Conceptual design of Ant Colony-like Robot System for Geology Exploration

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Abstract

Enlightened by ant's sophisticated movement and robust group communication, this paper will discussed a specific robotic system which is made of each ant-like robot. Generally speaking, an individual robot has the capability to completing complicated movements such as climbing vertical wall and collecting the geological data through the sensors installed on robot. Besides that, this group of robots resembles the working mechanism of ant colony which is desirable to achieving high efficient communication. With help of single ability and group work, this kind of robotic system longs for improving present calibrating precision of geological feature like inner construction of rock caves or tundra. In order to attain this goal, this paper mainly split into two parts: individual structure, optimization algorithm for group working. As for structural discussing, ant-like robot from Festo far outweighed the advantages of other hexapod designs due to its flexibility and stability. But this type of ant robot still lack the climbing skills which is required in working circumstance. Therefore, a assumption that climbing feature obtained via acquiring fruit fly habit added to Bionic Ant is made. Compared with structural design, the application of algorithms to communication seems to be more strenuous. Ant Colony Optimization and swarm intelligence is attempted to applied into process of coordinating each robot's work. Firstly, the ACO is utilized in allocation of multi-robot system. Secondly, ACO provides a strong support for path planning of each mobile robot. Finally, this paper introduced a energy-efficient ant-based routing algorithms (EEABR) for Wireless Sensor Networks (WSN).
Keywords: Bionic Ant, Ant Colony Optimization (ACO), Path planning, Wireless Sensor Network.

1 Origination of idea

1.1 Blend of robot and ant-colony optimization

Dating back to childhood, one might have interest and experience in observing the behavior of ant colony especially searching for shelters during rainy days and transporting food. Like most group living animals, ants do have their own special communication method which combined with using pheromones, sounds, and touch. Unique biological structure of antenna and complicated ways of exchanging information constructs the foundation of time-saving communication. After several entomologists unveiled the mask ant colony living habits, an increasing number of economists, programmers, robot designers, communication experts started to paid more attention to recondite working principle behind this magic colony.

Robot designers attracted by each individual (ant) structure since various types of ant are able to accomplish almost every single action like climbing, waking, lifting, and even flying. Many hexapods robots are biologically inspired by Hexapod locomotion, they can move and climb stairs. For communication specialists, every ant resembles an dependent radio sender and receiver and then they consists of an entire communication nest which possessed satisfied efficiency and stability of information interchanging.

As for computer scientists, ant colony optimization (ACO) is a probabilistic technique for resolving computational problems which shortened to find the optimal paths through graphs. The application of ACO can be dated back to research in cellular robotic system from Gerardo Beni and Jing Wang.[1]

Actually, a large number of hazardous works needed unmanned labor to substitute like mining exploration and chemical gas test. Imagine a scenario geologists need to explore an unknown cave which satellite is merely capable of finishing small part of calibration. This time a system merged above advantages will resolved this deadlock.

Therefore, with the assumption that there are plenty of hexapods behaves like ant-colony and they are highly autonomous to achieve complex movement and communication of ant colony, it is rational to devise a robotic system build on ACO to calibrate complicated terrain which traditional methods are unable to finish.

1.2 Organization of paper

The paper began with a brief introduction to central idea of devising this robotic system conceptually. Then, a description of physical structure of ant-like robot will be elaborated with numerical existed models and also some compound movements based on specific structure will be discussed.

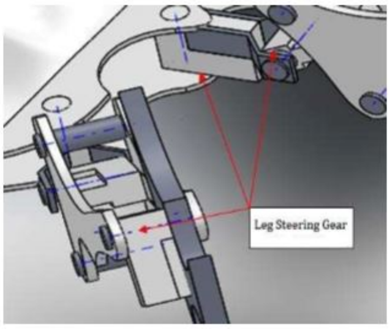
In the next section, ant colony algorithms was introduced to explain the communication principle resided in information nest constituted by group of ant-like robots and then this paper will take a great consideration of ant colony optimization into account. Finally, a concise conclusion of this robotic system will be presented.

2 Ant-like robot structure and movement

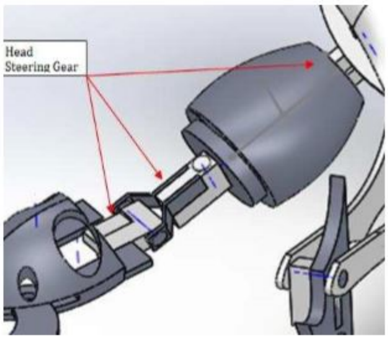
2.1 Hexapod structure

Robot researchers have seldom reduced their passion in developing high biomimetic robots. One of their main goal is to imitate a small simulated robot's physiological form, behavioral action and instinctive habits through production research, so as to explore new ideas and algorithm. Hence, the prerequisites of designing an ant-like robot is to analyze ant physiological structure and movement rule.
The rapid development in robotic system has intensely augmented working efficiency, decreased a product's manufacturing hours. For special working places which workers have no access, the use of intelligent flexible high biomimetic robot has made the environmental detection and rescue participation possible.
Compared with high developed robots such as mechanical arms, unmanned aerial vehicles and wheeled robots, the high biomimetic robots are still to be developed.
However, due to complex biological form of ant, it is hard to implement the existing control algorithm, resulting in high biomimetic robot's difficulty in practical activities. With this designing idea, Fantao Fang, Rui Pan[2] *et al* has provided a fuzzy model of ant's movement rules and following figures showed their work.

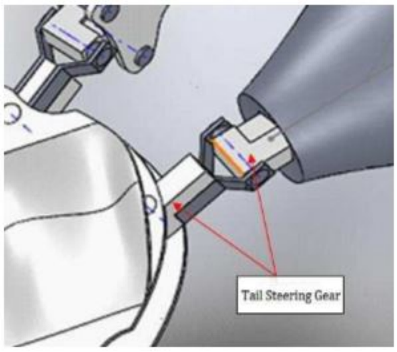
(a) Overall biomimetic Ant robot



(b) Connection between leg and body



(c) Connection between head and body



(d) Connection between tail and body

Figure 1: Shape design of ant-like robot

The sub-figures from (b) to (d) presented steering gear between legs, head, tail and body. According to Fang's paper, this ant robot required four basic sensors: GPS Positioning, Infrared Sensor, Photosensor, Depth Camera. The infrared hear sensor is used to intimate ant's physical characteristics against the heat sensitivity.
The whole designing of circuit peripheral equipment based on that four sensors sent signal to processor, then data from processor transported to PC station through wireless network. The wireless module can monitor various movement indicators of ant robot through PC, manually participate in correcting the robot's posture during training the ant robot, and monitor the ant's movement via PC during the robot's independent working period.
Above design, to a certain degree, was a fundamental ant-like robot which manages to emulate some characteristics of ant. Nevertheless, they lacks of enough locomotion, ability to reach the goal of exploring intricate terrain, cave etc. Therefore, the next subsection will introduce a powerful, stable hexapod robot from Festo.

2.2 BionicANTs

One reason to depend on this special type of ant-like robot is that bionic ants are responsible to cooperative behavior based on a natural model. Another main reason is that bionic ants are made up of a highly integrated individual systems to solve a common task.
Like their natural role models, the BionicANTs work together under clear rules. They communicate with each other and coordinate both their actions and movements. Each ant makes its decisions autonomously, but in doing so is always subordinate to the common objective and thereby plays its part towards solving the task in hand.
For the first time, laser-sintered components are subsequently embellished with visible conductor structures in the so-called 3D MID process. The electrical circuits are attached on the surface of the components, which thereby take on design and electrical functions at the same time. In this way, all the technical components can be fitted into or on the ant's body and be exactly coordinated with each other.
After being put into operation , an external control system is no longer required. It is possible, however, to monitor all the parameters wirelessly and to make a regulating intervention. Festo also makes use of benefits of piezo technology for the legs on the artificial ants. Piezo elements can be controlled very precisely and quickly. They require little energy, are almost wear-resistant and do not need much space. Three trimorphic piezo-ceramic bending transducers, which serve both as an actuators and a design element, are therefore fitted into each thigh.
By deflecting the top bending transducer, the ant lifts its leg. With the pair underneath, each leg can be exactly deflected forwards and backwards. To increase the relatively low lift, the team developed a flexible hinge joint, which extends the ant's step size significantly. The following figure shows a basic structure of BionicAnts.

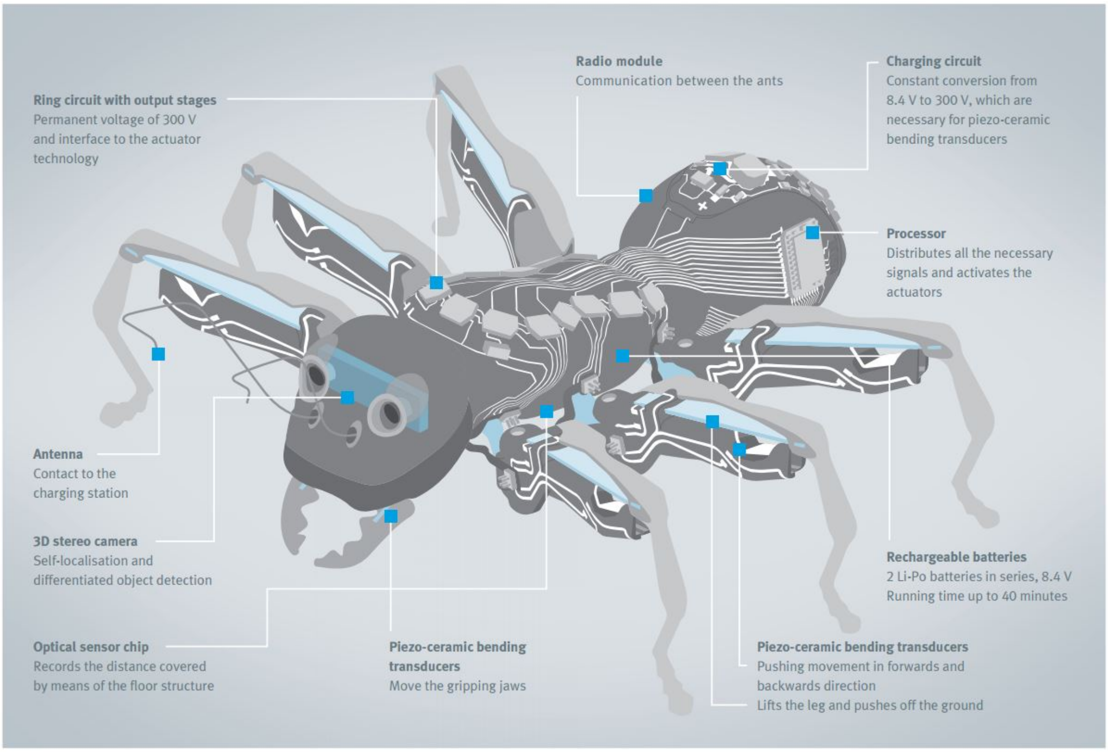


Figure 2: BionicAnts from Festo

BionicAnts develops a highly complex control algoriphms for cooperative behavior. With two rechargeable batteries on board, the ants can work for 40 minutes before they have to link up with a charging station via their feelers. All actions are based on a distributed set of rules, which have been worked out in advance using mathematical modeling and simulations and stored on every ant. The control strategy provides for a multi-agent system in which the participants are note hierarchically ordered.
Instead, all the BionicAnts contribute to the process of finding a solution together by means of distributed intelligence. The information exchange between the ants required for this takes place via the radio module located in the torso.
The ants use the 3D stereo camera in their head to identify the gripping object as well as for self-localistation purposes. With its help, each ant is able to contextualize itself in its environment using landmarks. The opto-electrical sensor in the abdomen uses the floor structure to tell how the ant is moving in relation to the ground. With both systems combined, each ant knows its position - even if its sight is temporary impaired.
The bodies of the BionicANTs are also made of polyamide powder, which is melted layer by layer with a laser. Selective Laser Sintering (SLS) is an additive manufacturing technique for Bionic Ant.
3D Moulded Interconnect Devices feature spatial conductive tracks, which are visibly attached to the surface of shaped parts and act as circuit boards for electronic and mechatronic subassemblies. The following is an tabular to indicate the basic data of

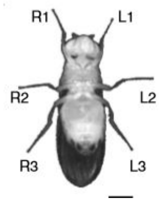
Bionic Ant:

Table 1. Technical data for Bionic Ants

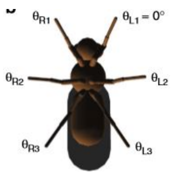
Length	135 mm
Height	43 mm
Width	105 g
Step size	10 mm
Material,body and legs	polyamide, laser-sintered
Mterial, feelers	spring steel
3D MID	laser structuring and gold plating by Lasermicronics
Actuator technology, gripper	2 trimorphic piezo-ceramic
Actuator technology, legs	18 trimorphic piezo-ceramic ,bending transducers (32.5×1.9×0.7 mm)
Stereo camera	Micro Air Vehicle (MAV) lab of the Delft University of Technology
Radio module	JNtec
Opto-electrical sensor	ADNS-2080 by Avago Technologies
Processor	Cortex M4
Rechargeable batteries	380 mAh Li-Po batteries in series, 8.4 V

2.3 Climbing feature

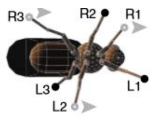
Even though Bionic Ants is stable and powerful, climbing steep terrain or wall of cave might still impede this type of ant-like robot to achieve the core goal mentioned in this paper. So this section will concentrate on the research of climbing features for robots. Most insects use a tripod gait that maintains at least three legs on the ground at any given time to escape danger or catch prey. Indeed, the tripod gait emerges to the exclusion of many other possible gaits when optimizing fast upward climbing with leg adhesion. Pavan Ramdya, Robin Thandiakal[3] *et al* in their paper put that the requirement to climb vertical terrain may drive the prevalence of the tripod gait over faster alternative gaits with minimal ground contact.
Climbing feature was aimed to design a physics-based insect model but minimized its complexity to reduce the computational cost of gait optimization. For similar articles, they used the simulation engine, Webot[4] to build a model based on the morphology and leg kinematics which showed in figure 3.
In this model, a vector of five numbers encodes a single gait: each number represents a single leg's phase of motion relative the left front leg. For example, the simplest way to generate a tripod gait is to fix the front left (θ_{L1}), middle right (θ_{R2}), and rear left (θ_{L3}) legs at a phase of 0° while setting the remaining three legs to a phase of 180°.



(a) A ventral view with six legs



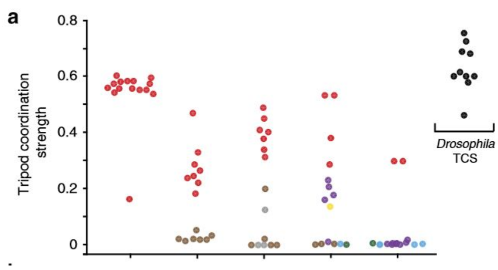
(b) Leg phases



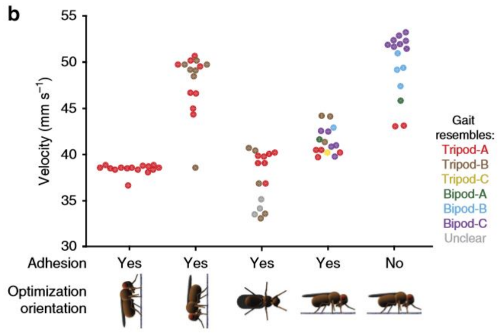
(c) Tripod status

Figure 3: Simulation model based on fruit fly

Tripod gaits are optimal for fast climbing with leg adhesion. Gait discovered as optimal for upward climbing using leg adhesion had high Tripod Coordinate Strength (TCS, functionally similar to the quantification used in Wosnitza[5] paper) Figure 4(a) indicating that their footfall diagram resemble that of the classic tripod gait while Figure 4 (b) indicates tripod gait possesses the most stable and fastest climbing status.



(a) TCS values



(b) Velocity

Figure 4: Climbing comparison between bipod and tripod

A bi-pod gait is faster than the tripod gait in a robot. In Floreano's findings can be sensitive to simulation conditions and may fail to capture the complexities of the physical world[6]. As it is not yet possible to genetically programmed insect leg coordination, we used a hexapod robot to validate finding that bi-pod locomotion is faster than tripod locomotion.

A test based on hexapod robot (57 cm long from front leg tip to rear tip at at full leg

extension and weights 1.9 kg) conducted this climbing experiment. This robot is quite different the ant model since it is much larger and lacks ahead, abdomen, and several leg segments. However, as morphologically diverse insects have similar footfall patterns and all these changes might be robust to morphological differences in experiments.
To compute this mapping between the robot and ant model , a Python script is needed here to measure the joint angles of the model through time. With known angles and segment lengths of ant model. The leg tip positions in their plane of motion by solving below equation:

$$x = a \cdot cos(\alpha) + b \cdot cos(\alpha + \beta) + c \cdot cos(\alpha + \beta + \gamma) + d \cdot (\alpha + \beta + \gamma + \epsilon) \quad (1)$$

$$y = a \cdot cos(\alpha) + b \cdot cos(\alpha + \beta) + c \cdot cos(\alpha + \beta + \gamma) + d \cdot (\alpha + \beta + \gamma + \epsilon) \quad (2)$$

where a, b, c and d are the lengths of the model's leg segments (proximal to distal) and $\alpha, \beta, \gamma, \epsilon$ are their respective joint angles. Using these data is to find the angles λ, σ that will place the tips of the robot's leg in the same position (x_1, y_1) as model's leg. To solve equations:

$$x = e \cdot cos(\lambda) + f \cdot cos(\lambda + \sigma) \quad (3)$$

$$y = e \cdot cos(\lambda) + f \cdot cos(\lambda + \sigma) \quad (4)$$

where e, f are the lengths of the robot's leg segments (proximal to distal), and λ, σ are their respective joint angles.

3 Ant Colony Optimization

3.1 ACO for Multi-Robot Task Allocation

Once the structure and movement of ant-like robot satisfied physical requirement, it appears to be the appropriate time to take communication and group work into consideration. Compared with building of ant robot, this part is more important since group work directly decided whether this system is efficient or not. By the way, communication could severely affected cost of time, energy. Hence an intelligent algorithm rather than a common communicating mode is needed here.
The multi-robots are used for carrying out different tasks and they can be either stationary or mobile robots. Tasks can be discrete or continuous and it varies due to complexity and specificity. There are various approaches used for multiple robot task allocation (MRTA). This paper presents overview of application of ANT Colony Optimization (ACO) algorithms for multi-robot task allocation.
The ant colony algorithm is mimic of ant's behavior with "stimulated ants" walking around the graph representing the problem to solve. For this purpose, sample problems consisting of cost matrix for multiple robots and multiple robots and multiple tasks are formulated and evaluated by using ACO algorithm developed by using simulation software and compared with conventional method.
Multiple-Robot Task Allocation (MRTA) deals with allocation of tasks to robots so as to accomplish the tasks in an optimal way in order to improve the operational efficiency with the increasing number of task and robots. MRTA is a typical combinatorial optimization problem.
MRTA problems can be described by three axes, the first one is Single-task Robot (ST) versus multi-task Robot (MT), the second axis is Single-robot tasks (SR) versus multi-robot tasks (MR) and the third axis is Instantaneous assignment (IA) versus time-extended assignment (TA).
Conventional multi-robot task allocation can be classified into five approaches[7]. One of these methods is approaches based on swarm intelligence and this approach stimulate the behaviors of insects to assign the task of robots. Swarm intelligence[8] include the threshold value method and ant colony optimization, used for robot system in unknown environment. Swarm intelligence methods have high robustness, stability, are very suitable for the ant robotic system.
Ant robot communicate and cooperate with each other by releasing "pheromones"[9], each robot through the concentration of pheromones to choose their path during movement to scan the terrain. The denser the pheromone concentration of the path the more likely ant robot will "notice" that this area has provided enough date for central computer to visualize geological map.

3.2 ACO for Path Planning

The path planning problem of ant-like robotic system is extremely significant since it will influenced how large is overlapping working area and how much time could saved

in each exploring job. Similarly, the process of path choosing almost equals ant foraging behavior which can be seen as ants finding the shortest path and avoiding obstacles from nest to food source.
Main feathers of ACO: Information element will become less with the passage of time; from the nest to food source the ants leave pheromone; ants are able to detect the existence of pheromone trail in a specific range; ant can perceive the strength of this pheromone to guide the direction of their own environment in the foraging process. Document[10] proved the validity and practicability of ACO with experiments.
When it comes to modeling process, 3D motion space is abstracted non planar discrete; the pheromone in the tracks on the dense degree (which influences the trend of convergence in a certain range) constructed the variables in the equation; discrete loss frequency of pheromones is known, specific; adding random search equation which reflects rapidity of the algorithms. This mathematical model is established to complete. Initially, each group contains x ants , all ants are starting in the origin of coordinates 0 point while the 0 point is into the traffic domain TXY_m , where $m \in [1, x]$, $m - integer$. Ant ant can be found in the traffic domain TXY_m. $\epsilon_{ij}(t)$ is the value of remaining pheromone between i point to j point when time is t. Notice that $t = 0$, the value of pheromone on each coordinate edge $\epsilon_{ij}(t) = \epsilon_0(constant)$. Number of iterations $n \in [1, n_{max}]$.
Nest point j is determined by the algorithm of equation. Probably is calculated by equation (5) when ant moves from i point to j point. In equation (1), $A_k \in [1, n]$ and A_k is integer. Then optional all coordinates in TXY_m. λ, σ are weight of parameter in random searching equations and weight of track pheromone $\xi_{ij}(t)$ is parameter of expect in random search equation.

$$F_{ij}^k = \frac{[\epsilon_{ij}(t)]^\sigma \cdot [\xi_{ij}(t)]^\lambda}{\sum\limits_{0 \in A_k} [\epsilon_{i0}(t)]^\sigma \cdot [\xi_{i0}(t)]^\lambda}, \; if \; j \in A_k \tag{5}$$

$$\xi_{ij} = \frac{1}{D_{ij}} \tag{6}$$

D_{ij} is the length between two coordinates.
Every time Δt refresh pheromone, The refresh strategy is below equation:

$$\epsilon_{ij}(t + \Delta t) = (1 - \delta) \cdot \epsilon_{ij}(t) + \Delta\epsilon_{ij}(t) \tag{7}$$

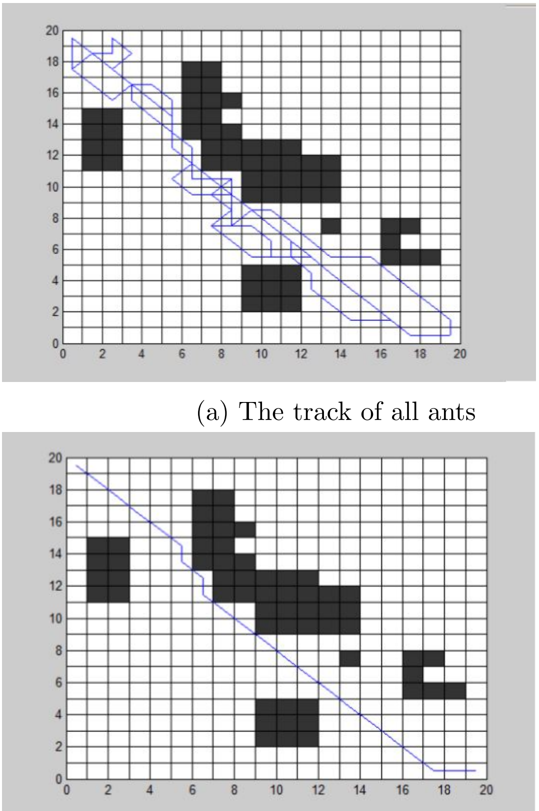
$\delta, (1 - \delta)$ are the loss frequency parameters of pheromone and residual frequency parameters pheromone respectively and $\delta \in [0, 1]$, pheromone are accumulation of upper limit, In Δt, the pheromone values is $\Delta\epsilon_{ij}(t)$ between i point to j point and when $\Delta t = 0 \implies \Delta\epsilon_{ij}(0) = 0$. In equation (8), $\Delta\epsilon_{ij}^m(t)$ is the value of pheromone when m moves from i point to j point at t. Then there are three kinds different type refresh algorithm of pheromone, the ant cycle type, the ant number type and the ant density type[11]. The difference lies in the solution of information entropy change value.

$$\Delta\epsilon_{ij}(t) = \sum_{m=1}^{x} \Delta\epsilon_{ij}^{m}(t) \tag{8}$$

In the ant cycle type:

$$\Delta\epsilon_{ij}^{m}(t) = \begin{cases} \dfrac{T}{L_m} & \text{if ant } m \text{ moves from } i \text{ to } j \\ 0 & \text{else} \end{cases}$$

Increasing the iteration number n then optimal path obtained. The following figure compared the track of all ants to the optimal track:



(a) The track of all ants

(b) The optimal path

Figure 5: After applying ACO algorithm

3.3 Energy-Efficient Algorithm

The whole of this robotic system can be regarded as a special case of wireless sensor networks which is responsible to calibration of geological feature and probably this

robotic system could applied in environment supervising etc. As mentioned above, the energy of this system is one of the major concerns that might strongly affected efficiency of this system.
Wireless Sensor Networks (WSN) are characterized by having specific requirement such as limited energy availability, low memory and reduced processing power. On the other hand, these networks have enormous potential applicability. WSN that try to overcome the constraints that characterize this type of networks. Ant-based routing protocols can add a significant contributions to assist in the maximum of the network lifetime, but this is only possible by means of an adaptable and balanced algorithm that takes into account the WSN main restrictions.
The ACO metaheuristic has been applied with success to many combinatorial optimization problems[12]. Its optimization procedure can be easily adapted to implement an ant based routing algorithm for WSNs, A basic implementations of such algorithm can be informally described as follows:

(a) At regular interval, from every network node (ant robot), a forward ant K is launched with mission to find a path until the destination. The identifier of every visited node is saved onto a memory M_k and carried by the ant.

(b) At each node r, a forward and selects the next hop node using the same probabilistic rule proposed in the ACO metaheuristic:

$$p_k(r,s) = \begin{cases} \dfrac{[T(r,s)]^\alpha \cdot [E(s)]^\beta}{\sum\limits_{U \notin M_K} [T(r,s)]^\alpha \cdot [E(s)]^\beta} & \text{if } s \notin M_k \\ 0 & \text{otherwise} \end{cases}$$

where $p_k(r,s)$ is the probability with which ant k chooses to move from node r to node s, T is the routing table at each node that stores the amount of pheromone trail on connection (r,s) , E is the visibility function given by $\dfrac{1}{C - E_S}$ (C is the initial energy level of the nodes and e_s is the actual energy level of node s), and α, β are parameters that control the relative importance of trail versus visibility. The selection probability is a trade-off between visibility and actual trail intensity.

(c) When a forward ant reaches the destination node, it is transformed in a backward ant which mission is now update the pheromone trail of the path it used to reach the destination and that is stored in its memory.

(d) Before backward ant k starts its return journey, the destination node computes the amount of pheromone trail that the ant will drop during its journey:

$$\Delta T_k = \frac{1}{N - Fd_k} \tag{9}$$

Where N is the total number of nodes and Fd_k is the distance traveled by the forward ant k (the number of nodes stored in its memory)

(e) Whenever a node r receives a backward ant coming from a neighboring node s, it updates its routing table in the following manner:

$$T_k(r,s) = (1-\rho)T_k(r,s) + \Delta T_k \tag{10}$$

where ρ is a coefficient such that $(1-\rho)$ represents the evaporation of trail since the last time $T_k(r,s)$ was updated.

(f) When the backward ant reaches the node where it was created, its mission is finished and the ant is eliminated.

To consider the energy quality of the paths on the basic algorithm a new function is proposed to determine the amount of pheromone trail that the backward ant will drop during its returning journey:

$$\Delta T_k = \frac{1}{C - \left(avg(E_k) - \frac{1}{min(E_k)} \right)} \tag{11}$$

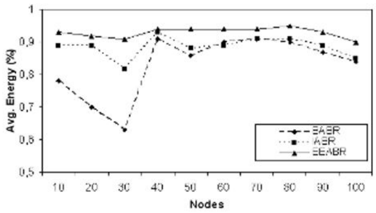
where E_k is a new vector carried by forward ant k with energy levels of the nodes of its path, C is the initial energy level of the nodes, $avg(E_k)$ is the average of the vector and $min(E_k)$ is the minimum value of the vector.
When the forward ant reaches the sink-node these values are used to calculate the amount of pheromone trail used by the corresponding backward ant:

$$\Delta T_k = \frac{1}{C - \left[\frac{E_{min_k} - Fd_k}{E_{avg_k} - Fd_k} \right]} \tag{12}$$

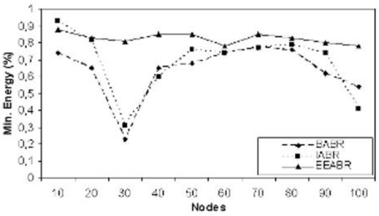
With these changes it is possible to reduce the ant's length by $\cong 700\%$, and save on each ant hop the transmission of $\cong 250 bytes$. This is a significant achievement, since it allows the saving of precious energy levels on sensor nodes. The equation used to update the routing tables at each node is now changed:

$$T_k(r,s) = (1-\rho)T_k(r,s) + \left[\frac{\Delta T_k}{\psi Bd_k} \right] \tag{13}$$

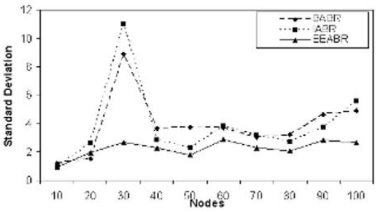
where ψ is a coefficient and Bd_k is the traveled distance (the number of visited nodes), by backward k until node r. On all scenarios the nodes were deployed in random fashion, since in real sensor networks the device deployment, in general, cannot be controlled by an operator due to the environment characteristics. The number of deployed sensor nodes varied between 10 and 100 nodes. Sub-figures from (a) to (d) showed energy consumption based on basic ant-based routing algorithm (BABR), the improved ant-based routing algorithm (IABR), and the energy-efficient ant-based routing algorithms (EEABR).



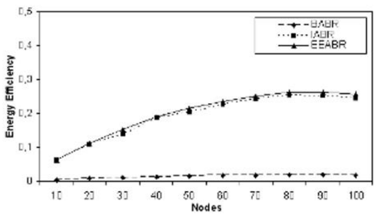
(a) Average Energy



(b) Minimum Energy



(c) Standard Deviation



(d) Energy Efficient

Figure 6: Performance in WSN with static pheromone

Energy-Efficient Ant-Based Routing (EEABR), uses "light-weight" ants to find routing paths between the sensor nodes and the sink nodes which are optimized in terms of distance and energy levels. These special ants minimize communication loads and maximize energy savings, contributing to expand the lifetime of the wireless network. The experimental results showed that algorithm leads to very good results in different WSN scenarios.

4 Conclusion

In a nutshell, this paper starts with a discussion pros and cons of current multi-pods. During this section two main types of hexapods were introduced, the first one focused on shape design especially the steering part between head, tail, pods and body while the second called Bionic Ants is a highly developed hexapod which is powerful and stable. Although Bionic Ant robots have no difficulty in ground moving , this type of robot is insufficient of climbing features which is an indispensable part for geological calibration. Hence some research in climbing skills for muti-pod was covered in paper via analyzing fruit fly's climbing habit. With adequate assumptions and combination of different types of muti-pod robots, structure and movement of ant-like robot build the fundamentals of achieving the goal of geology scanning and calibration.
The later sections of this paper paid much attention to constructing the communication net between each ant robot. Inside conceptual design of communication, Ant Colony Optimization and swarm intelligence dominates the algorithm no matter from allocation of job for multi-robot system or path planning. Additionally, the energy-efficient design aims at accomplished geological exploration with minimum energy and highest efficiency.
This conceptual design merged several researching filed included bio-robot, communication, locomotion, even artificially intelligence. Probably the idea of this paper and assumptions surpassed present techniques. There is still a possibility to achieve this conception in future.

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