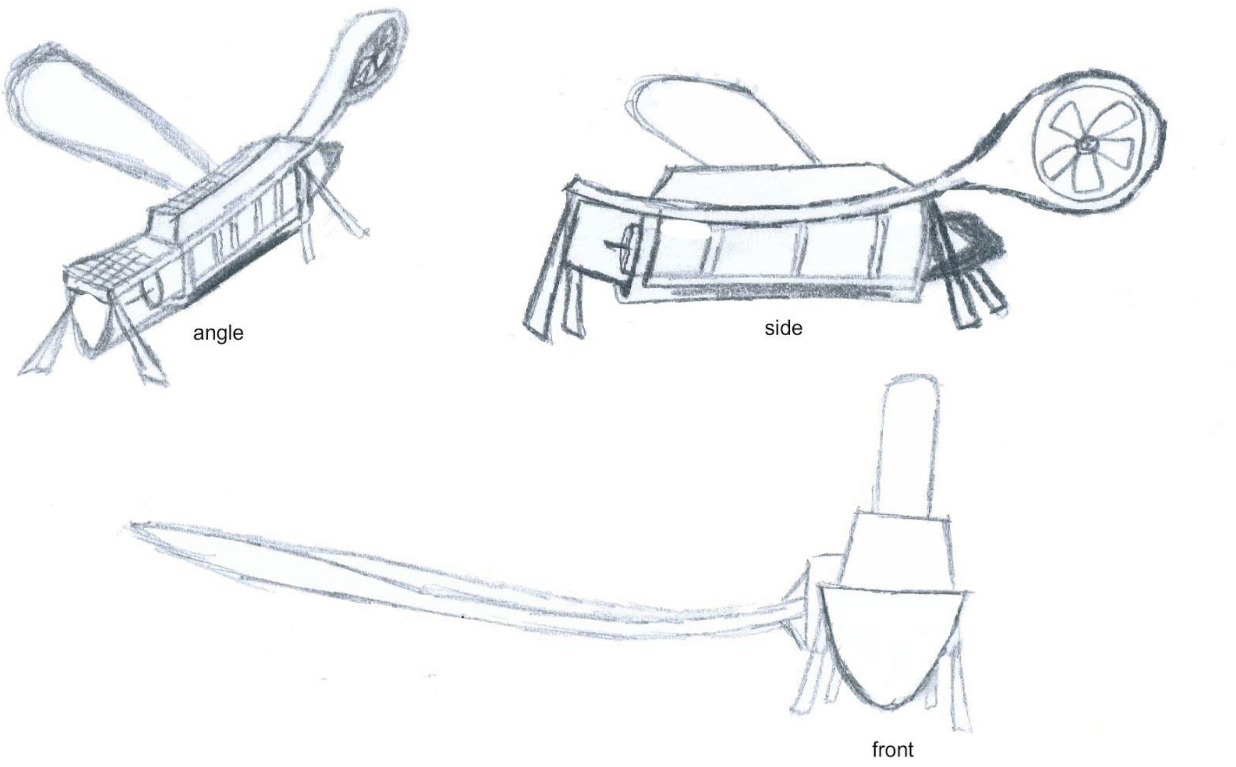

Figure 5. PascoBot Views

In the launch phase, a pack of PascoBots loaded into a rapid-delivery rocket is aimed towards the target zone by a researcher stationed on the perimeter. This allows the human to specifically target areas for exploration using simple trajectory calculations, rather than allowing the robot swarms to randomly scatter in all directions. The rocket, modeled after inexpensive hobby model rockets, is little more than an engine connected to a cargo tube, but with the same simplified navigational sensors and processor as in the PascoBots themselves. As the rocket flies through the air towards the peak of the trajectory, it records its position and orientation and passes this information to each individual PascoBot via the RFID technology embedded in each unit. Like a model rocket, the engine triggers the release of the PascoBots at the peak of flight, scattering them over the affected area. From this point, each PascoBot operates independently and autonomously. The rocket vehicle itself is considered a disposable, one-time-use device.

In the dispersion phase, assuming the design team could obtain rights to the University of Maryland's samara-inspired robot, the PascoBots would spiral safely towards the earth and spread themselves out from each other. Most foraging robots explore actively using powered locomotion and employing algorithms like the Rapidly-expanding Random Tree (Sanchez, 2010), but this requires additional communication, sensor devices, and battery power. Instead PascoBot replaces active exploration with a more efficient, fully passive mechanism. Our Pascobots capitalize on the randomness of wind currents and turbulence to automatically distribute themselves over an area. During the launch and random dispersion periods, the polarized light sensors are intermittently collecting data to maintain knowledge of their orientation and distance from home and ultimately perform the ant-like calculations to return to the base. They are simultaneously collecting the target environmental contamination data and mapping this to distinct points in their internal maps.

In the retrieval phase, the robot touches down on the ground and a pulse in its accelerometer triggers the robot to switch behaviors from the passive “exploration” mode to the active “homing” mode. Its motors are activated, and the PascoBot follows a simple subroutine, flying itself towards the homing vector that it had been continuously calculating all along. It continues collecting and mapping information concerning the contaminants as it returns to the base.

Simple navigational calculations such as these are bound to develop small, accruing errors during the robots’ flights. This is partially the motivation for reducing the length of time spent in the “exploration” period. As a simple corrective measure, the base station has a large IR flood lamp pointing upwards. This serves as a broad “collection net” for passing PascoBots to more precisely home in. Two spatially separated infrared (IR) sensors located on the bottom of the robot trigger the robot into collection mode once the IR readings reach a certain threshold. From there, they move in the direction of higher reading until they safely land within the collection container. This collection container reads the collected data from all of the returned PascoBots via RFID, and finally a single pre-programmed computer processes the data to generate a three-dimensional map showing the contamination variations over the area. The entire process is summarized in **Figure 5**.

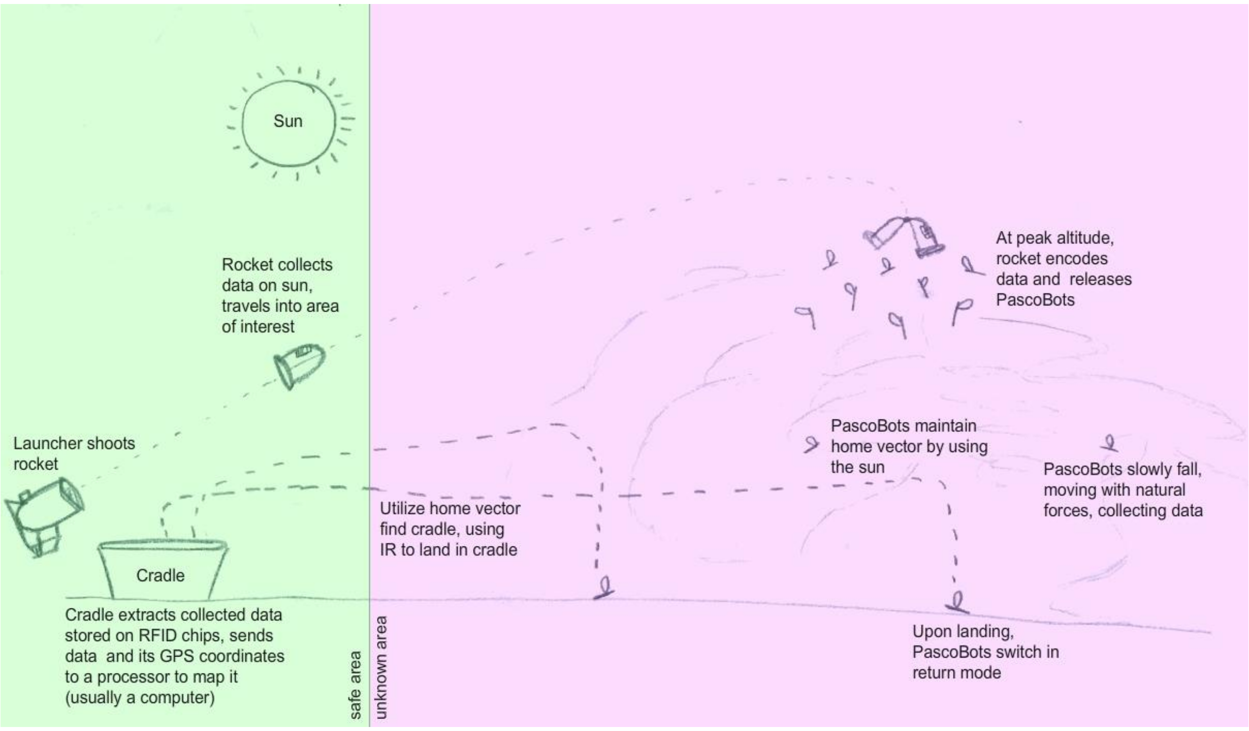

Figure 6. PascoBot System Operation

Quantitative Assessment

For our concept, we have provided sample “pseudo-code” which demonstrates the efficiency and functionality of the programming needed for our robots.

```
---Foraging Pseudo Code---
setup(){
    isDormant = true;
    isExploring = true;
    distanceToHome = 0;
    gotoCollector = false;
}
loop(){
    getSensorReadings();
    if(gotoCollector){
        movetoCollector();
    }
    else{
        if(accel>landingThreshold){
            isExploring = false;
        }
        if(isExploring){
            calculateHomingVector();
            moveExploratoryStep();
        }
        else{
            followVectorHome();
        }
    }
}

calculateHomingVector(){
    $Homing\ Vector = 180^\circ - \frac{\int_0^{Exploration\ Time} Orientation\ away\ from\ Sun}{Exploration\ Time}$
}

followVectorHome(){
    moveinDirection(AngleHome);
    distanceToHome --;
    if(distanceToHome <0 ){
        gotoCollector = true;
    }
}
movetoCollector(){
    calculateIRDirection();
    moveinDirection(IRDirection);
    if(IRSensor>collectorThreshold){
        stop();
    }
```

```
}
```

Comparative Mapping Speed

The overarching goal of the PascoBots system is to keep humans safe and map a three-dimensional region as quickly as possible. Like any real-world system, the robot swarms will be prone to error and corruption, but through speed and redundancy, they can provide highly accurate readings in comparatively shorter periods of time.

Assumptions

- The navigational basis (location of polarization of sunlight) will be considered constant, due to relatively short total operation time
- A heavy model rocket can travel around 100 km/Hour (60 mph)
- A heavy model rocket can carry 40 Pascobots
- A heavy model rocket can travel at least 4 km
- The PascoBots can disperse randomly over a 1 km radius
- It takes PascoBots 5 minutes to fall to the ground
- A person can walk around 4 Km/Hour (2.5 mph)
- A unicopter can cover a distance of about 2 km/Hour (1.24 mph)
- A contamination zone of unknown significance has a 3 km radius
- The Pascobot stations require only two human operators

Using these assumptions, we can test the validity of our design by comparing it to currently available alternatives (manual sensing by humans). Once a disaster occurs, we will assume for the calculation purposes that both a team of human sweepers and the PascoBot system take the same amount of time to set up at the perimeter of the catastrophe, although we anticipate faster deployment with the PascoBot as well. The goal is to compare the speed with which each team can survey the 3km zone and the resolution of the data collected. In our simulation, five PascoBot stations (each with five rockets carrying a total of 200 PascoBots) set up on the perimeter, and 100 human sweepers were prepared. Each PascoBot unit or human sweeps an area 1 square meter wide. The total area of potential contamination is $\pi*(3{,}000\text{ m})^2 = 28.3$ million square meters. The perimeter is 18 kilometers, and the human sweepers are spaced 180 meters apart. This can be visualized in **Figure 6**.

Human Method

A single human walks towards the center of the zone and back. This round trip takes 48 minutes and covers that individual's 1% segment of the total circle. A unique 2 meter wide area is scanned by this individual. This is an area of 2 meters*3000 meters, or 6000 square meters. The total area scanned by all 100 humans will be 600,000 square meters. Thus the resolution of the area scanned by a single human is

$$\frac{area\ scanned}{total\ area} = \frac{6000\ m^2}{0.01 \times 28.3(10^6)m^2} = \sim 2\%\ sample\ rate$$

Therefore, with all workers moving simultaneously, full coverage of the area can occur in 48 minutes but with a sampling resolution of only 2- 2.5% per hour. A total of 80 man-hours are required and 100 humans were subjected to high levels of potential danger.

PascoBot System

A single rocket carrying 40 robots is launched 4 kilometers to a point over the center of the contaminated area. This takes only 2.4 minutes. Another five minutes pass as the units fall from the launch vehicle and sample the environment during their passive falling. It then takes each PascoBot an average of 120 minutes to return home. Thus the average sampling time for a packet of PascoBots is 120+2.4+5 = 127.4 minutes. The operators can launch all 5 rockets from the same base one almost immediately after the other. If the delay between rocket firings is conservatively 2 minutes, all 1000 Pascobots will have surveyed the area in about 127.4+2*4 = 135.4 minutes. During this time the total area swept will be about 1000 units * 1 meter * 4 kilometers = 4 million square meters. This gives a spatial resolution of 4 million m^2 / 28.3 million m^2, or 14% sample rate per meter.

Though our robots are small, some overlap may occur due to randomness, so we can conservatively estimate that 5% of our data will be redundant. We can also anticipate that another 5% will be lost due to unrecovered or damaged units. Thus our effective swept area is reduced 10% to 3.6 million square meters, which still yields a 12.6% sample rate, divided by the total time produces 5.6% resolution obtained per hour, more than double the generously estimated 2.5% obtained with the human method. The entire PascoBot process requires only 135.4 minutes * 2 operators * 5 stations = 22.5 man-hours, compared to 80 man-hours with the human method, and additionally the PascoBot system avoids the risk to human health.

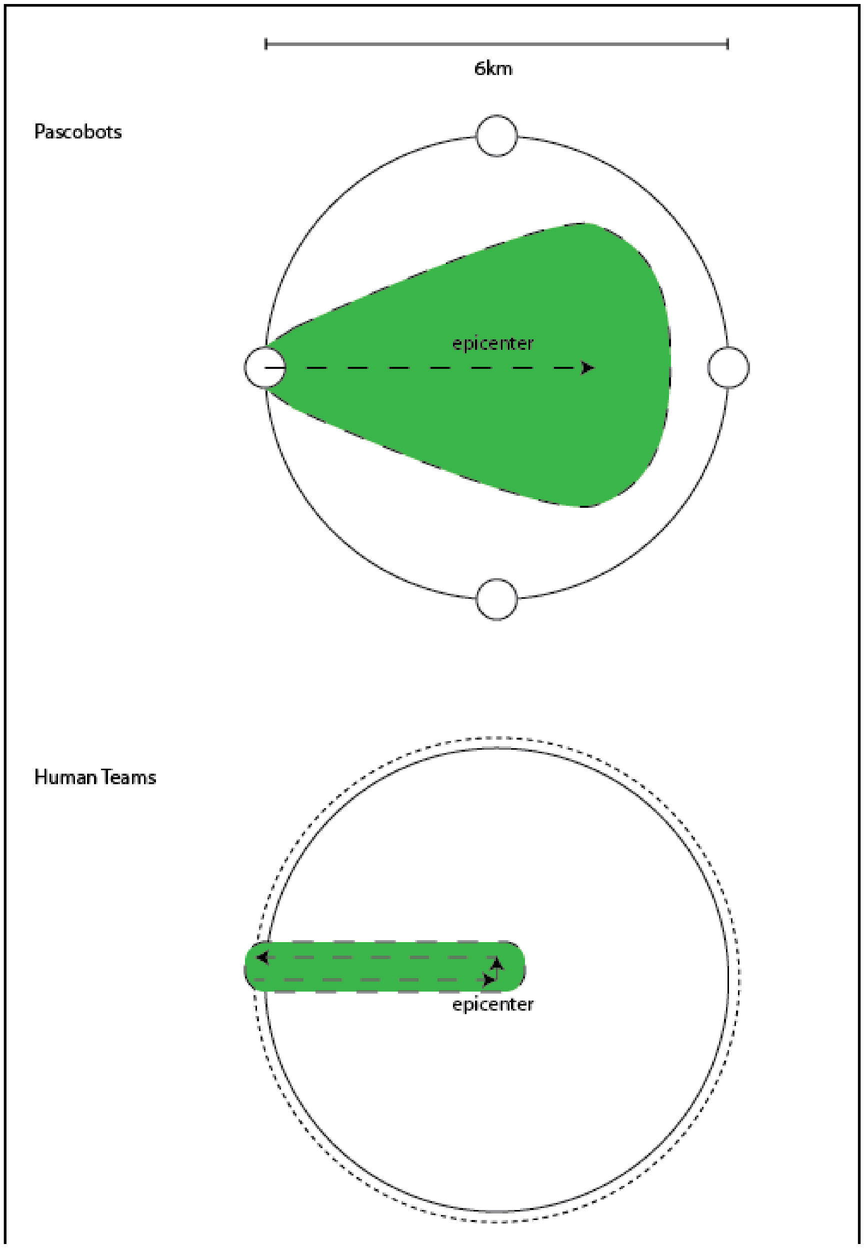

Figure 7. Comparing the Human vs. PascoBot Sweeping Methods

Map Synthesis

Since the Pascobots do not possess a GPS tracker of their own, each of the Pascobots can return with a only a relative map of the area it has surveyed. This relative map gives coordinates based on the common starting point at the base station. Before launch, the base station collector, which is equipped with a GPS device, encodes all the Pascobots launching from this point with the same GPS location. Basing their original position off this global coordinate lets each Pascobot's relative map acheive absolute status in the world. Then once the robots have returned to the collector, a full survey of all the absolutely mapped data from each bot can be automatically collected and synthesized instantly. This gives the humans, who are using continuous GPS readings throughout their mappings, no comparative advantage over the robotic system.

Transfer Challenges

Because our design's inspiration from ants is primarily behavioral, scaling concerns are not relevant. The inspired behaviors, including foraging and the solar navigation method, scale to larger systems such as ours without a problem. However, scaling issues do exist from the perspective that our robots must be made small enough so that they are portable/ deployable in mass quantities and can be manufactured relatively inexpensively. For this reason, we have compared the components of our system to comparable existing components on the open market, in order to prove that our design is feasible. If we assume that wholesale prices are approximately 10% lower than retail prices advertised online, it is easily conceivable that our design could be constructed for less than $100 per unit. The launch units and collection system would cost a fraction of the price for a group of individual autonomous units themselves, due to those components' limited number of electronic parts. Overall, a complete system consisting of 5 rockets with 40 robots each, and including the launch and recovery devices, would probably cost between $50,000 and $100,000, with most components being recoverable and reusable. Of course, other factors stand in the way of our design being a complete answer to the problems posed by radiation detection, such as the means of "re-arming" the robots after being launched, for a second use. A marketable product would require further testing refinement.

Value

PascoBot is designed for speed, material and energy efficiency, redundancy, durability, and simplified navigation. The designers of PascoBot wanted to create an affordable, easy-to-use rapid-response system to determine the severity of the situation immediately after a hazardous materials disaster. The system accomplishes this more effectively than large, conventional robots on many levels. While large robots may take hours or even days to sweep an area for samples, depending on the number deployed (which can multiply the cost), the PascoBots can be launched and return to the "nest" within a matter of minutes. This could have profound implications for disaster response efforts. PascoBot is also superior to conventional robotics in its overall low cost. Low materials cost from simple devices and energy needs barely demanding a small battery per unit make the system as a whole perhaps a fraction of the cost of one of its more "advanced" cousins. Additionally, redundancy ensures that if some units fail or become damaged in the field, the rest of the system is still fully functional, the data collection is not compromised, and the financial cost of the loss is negligible. Of course, the designers anticipate that each device will be reliable and durable enough to prevent such losses in most cases, since the rapid ant-inspired return mechanism prevents damage to the sensors from prolonged exposure to corrosive or radioactive substances. Each unit should therefore be reusable for many cycles, as opposed to a single $60,000 robot which may become useless after just 4 hours at a single disaster site.

Reflections (Extra Credit)

In our design team, the engineers were impressed by the ant's ability to perform what is essentially vector mathematics using hard-coded neural templates. Vector math is difficult for most humans to perform without drawing out the vectors, but the desert ants' specialized pattern of sensors enables them to calculate the home vector instantly. The biologist's reaction to the quantification approaches was that a system which could integrate the biological function with the technological need without any scaling complications is an efficient design that uses the best of both worlds.

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