Cognitive Artropods

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1 A brief review of the state of the art in arthropod-inspired robotic systems

Insects are nature's engineering marvels. They can perform marvellous feats such as jumping many times their own body length, lifting many times their own body weight, moving around even with multiple missing limbs and doing all this with amazing efficiency. It is little wonder then that roboticists have been attempting to replicate nature's design feat in robots. The primary thrust in the area of arthropod robotics has been locomotion. Various insect-like robots directly inspired by biology have been built using knowledge discovered about insect locomotion. As the literature in the area is vast and is much beyond the scope of this article, a brief review focussed on a critical analysis of a few hexapod robots is presented here. The robots discussed here include the series of cockroach-like robots built at Case Western Reserve University, the RHex program [Saranli01] at the University of Michigan and the joint work done by Stanford University and the University of California, Berkeley [Clark01]. It is not a mere coincidence that all these robots have the cockroach as their biological basis (as does the example scenario given in the workshop prospectus). Cockroaches, in addition to being extremely hardy and agile, are also easy to study, as the vast literature on cockroach locomotion shows. Hence, these omnipresent pests are ideal models for roboticists.

So as to increase performance as much as possible, bioroboticists (as they are known) try to incorporate the mechanics of a single species throughout the design of the robot. The study of cockroach gait has revealed that the legs of the cockroach essentially act as inverted pendulums on which the body swings. The cockroach has a tripod gait where only three legs are in contact with the ground at any given instant. Each leg passes through a *stance* and a *swing* phase in one motion cycle, where the stance phase involves the part where the leg touches the ground and provides reaction force for movement and the swing part involves the forward motion of the leg.

The cockroach robot series at Case Western Reserve consists of a series of roach-robots of different sophistication levels. Robot I [Beer92] and II [Quinn93] are basic in design and demonstrate simple walking behaviors. Robot III [Ritzmann00] is described in greater detail here. The robot legs in Robot III are designed to closely match the design of cockroach legs. The hind legs of a cockroach provide maximum thrust for locomotion while the front legs are solely to provide deceleration. The legs of Robot III follow this trend in that the hind legs are more powerful than the front pair. The legs possess potentiometers that measure all the joint legs. This provides proprioceptive feedback, which is crucial for agile locomotion, to the robot. Other possible proprioceptive sensors include strain measurements on the exoskeleton and reaction force measurements from the ground. Proprioceptive sensors are used in Robot III to maintain postural control. Information from the joints is used to compute the center of mass. This in turn is used to compute position and orientation and then adjust the legs to maintain a stable configuration. Due to this robust postural control, Robot III can lift a load equal to its own body weight of 30 pounds. The actuators used in Robot III's legs are referred to as dual acting pneumatic cylinders. These actuators provide a high power-to-weight ratio but are difficult to control. Electric motors provide better control but do not provide passive stiffness in the legs, nor do they possess sufficient power-to-weight ratio to enable tasks such as climbing.

The RHex robot [Saranli01] at the University of Michigan is based on a less biologically-viable model. The robot's design consists of six compliant ("springy") legs, each of which has only one independent revolute degree of freedom. Each leg functions as a "rimless wheel" through its motion. Each leg is driven independently to a clock step in an open-loop manner by its motor which keeps track of the leg's location in a pre-defined trajectory sequence. A tripod gait is maintained with three opposing legs acting in relative antiphase. Direction control is achieved through differential leg motion. The robot uses two 12V batteries on which it can travel for a maximum of 15 minutes. The RHex can cover a maximum distance of its own body length in a second, which is about 50 times slower than the maximum speed of a Death's Head cockroach.

The final case study of this review focusses on the Sprawlita [Clark01]. This cockroach-like hexapod is of interest as it is fabricated using a novel technique and also displays extraordinary agility by moving at up to 2.5 body-lengths per second. The robot uses a sprawled hexapedal posture that gives it an advantage in posture maintainance and provides static stability without loss of speed. Each leg is actuated by a prismatic actuator implemented as a pneumatic piston. The control used is an open-loop, feed-forward strategy which acts on a tuned mechnical system and provides stability in the face of sudden perturbations and environment changes. However, Sprawlita can only perform a simple straight-ahead running task as the design of legs do not permit turning operations. The robot is fabricated using a novel integrated construction technique. This is done to avoid numerous joins and fastenings, which may be the cause of the robot's failure (especially in robots of such small size). The technique used, called Shape Deposition Manufacturing (SDM), is a layered prototyping method where parts are built up through a cycle of alternating layers of structural and support material. After a layer of material is added, it is shaped to a precise contour before the addition of the next layer. This method allows fabrication of arbitrary geometries and high-precision features. The design of the compliant leg is done using soft visco-elastic polyurethane while the structural members are composed of a stiffer grade of polyurethane. This design combined with the simple control and the sprawled gait make Sprawlita nimble and quick even while running up or down a slope (on ground without obstacles). The robot can also clear obstacles of up to "belly height" successfully.

The above descriptions provide a cross-section of current technology in the domain of arthropod robots. As can be seen, none of these designs satisfy the requirements for Cognitive Arthropods *per se*. Firstly, current robots are too large and heavy (certainly not of cockroach-size) and contain no sensing technology (other than proprioception). The sole competency of these robots is locomotion and even that does not reach speeds comparable to insects. The power requirements do not permit endurance beyond 15-20 minutes and certainly do not permit the on-board computing power required for Nano-cognition. However, technology used in these robots is promising in the sense that it offers opportunities for scaling down to the level of Cognitive Arthropods. The simplicity in the actuation of the RHex is essential as small , smart robots will not offer much room for basic locomotion. Similarly, the actuation technology used in Robot III has been improved in the recently released Robot V [Kingsley03], which uses Braided Pneumatic Actuators (BPAs). These offer significant advantage over similar earlier actuators in weight, strength, power-to-weight ratio and actuation principle. The BPA works on a similar principle to natural muscle and inflatable bladder surrounded by an expandable fiber mesh. The invention of artificial muscle, used in the robot FLEX [Eckerle01], also holds out much promise in the near future. Though currently this technology (which is actually a field-effect electro-active elastomer) performs worse than other traditional actuators, it offers much scope for improvement and possesses valuable properties such as very light weight and extremely high power-to-weight ratio. Finally, an integrated fabrication technique, such as the one used to fabricate Sprawlita, is essential for the design of small but complex robots which require exo-skeletons and other nano-scale components.

In conclusion, though current technology does not possess a means to build a Cognitive Arthropod capable of long endurance, cognition and navigation, these capabilities certainly seem feasible given the technological advances in the last few years. A giant leap in the understanding of insect behavior has already made near-biological robots a reality. It requires only a much smaller effort in the areas of miniaturization, nano-fabrication and long endurance power generation from light-weight sources to make Cognitive Arthropods a reality.

2 Design of a Cognitive Arthropod

The small size of a cognitive arthropod places very specific limitations on its design. At sizes of the order of that envisioned for the cognitive arthropod (microrobot size;2-3 cms long), a major portion of the body volume is taken by the motor and the power source. Sensing, computation power and communication have to be designed around the constraints posed by the actuation technology and power source used. The design proposed here is optimized for use in scenarios envisioned for a cognitive arthropod. Currently available technology is used wherever possible in the design, though some parts of the design may use components that will be available only in the near future.

Piezoelectric motors, based on piezoelectric crystals, are one of the obvious choices for actuators in a micro-scale robot. These motors are high precision, high power-to-weight ratio and have a small packaging envelope. Piezoelectric motors have been available for years and 6x3 inch boards containing such motors are commonly available (Figure 1), though smaller motors are harder to design. These motors are capable of moving small loads at speeds of up to 250 mm/s and with a positional accuracy of 0.1 micron. They have the additional advantage of being able to work under a low voltage power supply.Given these superior characteristics of the piezoelectric motor and the large body of mature literature in existense in this area (for eg., [Flynn92]), this motor becomes a natural choice for the actuation in the current design.

The power supply is the most crucial design aspect of a micro-robot. An autonomous robot has also to be power autonomous and also have reasonable endurance. Due to its importance, a large body of research has this problem as its focus. A viable solution is to use solid-state high-density

Figure 1: A piezo electric motor on a circuit board (from *http://www.sensorsmag.com/articles/1201/33/main.shtml)*

solar cell arrays for this purpose. These arrays have been used in earlier implementations , both to power piezoelectric motors and to power MEMS devices (explained below)[Lee95]. However, in some cases the deployment environment may not favor solar power (for example, in caves). In such cases, two other technologies offer themselves as suitable alternatives. These are dry polymer electrolyte cells (Lithium-polymer cells) and Carbon-nanotube hydrogen storage fuel cells. Both these technologies have yet to be proven in the micro-scale domain (and the nanotube fuel cell is still in prototype stage) but they offer the promise of clean, long endurance, miniature batteries for microrobots. Thus, a choice between one of these two technologies and the solar cell array is made for the power source in the current design, depending on the environment of interest.

The control of a microrobot has to be simple out of necessity. There is often no room for the large computational power needed for elaborate path or motion planning. Navigation is mostly confined to pre-programmed maneuvers, though occasionally maps may be sent to the robot for its use. Simple behavior-based controllers (for example, pre-compiled FSAs) are ideal as these provide low computational-cost, but general-purpose, navigation. The use of such simple controllers in the past has been successful [Flynn89], which also argues for its use.

Sensing and localization on microrobots is limited by power and space constraints. On-chip solid-state sensing circuits are the best option with regard to sensing, while MEMS (Micro-Electro-Mechanical-Systems) inertial navigation provides accurate localization to the robot. No other discrete fabrication technology is capable of providing the miniaturization and power-efficiency that these solid-state devices provide, making them the best choice for a cognitive arthropod. A cognitive arthropod may or may not require communication capabilities depending on its environment and task. Even in the case where communication is necessary, this has to be limited to a downlink as broadcasting is much more space and power inefficient than reception. Thus, each robot may be augmented with the capability to receive communication signals. This may also aid in scenarios where teloperation or other forms of external guidance is necessary.

Finally, it is not possible to pack significant cognitive capabilities into a single robot the size of a cognitive arthropod after all the above components have been added. However, a team of such robots may be capable of performing tasks requiring reasoning and planning by use of distributed control algorithms and swarm intelligence techniques. These algorithms do not place a significant computational burden on any individual robot but enable the group to perform complex tasks.

To summarize, the current design of the cognitive arthropod uses piezoelectric actuation and a solar array or carbon-nanotube/lithium-polymer technology for power. Sensing and localization are provided by on-chip MEMS devices and one-way communication may be included depending on the task. No complex individual capabilities are available, but distributed algorithms using swarm intelligence and/or other techniques are added to the repertoire of the robots to enable them to perform complex tasks as a group.

3 Precision Nano-navigation

As described above, the design of a Cognitive Arthropod described in this article relies on MEMS-based inertial navigation. Micromachined silicon inertial sensors [Yazdi98] offer revolutionary improvements in guidance, navigation and control. Inertial units have always been presented as a valuable sensor in many applications. The advantages of inertial navigation are well known: high update rates, position and velocity in three dimensions along with attitude and heading information, the ability to operate at all places where gravity is present, and with no requirement of a vehicle model. The ability to provide 3-D information along with heading is especially crucial as cognitive arthropods may have to travel in three-dimensional space (for example, climb over a soldier), where just a two-dimensional x-y coordinate is insufficient for navigation. GPS cannot be used for this reason alone as elevation provided by GPS is least accurate of all the information provided (often upto 15 feet in error). Also GPS is not useful in the presence of overhead obstructions, which will often be the case for the scenarios envisioned for cognitive arthropods. In addition to possessing all the above benefits, inertial MEMS (for Microelectromechanical systems) are easy to manufacture, accurate, and provide multi-axis motion integration. These superior characteristics of Inertial navigation provide strong motivation for their use in the domain of precision nano-navigation.

A typical IMU consists of three accelerometers and three gyroscopes mounted in a set of three orthogonal axes [Kelly94]. The IMU measures the acceleration and the rotation rate of the vehicle in all three dimensions at a high sampling rate, typically at frequencies higher than 100 Hz. From this information, attitude, velocity and hence position of the vehicle can be derived. The naive IMU positioning algorithm just performs a double integration over the three axes accelerometers to obtain the positions along the axes. However, this algorithm does not work as it does not take in account the forces acting on the robot due to the earth's rotation and the transformations required to express the output in the coordinate system of the robot. To correct these problems, firstly the accelerometer output is converted to inertial acceleration from specific force (which is what the accelerometer actually measures). This requires the knowledge of gravitational force acting on the robot and hence, inertial positioning algorithms cannot function if the this value is unknown or inconstant. Subsequently, corrections are made for the centrifugal force acting on the robot (due to distance from the center of the earth and the earth's rotation) and the coriolis force due to motion on the earth's surface. While the absolute magnitude of these forces is extremely small, they affect the final position computation vastly. For example, the coriolis force at the equator is only $0.03g$ but this error propagates over time due to the double integration. One hour is 13 million seconds squared and converts to an accumulated error of over 3 kilometers. As this error does not depend on the motion of the robot (i.e., it accumulates even if the robot is stationary), it is all the important to compensate for it. The above algorithm measures only position and velocity of the robot. Three gyroscopes oriented along the three axes are used to track orientation. An integrated sensor containing a accelerometer and a gyroscope is referred to as an *Inertial Measurement Unit (IMU)*.

The accelerometers require a stable platform or a knowledge of the robot's orientation to function properly. To accomodate for this, three different designs of IMUs exist. A *Gimballed* system is one which contains a stabilized platform that is actively servoed to the required orientation. A *Semi-analytic* system servoes to the desired orientation only in the navigation frame. Lastly, a *Strapdown* system passively tracks the vehicle orientation (in contrast to active correction in previous systems), and corrects for the orientation in software. Thus, there is a trade-off between computational and mechanical complexity. A strapdown system is proposed for use in the arthropod design here as this would not require the use of a servo motor for stabilization.

Inertial MEMS have demonstrated extreme ruggedness and endurance on robot and vehicular platforms [Connelly01]. Ruggedness is an essential characteristic as even a 6 inch drop is terrain is large for a robot 1-2 inches in size. Hence, it is important that a cognitive arthropod is capable of withstanding drops many times its own body size. Currently, inertial MEMS that can withstand up to 15 *g*'s of force but are still under a cubic inch in size, are available. System-on-a-chip MEMS with several digital I/O channels and ASIC chips will be available in the near future. These MEMS will have less than 1 deg/hr of angular bias, shock survival capacity of 50,000*g* and a power consumption of less than 1W. A next-generation IMU chipset (though not of the specifications mentioned here) is shown in Figure 2.

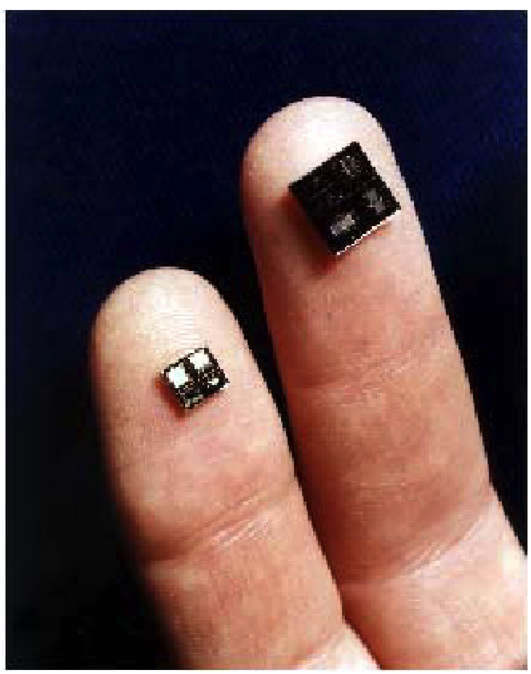

Figure 2: A high performance IMU chip set - accelerometer (left) and gyroscope (right) (from *draperlabs paper*

The navigation architecture used in the design of the cognitive arthropod consists of a behavior-based framework on top of a biomechanical locomotion strategy. Piezoelectric actuators are proposed as actuators to drive pneumatic piston-like legs as used in Sprawlita [Clark01]. This type of locomotion provides superior agility with extensions capabilities up to speeds of a real cockroach. In addition, the nanoscale control capability provided by the piezoelectric motors are useful in behavior-based control. Behavior-based control has been chosen as it is computationally simple to achieve, modular, offers computational flexibility and is hardware-retargetable [Arkin98]. Also, many group behaviors, such as maintaining a formation, which are essential for distributed cognition or swarm intelligence algorithms can be implemented as behaviors without need for additional navigational capabilities (eg., trail following). A behavior-based controller has also the advantage of not requiring a prior map of the environment. In most scenarios envisioned for cognitive arthropods a map cannot be available or in some domains will not even be feasible (for example, traversing an enemy soldier's body). The major problem with behavior-based control is local minima. However, a number of solutions to this problem exist [Balch93] [Lee02]. Though these reactive solutions are not guaranteed to help the robot out of the local minima, they fail only in rare cases. The choice of using reactive schemes to overcome the local-minima problem is an important one as planning requires accurate sensing which may not be present in robots of such small size. Hence, planners and hybrid architectures are not incorporated in the design. The localization provided by the IMU unit is used by the robot to accurately locate the goal so that the behavior may direct the robot towards it. The localization unit would not be required if the goals are presented in egocentric reference frame but this is rarely possible, especially as the robot is extremely small. The robot may also be required to shift goals (such as switch from a Move-to-Goal behavior to a Maintain-formation behavior) and lose sight of the goal. The robot will have to be redirected by presenting it with the goal again (over a communication link) and hence the robot should be capable of converting a goal location in global coordinates to a egocentric frame. This requires localization.

Sensing technology for a microrobot is bound by the same constraints of space and power as all the other components are. Currently, on the macro scale, laser range scanners offer the best, most accurate range sensing and are rapidly replacing sonars which were the workhorse for the robotics field earlier. The arguments against using sonar are even more forceful at the small scale. Sonar cannot detect obstacles at less than 10-15 cms and this presents a major difficulty to employing sonar on the small scale. Additionally, specular reflections make sonar even more unreliable as microrobots will not have large area sonar arrays. This means that even a slightly angular surface may result in the reflected signal being missed. Noting the success of lasers at the macro scale, it is logical to try to use micro scale lasers as sensors on cognitive arthropods. Microlasers based on zeolite dyes that are only a few tens of micrometers across have been in existence for a few years now [Vietze98]. While such small lasers may not be powerful enough for use as sensors, larger lasers (but still less than a centimeter in size) may be of use. Microlasers are currently used in high-speed communications, optical signal processing and optical computing devices. As no prior use of microlasers as robot sensors is evidenced from the literature, an evaluation of microlasers as robot sensors will also have to be performed. Other sensors that could possibly be used depending on the task at hand are on-chip machine vision, infra-red sensors and on-chip chemotactic sensing. However, vision implies a large computational and/or communication requirement (if the image is to be transmitted). A more suitable approach is to use active vision techniques to extract only useful knowledge from an image and hence reduce computational requirements. The chemotactic sensor can be used as a mechanism to guide the cognitive arthropods towards a location by marking that location with the chemical for which the taxis is activated (similar to a beacon or flare being dropped on a bombing target to guide the bombers, to make a more gruesome analogy). It is to be noted that it is not the idea of this design to use this sensor for trail laying and following behaviors. Trail-laying would require a generation or storage mechanism for the chemical (or "pheromone") which forms the trail. This would be a misapplication of the space and power of the cognitive arthropod, which are already limited. It also would not allow for endurance as the robot would be unable to navigate if its store of "pheromone" ran out. Finally, IR is another cheap sensor that uses very little power and is ideally suited for small robots.

In summary, the design in this article calls for a navigation architecture based on behavior-based control with underlying locomotion being performed using piezoelectric actuators and pneumatic legs. Localization is provided by an inertial MEMS system. Sensing is provided by a microlaser and may be augmented using on-chip vision or chemo-tactic sensors as required. All of these components satisfy size and power criteria for the cognitive arthropod and have all previously been used in robot applications excepting the microlaser. Hence, this design would enable research on applications of cognitive arhthropods to various scenarios without requiring a long interval for the development of hardware prior to this.

4 Nano-Cognition

This section deals with infusing cognitive capabilities into arthropods robots. Cognitive capabilities enable a robot to recognize changes in its environment and respond to such changes in a suitable manner. Cognition algorithms have also to take into consideration the uncertainty in the environment and plan for relevant contingencies. It is important that the robot not make gross assumptions about the world which may lead to inconsistent or unwanted behavior. At the same time it cannot try to model the world too closely, as this leads to combinatorial explosion in the planning and may also lead to the qualification problem. The problem of augmenting robots with general purpose deliberative capabilities has proved intractable thus far, even for macro scale robots. Hence, it can be expected to be significantly harder for the case of microrobots with computational constraints. Similarly, current learning algorithms require a large amount of time and a large number of trials to accomplish even simple tasks and are thus unsuited for cognitive arthropods as these robots may have only a limited amount of time in a particular domain.

The design of a Cognitive Arthropod suggested here does not consider putting traditional deliberative techniques in the design. The disadvantages of using traditional deliberation, even in combination with reactive mechanisms, far outweigh the advantages. Firstly, planning requires a map or some other model of the world on which the planning can be done. The working scenarios envisioned for a cognitive arthropod do not make this option a feasible one, as also discussed earlier. While mapping techniques and methods to build symbolic reasoning models of the world exist, these are too slow and computationally expensive today to allow their use. Even if the performance of these algorithms improves dramatically in the near future, the cost of these algorithms in comparison to distributed algorithms - explained below - would be hard to justify. Secondly, even in macro scale robots, deliberation can only work in constrained environments or in cases where a large amount of domain knowledge has been supplied to the deliberative module. This introduces brittleness into the robot while making it peform better in the specific niche it has been prepared for. In the case of Cognitive Arthropods, the extreme variability of environment may make the brittleness introduced by deliberative components intolerable. Primarily due to the above reasons (among many others), it has been decided to forego the use of traditional cognitive algorithms in this design.

This design proposes the use of highly multi-agent, distributed algorithms for group, rather than individual, cognitive displays. Such algorithms are often biologically inspired from social insect colonies and employ the principle of emergence to create group-level behaviors. This area is also known as *swarm robotics*[Bonabeau99]. In a swarm system, each individual robot acts out a set of simple behaviors that affect only the local environment around it. It also interacts only with robots near it i.e., all the interactions are local. The group behavior emerges out of these local interactions and is often unexpected or unintuitive, based on just the knowledge of the local behavior rules that the robots follow. As a single robot never has to perform complex tasks, the robots can be extremely simple (like ants in an ant colony). Swarm systems are based on self-organizing algorithms. Self-organizing algorithms use either stigmergy (inter-robot interaction by modification of the environment) or by employing positive feedback mechanisms (the more a group of robots performs a task, the more frequently it is driven to perform it). The advantages offered by swarm robotics include robustness, simplicity, scalability, and decentralization. In addition, memory is required only by the group and not by any individual.

Cognitive arthropods offer a suitable platform for the implementation of ditributed algorithms. All scenarios envisioned for cognitive arthropods make use of them in a multi-robot team, often in large numbers. For example, a group of robots may be given the task of covering an area effectively to provide surveillance or act as communication relays. They may be required to carry an object out of confined spaces such as sewer pipes as a group. Such tasks require a large amount of planning if a centralized approach is used. Instead, swarm robotics algorithms can be used to accomplish the same tasks much more reliably even in dynamic environments. Also, as these algorithms require individual robots to execute simple behaviors, the use of such algorithms fits perfectly with the earlier design decision to use behavior-based control for the cognitive arthropods.

To illustrate the flavor of self-organizing algorithms and demonstrate their capabilities, a few such algorithms are described here. Self-organizing algorithms exist for flocking, maintaining formation, foraging, map building, multiple goal problems (generalizing to the Travelling Salesman Problem) and sorting objects. The algorithms are usually simply collections of rules that each robot must follow. Algorithms for maintaining formation and for foraging are presented here.

A flocking behavior using self-organization techniques can be used to maintain formation in a group. Each individual constantly attempts to correct his position based on the position of its neighbors. Three simple rules are used to maintain a robot's position in the group [Reynolds87]

1. **Separation:** Steering away from neighbors to avoid crowding
2. **Alignment:** Orienting ineself toward the average of the alignments of the neighbors
3. **Cohesion:** Steering to move towards the average of the positions of the neighbors

These three rules suffice to make the robots flock, school or herd with similar behaviors to actual animal congregations being observed when the group moves around obstacles. In a large group of tens of robots, this operation of maintaining formation would have been massively expensive computationally, especially if all the robots cannot see each other. This simple example illustrates the superiority of distributed algorithms in multi-robot domains.

Foraging and sorting are similar tasks and have been widely studied in the multi-robot domain. Foraging requires a group of robots to collect certain objects spread outin the environment and bring them back to the “home base”. Similarly, sorting involves finding and bringing back objects except that in this case, more than one object type may be present and each object has its own storage bin in which it has to deposited. Many relatively complex reactive and learning approaches [Balch99][Mataric94] have been used to perform this task. The self-organized algorithm for this task is described here. This algorithm uses stigmergy in that each robot modifies the environment and changes its behavior depending on this environment. Two different conditions are detected by the robot - the presence of an obstacle and the presence of a stopping force when no obstacle is detected. In the latter case it is assumed that another object is present if the robot already has an object. The following rules suffice to bring about a clustering behavior [Holland99].

1. If obstructed and obstacle ahead, make random turn and head straight

2. If obstructed and no obstacle ahead and there is an object in possession, drop object, back off some distance and make random turn left or roght.

3. Else move straight ahead

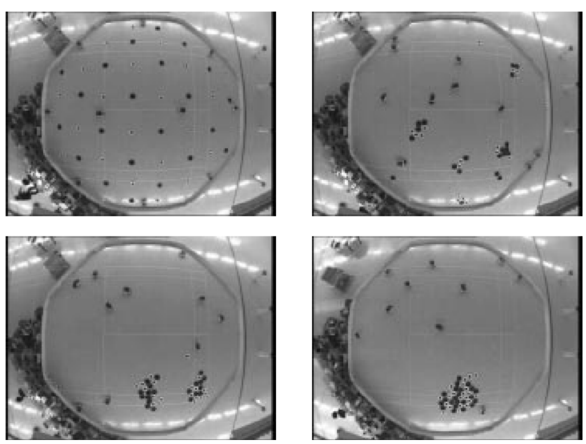

Figure 3: Clustering action by foraging robots using a self-organized algorithm (from [Holland99])

Figure 3 shows the foraging action by a group of robots. Sorting can be accomplished similarly just by having the robots pick up only one of the types of objects instead of both.

As can be seen, swarm robotics offers cognitive capabilities to groups of robots without the need to make individuals complex. However, so far this approach can only tackle relatively simple problems such as have been described above. It is one of the goals of this design to apply swarm intelligence to the new domain of cognitive arthropod robots and develop new algorithms that enhance the perform of cognitive arthropods working in a group.

5 Nano-INFOSEC

Security of devices is of crucial importance, especially in military applications. Valuable information may be gained by the capture of an insecure device. Such information may include knowledge about the goal (or mission) of the robot(s), communication protocols among devices and strategies being used to achieve the goal. Worse, a robot may be subverted and start misdirecting its teammates. Fault detection mechanism, trust and confidence levels, and reliability have to be built into a robot design to avoid such scenarios. However, notions of trust and reliability are hard to define for robots that are designed to collaborate with people, even in mundane everyday tasks. As can be imagined, the problem is much harder (and philosophically much more complicated) in the case of miniature robots. Any generalizations, that may help in the design, are hard to find. Currently, robots are disallowed autonomy in crucial or dangerous situations, for example with respect to firing weapons amd deciding when to take pictures in the case of an unmanned reconnaisance vehicle. However, the relentless pressure to automate tasks or make tasks less personnel-intensive makes the problem of entrusting robots with vital decisions even more important.

Traditional information security systems can provide solutions to some of the problems listed above. Communication protocols can use reliable and proven encryption techniques to deter cracking, and hence, misdirection of the robots. The robots may also be enclosed in tamper proof packaging to prevent abuse. The use of swarm intelligence in large groups of robots enhances security as the organization is decentralized. As each robot is concerned only with its neighbors, whom it can sense, it need not communicate unnecessarily (communication may still be required to relay commands from a human or to transmit sensor data). Additionally, a swarm does not have a leader or a centralized “brain” that controls the robot group. This promotes group robustness in the face of individual loss, as no one member of the group is crucial to the group’s survival. This robustness is a direct result of the design of swarm algorithms, which is based on social insects such as ants.

While physical security of the robot and security of communications can be guaranteed easily in such a way not to compromise the group’s mission, notions of trust are harder to deal with. How can a user be sure that a cognitive arthropod with an explosive will explode when required to and not before or after? Such questions require building of trust between the robot and its user. A logical definition of trust given in [Marsh94] is the following -

> ”trust, (or symmetrically, distrust) is a particular level of the subjective probability with which an agent will perform a particular action, both before he can monitor such action (or independently of his capacity to monitor it) and in a context in which it affects his own action.”

This definition leads directly to a trust model of a robot, which consists of a probability distribution which is updated whenever the robot is expected to perform in a particular manner and either lives up to the expectation or fails to perform as required. In the former case the trust level goes up while in the latter case it falls. Weights can be assigned to each expected action according to its importance. For example, activating an explosive would have a much greater weight than going around an obstacle using a longer path. This interpretation of trust is easy to implement and most importantly, does not involve adding complexity to the robots. While inter-robot trust can also be provided using the same mechanism, it is not the aim of this design to do so. Instead, inter-robot trust can be controlled by a user through directed commands to a group that encode the untrustworthiness of the robot. All robot *belonging to the group* can be assumed trust worthy by default. It is to be noted that the use of such commands makes the need for secure communications all the more important, as otherwise an enemy could make robots untrustworthy at will. The technique also requires a method to recognize robots not belonging to the group and also untrustworthy robots. This can be done simply by assigning each member of the group a unique id and also assigning a unique id to the group itself. Then, each robot maintains a list of untrustworthy members and identifies members of its group by exchanging the group id with them. The trust acquisition itself can be implemented through Bayesian Learning [Brainov99]. This method is often called *Trust acquisition by observation*. Other methods for trust acquisition include Trust acquisition by interaction and through institutions. In the interaction technique, the robot asks another robot "questions" for which it already knows the answers and increases the other robot's trust level with every right answer. Trust acquisition using institutions is a very human-like technique that uses an agent that both the agents who want to establish trust believe in.

While trust is an important aspect of human-robot interaction, it also lowers the security of the system as individuals now have to communicate to establish trustworthiness and identities within a group. Tough safeguards may exist, a smart misbehaving robot can still masquerade as a group member and misdirect the group, leading to malfunction. To counter this threat, security measures need to applied. The two major security concerns in this scenario are insecure communications and misbehaving agents. Communication channels can be secured using encryption. In general, all messages should be authenticated and any corruptions should be detectable. Misbehaving robots may be performing wilful deception or may be deceiving other group members accidentally. In the latter case, the cause may, for instance, be a damaged sensor. In such cases, the trust level of the robot drops due to its errors and no damage is done, except possibly, for some lost time. If, however, the robot is deceiving wilfully, detection becomes harder. To detect such deception, the robot should be capable of detecting command context and obeying only valid commands [Wong99]. A command can be considered valid if it comes from a rightful source (someone that is a deployer), and the command itself 'makes sense' in the current state of the robot. For example, a command to blow up when not deployed (i.e. still in the deployer's pocket) will be ignored. This requires some domain knowledge (possibly in the form of a rule set) in the robot.

To summarize, in a cognitive arthropod the notion of trust and its applicability is not as generalized as in the case of web-based agents - to consider another domain where trust is widely studied. However, as levels of autonomy increase the requirement for trust correspondingly increases. This need becomes all the more crucial when autonomous actions by the robot may lead to irreversible consequences, such as detonating an explosive. It is proposed that in this design trust acquisition will be implemented through observation. Security of the robot team will be safe-guarded by the use of unique ids for robots and for the group and by encrypting communications. Further a rule set for contextual command following will be embedded in each robot to overcome wilful deception by a masquerading robot. This proposal is novel in the sense that none of these ideas have been implemented on physical robots yet, but only in the agent domain. The research issues arising out of an implementation of these issues on the cognitive arthropods also form the domain of this proposal.

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