Journal of The British Interplanetary Society, Vol. 42, pp 478-485, 1989

FAST, CHEAP AND OUT OF CONTROL: A ROBOT INVASION OF THE SOLAR SYSTEM

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Complex systems and complex missions take years of planning and force launches to become incredibly expensive. The longer the planning and the more expensive the mission, the more catastrophic if it fails. The solution has always been to plan better, add redundancy, test thoroughly and use high quality components. Based on our experience in building ground based mobile robots (legged and wheeled) we argue here for cheap, fast missions using large numbers of mass produced simple autonomous robots that are small by today's standards (1 to 2 Kg). We argue that the time between mission conception and implementation can be radically reduced, that launch mass can be slashed, that totally autonomous robots can be more reliable than ground controlled robots, and that large numbers of robots can change the tradeoff between reliability of individual components and overall mission success. Lastly, we suggest that within a few years it will be possible at modest cost to invade a planet with millions of tiny robots.

1. INTRODUCTION

Over the last four and a half years the MIT Mobile Robot Group has pursued the goal of building totally autonomous mobile robots for a variety of tasks. We have refined hardware and software tools so that we can quickly build robust interesting robots. For instance Genghis, a six legged walking robot shown in Fig. 1 was completed 12 weeks after initial conception, in response to a JPL workshop on micro spacecraft [1]. The robot [2,3] was principally built and debugged by two people, with occasional supporting help from about half a dozen others. The robot weighs less than a kilogram and can scramble over very rough terrain. A follow-on vehicle [4] will be able to climb metre high rocks, and travel at around three kilometres per hour. Such easy to build high performance robots suggest some new ways of thinking about planetary exploration.

Two of the principal costs in planetary surface exploration missions arise from the mass of the planetary rover upon launch, and hand construction of the unique vehicle itself. In this paper, we demonstrate that technology has progressed to the stage where we can tackle both of these problems simultaneously by creating swarms of totally autonomous microrovers in the I to 2 Kg range. This way, total mass delivered to the planetary surface is minimised and in addition, the multiple copies of the rovers increase the chance of the mission's success. Cost savings in terms of construction dollar per Kg result, due to the opportunity to apply mass production techniques to the roved manufacture.

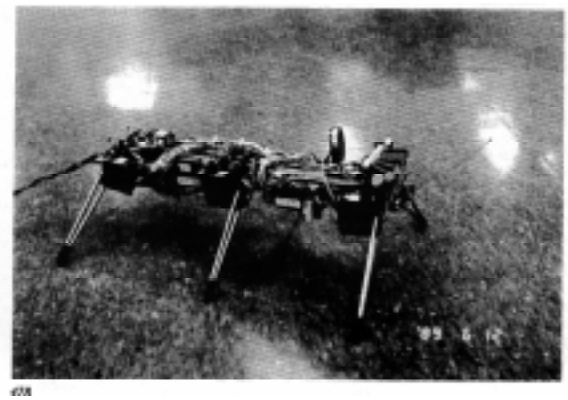

Fig. 1 Genghis is a 1 Kg six logged robot. It can walk and climb over rough terrain It has four onboard processors, twelve actuators with force feedback, six pyroelectric sensors two whiskers, and pitch and tall inclinometers Total time for the project between initial conception and completion of the robot was twelve weeks.

Total autonomy actually increases mission reliability. Out of control of ground based operators, the robots can use force control with tight sensing feedback loops. This is in contrast to the minutes to hours long position control feedback loops of long delay teleoperation. Force control is the key to reliable performance in the face of any uncertainty. By completely removing all ground based control of the rovers, their complexity goes down drastically as there is no need for much of the communications equipment, and no need for the ground support maintaining communications. Simplicity increases reliability. In fact, the resulting reduced complexity of the overall mission will allow complete programs to be conceived, researched, developed and launched on time scales more reminiscent of the sixties than those of today.

In the last part of this paper we present some radical ideas on how to scale down the size of planetary rovers even further, to the milligram range inspiring missions which will capitalise on thousands or even millions of rovers roaming a planetary surface.

2. CREATING INTELLIGENCE

The general problem we set out to solve 4 1/2 years ago was how to build a brain, or, to answer the question of what it would take to build something that we would consider clever. What were the essential components that would be needed to create an intelligent entity and how should those components be put together?

Driven by the reality of experiments with actual robots our ideas took a route different from the traditional approach in Artificial Intelligence. Our approach emphasized

(1) that there would be no traditional notion of planning

(2) that no central representation was needed

(3) that notions of world modelling are impractical and unnecessary

(4) that biology and evolution were good models to follow in our quest

(5) that we insist on building complete systems that existed in the real world so that we would not trick ourselves into skipping hard problems

To encapsulate these ideas and to address the real-world, real-time issues, we developed a general layering methodology for the organisation of the intelligence system. Simple behaviours were built first connecting sensing to actuation. Then higher level task behaviours were layered on in parallel. Because certain higher layers of task achieving behaviours could subsume lower level behaviours in our system, we called this framework the *subsumption architecture* [5]. We have used this organisation to implement a variety of behaviours on a number of mobile robots.

In essence, the subsumption architecture is a parallel and distributed computational formalism for connecting sensors to actuators in robots. One writes a subsumption programme by specifying layers of networks of augmented finite state machines. Augmented finite state machines are traditional finite state machines augmented with timers which can be set to initiate a state change after some fixed time period has passed. Details of the subsumption architecture can be found in [2, 5 & 6].

The three key aspects of the subsumption architecture are that (1) it imposes a layering methodology in building intelligent control programmes, (2) within each network, the finite state machines give the layer some structure and also provide a repository for state, and (3) with this organisation, very small amounts of computation are needed to generate intelligent behaviours.

The underlying architecture is very distributed. There is no "free" communication network nor any shared memory between computational elements. Any communication path must be made quite explicit by specifying a wire. It is thus difficult to maintain a central world model. Indeed it often becomes easier to use the world as its own model, and sense the pertinent aspects of the world when it is necessary. This is a good idea as the world really is a rather good model of itself. Continual sensing automatically adds robustness to the system as there is neither a tendency for the world model to be out of date, nor are large amounts of computation poured into making sure it is not. We take this idea even further and often actually use the world as the communication medium-between distributed parts of the subsumption programme. Thus, one layer senses what really happened in the world, rather than being told what another layer expects to happen.

Given that there is no world model, there is also no place for traditional AI planning which examines a world model and reasons about consequences of actions. Rather, in the subsumption architecture, it is more natural to locally react to sensed aspects of the world, and let a pre-wired priority scheme resolve any conflicts generated within the distributed system. It is entirely plausible for different parts of the system to "believe" wildly inconsistent things about the world. Of course, belief is all in the mind of an outside beholder as there are no explicit symbolic representations of any believed facts within the subsumption architecture.

Lastly, with no central world model there is no need for sensor fusion in the usual sense of the phrase. There is no perception system which delivers descriptions of the world to a “central” system which controls an “actuation” system. In the subsumption architecture, the fusion of data from different sensors, or even from different processing applied to the same sensor data (e.g., stereo and motion algorithms applied to the same camera inputs), does not happen in the “perception” end at all. Individual strands of perceptual data are delivered to individual subsumption layers and then actuator commands are generated. Fusion happens in resolving conflicts between these actuator commands.

3. EXISTING SUBSUMPTION ROBOTS

In this section we briefly review some previous successful robots built with the subsumption architecture and highlight the ways in which they have exploited or epitomise that architecture. The family portrait of all the robots is shown in Fig. 2.

3.1 Allen

Our first robot Allen, had sonar distance sensors and odometry onboard and used an offboard lisp machine to simulate the subsumption architecture. In [5] we described three layers of control implemented in the subsumption architecture.

The first layer let the robot avoid both static and dynamic obstacles; Allen would happily sit in the middle of a room until approached, then scurry away, avoiding collisions as it went. The internal representation used was that every sonar return represented a repulsive force with an inverse square drop off in strength. The vector sum of the repulsive forces, suitably thresholded, told the robot in which direction it should move. An additional reflex halted the robot whenever there was something right in front of the robot and it was moving forward (rather than turning in place).

The second layer made the robot randomly wander about Every 10 seconds or so, a desire to head in a random direction would be generated. That desire was coupled with the instinct to avoid obstacles by vector addition. The summed vector suppressed the more primitive obstacle avoidance vector, but the obstacle avoidance behaviour still operated, having been subsumed by the new layer, in its account of the lower level's repulsive force. Additionally, the halt reflex of the lower level operated autonomously and unchanged.

The third layer made the robot look (with its sonars) for distant places and try to head towards them. This layer monitored progress through odometry, generating a desired heading which suppressed the direction desired by the wander layer. The desired heading was then fed into a vector addition with the instinctive obstacle avoidance layer. The physical robot did not therefore remain true to the desires of the upper layer. The upper layer had to watch what happened in the world, through odometry, in order to understand what was really happening in the lower control layers, and send down correction signals.

In [7] we described an alternate set of layers for the robot Allen.

3.2 Tom and Jerry

Tom and Jerry [8] were two identical robots built to demonstrate just how little raw computation is necessary to support the subsumption architecture. A three layer subsumption programme was implemented, yet all data paths were just one bit wide and the whole programme was implemented on a single 256 gate programmable array logic chip. Tom and Jerry physically are toy cars with three one-bit infrared proximity sensors mounted on the front plus one at the rear. The sensors are individually tuned to a specific proximity distance at which they will fire. The central front sensor fires only on much closer objects than the two side sensors, which point slightly outwards.

The lowest layer of Tom, and Jerry implements our standard pair of first level behaviours. These are a vector sum of repulsive forces from obstacles to perform an avoidance maneuver or to trigger a halt reflex to stop when something is too close ahead, as detected by the central front looking sensor. There are extra complications with Tom and Jerry in that we need to use the subsumption architecture to implement an active braking scheme because of the high speed of the robots relative to their sensor sensitivities. Tom and Jerry's second layers are much like Allen's original second layer - an urge to wander about, which is implemented by an attractive force which gets added to the repulsive forces from obstacles. The third layer detects moving objects using the front three sensors and creates a following behaviour. When something is detected, it is attracted and moves towards it. The lower level collide behaviour stops the robot from actually hitting the target, however. While the robot is chasing its target, the wander behaviour is suppressed.

We see with Tom and Jerry both the notion of independent behaviours combining without knowing about each other (chasing obstacles but staying back from them a little ways) and the idea again of using the world as its own best model. Tom and Jerry also demonstrated that the subsumption architecture could be compiled (by hand) down to the gate level, and that it could be run at clock speeds of only a few hundred Hertz.

3.3 Herbert

Herbert [9,10] is a much more ambitious robot which is now complete. It has a 24-processor distributed, loosely coupled, onboard computer to run the subsumption architecture. The processors are slow CMOS 8-bit microprocessors (which ran on low electrical power, an important consideration when carrying batteries), which can communicate only by slow serial interfaces (maximum 10 packets each, 24 bits wide per second). Onboard Herbert, the interconnections have physical embodiments as actual copper wires which provide the medium to support the serial sending of messages.

Herbert has 30 infrared proximity sensors for local obstacle avoidance, an onboard manipulator with a number of simple sensors attached to the hand, and a laser light striping system to collect three dimensional depth data in a 60 degree wide swath in front of the robot out to a range of about 12 feet. A 256 pixel wide by 32 pixel high depth image is collected every second. Through a special purpose distributed serpentine memory, four of the onboard 8-bit processors are able to expend about 30 instructions on each data pixel. By linking the processors in a chain we are able to implement quite high performance vision algorithms.

Connell [6] has programmed Herbert to wander around office areas, go into people's offices and steal empty soda cans

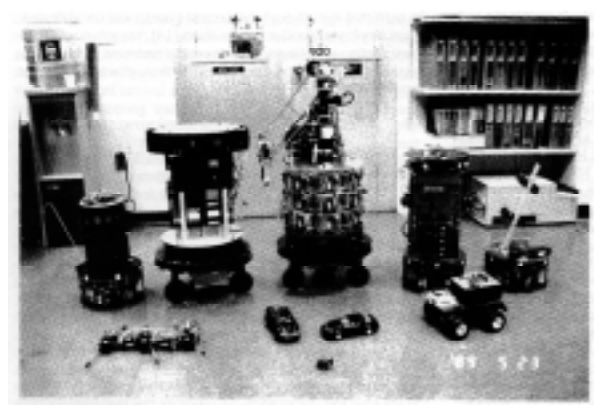

Fig. 2 The MIT Mobile Robots include, in the back row, left to right; Toto, Allen, Herbert, Seymour and Tito. In the middle row are Genghis, Tom and Jerry, and Labnav. Squirt, although rather hard to see, is down in front.

from their desks. He has demonstrated obstacle avoidance and wall following, real-time recognition of soda-can-like objects and desk-like objects, and a set of 15 behaviours [10] which drive the arm to physically search for a soda can in front of the robot, locate it and pick it up.

Herbert shows many instances of using the world as its own 'best model and as a communication medium.

The laser-based table-like object finder initiates a behaviour which drives the robot closer to a table. It does not communicate with any other subsumption layers, However, when the robot is close to a table there is a better chance that the laserbased soda-can-like object finder will trigger. In turn, it centers the robot on the detected object, but does not communicate anything to other subsumption layers. The arm control behaviours notice that the robot is stationary, and reaches out looking for a soda can. The advantage of this approach is that there is no need to set up internal expectations for what is going to happen next; this means that the control system can both (1) be naturally opportunistic if fortuitous circumstances present themselves, and (2) it can easily respond to changed circumstances, such as some other object approaching it on a collision course.

In a similar vein, the arm and hand do not communicate directly either. The hand has a grasp reflex that operates whenever something breaks an infrared beam between the fingers. When the arm locates a soda can with its local sensors, it simply drives the hand so that the two fingers line up on either side of the can. The hand then independently grasps the can. Given this arrangement, it is possible for a human to hand a soda can to the robot. As soon as it is grasped, the arm retracts -it does not matter whether it was a soda can that was intentionally grasped, or one that magically appeared.

3.4 Seymour

Seymour is a new robot we are building with all onboard processing to support vision processing of 9 low resolution cameras at approximately 10 frames per second [11]. The cameras feed into different subsumption layers which act upon those aspects of the world they perceive. A number of vision based behaviours developed for Seymour have been prototyped on earlier robots.

Horswill and Brooks [12] describe a subsumption programme that controls two simple and unreliable visual processing routines to produce, a reliable behaviour which follows moving objects using vision. One vision process tracks a single moving blob. It gets bootstrapped by another process which overlays the blob image with an indication of where motion is seen. The robot then tries to servo a selected blob to stay in a fixed location in image coordinates. The blob tracker often loses the blob it is tracking. The motion finder produces a lot of noise especially when the robot is moving, but between the two of them they let the robot reliably follow a moving object (any moving object; we have seen the robot chase a black trash can dragged by a string, a radio controlled toy blue car on a blue floor, a pink plastic flamingo, a grey notebook on a grey carpeted floor and a drinking mug moved around by hand), by switching back and forth between the visual routines as either one fails. Nowhere internally does the subsumption programme have the notion of an identifiable object, yet to an outside observer it, certainly appears to follow a moving object very well.

Using the robot Tito, [13] demonstrated two visually guided behaviours which will be used in support of Seymour. Each behaviour used a stem pair of linear camera . A vertically mounted pair made use of rotational motions of the base to produce images from winch the dimensions of the room could be extracted even though the camera system was uncalibrated. Then employing earlier results from [14], the robot used forward motion to calibrate a horizontally mounted pair of cameras, which were used to find doorways through which the robot drove.

3.5 Genghis

Genghis [2] is a six legged robot which walks under subsumption control and has an extremely distributed control system. The robot successfully walks over rough terrain using 12 motors, 12 force sensors, 6 pyroelectric sensors, one inclinometre and 2 whiskers. It also follows cooperative humans using its pyroelectric sensors.

The software that implements Genghis' intelligence is organised in a novel way. There is no notion of a central controller which directs where to put each foot or how high to lift a leg should there be an obstacle ahead. Instead, each leg is granted a few simple behaviours and each independently knows what to do under various circumstances. For instance, one of the most basic behaviours can be thought of as “If I'm a leg and fin up, put myself down”. Additionally, there are behaviours such as “If I'm a leg and I'm forward, put the other five legs back a little” and “If I'm a leg and I'm up then swing forward”. Nowhere in the control system is there any notion of a central controller calling these behaviours as subroutines. These processes exist independently, run at all times and fire whenever the sensory preconditions are true.

To create walking then, there just needs to be a sequencing (this is the only instance where any central control is evident) of lifting legs. As soon as a leg is raised it automatically swings itself forward, and also down. But the act of swinging forward causes all the other legs to move back a little. Since those legs happen to be touching the ground, the body moves forward. Now the leg notices it is up in the air, and so puts itself down. The process repeats by lifting the next leg and so on, and the robot starts to walk.

Once these first few basic layers of software are implemented and the robot begins to lumber across flat terrain additional layers can be incorporated which pay attention to new sensors such as pitch and roll inclinometres or force sensors on the legs. With these sensory triggers, new behaviours can be composed which make the robot walk better. Note however, that there is no need to modify the original basic layers. The new higher level behaviours just suppress the original layers whenever the higher levels get triggered. So if Genghis is climbing over a pile of books and one leg detects a high force before it has reached its set position, it triggers a behaviour to move the set position closer to the current position. This is implemented by suppressing the original layer's command to the leg. The code for the lower level behaviour has not been altered, just ignored in appropriate circumstances. The result of this force balancing is that the robot's legs comply With rough terrain. When back on flat terrain Genghis' force sensor does not trigger the higher level behaviours, so the lower level conducts its business as originally designed.

The control system is organised into eight incremental layers: Standup, Simple Walk, Force Balancing, Leg Lifting, Whiskers, Pitch Stabilisation, Prowling and Steered Prowling. Prowling and Steered Prowling are levels that pay attention to pyroelectric sensors which detect people. These levels initiate behaviours that suppress walking unless triggered. Thus the net effect is that Genghis sands up and stays still until a person walks through his field of view. Then he attacks.

The control system utilizes 57 finite state machines, 48 of which are organised as 6 complete copies of an 8-machine control system for each leg, 2 of which are associated with local behaviours connecting whiskers to the front legs and 2 of which are associated with inhibition of balance behaviours in the front and back pairs of legs. This leaves only 5 finite state machines with any sort of central role, of which 2 coordinate walking, 1 coordinates steering and 2 produce the high level following behaviour using pyroelectric sensors to track and follow people.

The notion of organising the sensors into the control system in this way, that is, by having various sensors trigger distinct behaviours which are then arbitrated by interconnections of suppressing mechanisms, is very powerful. Specifically, this matter of organisation does away with any need for sensor fusion or having to make judgements about which sensors to believe and when. Those decisions are put off until after behaviours are initiated and those behaviours are arbitrated through the fixed priority interconnect scheme in a way specified by how the control system has been programmed. For instance, one fallout of this approach is that there is no need to calculate footfalls, or safe places for the robot to place each leg. Genghis does not bother to try to place a rear foot on a footprint from an earlier leg either. Instead, it just goes to put its foot down ballistically, but if that causes the body to pitch, then the pitch stabilisation behaviour kicks in and adjusts the stiffness of the force balancing behaviour on the load bearing legs. Failure to make this adjustment would allow those load bearing legs to collapse in a misguided effort to shift weight to other legs. By having lots of tight, real-time feedback loops that run in parallel and respond to sensory input we can get around the bottlenecks of long contemplative thought about what to do about input from a multitude of sensors.

We are currently building a new version of Genghis [4] which will be a much stronger climber and able to scramble at around three kilometres per hour. Each leg has three degrees of freedom and three force sensors mounted on load bearing beams. A single-chip microprocessor with onboard RAM and EEPROM is easily able to force servo the complete leg. Figure 3 shows the first prototype leg for this new robot The total mass of the final robot will be 1.3 Kg. Attila will have batteries which will power it for about 30 minutes while actively walking. Following that, it will have to recharge from solar cells for about 4.5 hours in Earth Sunlight.

3.6 Squirt

Squirt is the smallest robot we have ever built [15]. However, we are sure he is the world's largest one cubic inch robot. We have noticed from engineering all our previous robots that the bulk of most robots is made up of motors and batteries, whereas the components wherein we focus our research, the sensors and computers, take up only a small amount of space. We built Squirt as an exercise in shrinking brawn down to the scale of the brain using strictly off the shelf components. The design goal was a final volume of one cubic inch, but Squirt came in a little over spec, about 1 1/4 cubic inches, hence the accolade.

Even at his modest dimensions however, Squirt incorporates an 8-bit computer, an on-board power supply, three sensors and a propulsion system, all of which can be seen in Fig. 4. His normal mode of operation is to act as a “bug”, hiding in dark comers-and venturing out in the direction of noises, only after the noises are long gone, looking for a new place to hide near where the previous set of noises came from.

Squirt’s lowest level of behaviour monitors a light sensor and causes him to move in a spiral pattern searching for darkness. The spiral trajectories are created by a coupling of a forward motion along with a back-and-turn motion, implemented through the use of only one motor and made possible by a unidirectional clutch on the rear axle. Once he finds a dark spot, he stops.

Squirt’s second level of behaviour is triggered once a dark hiding place has been established. This behaviour monitors two microphones and measures the time of arrival of sound at each microphone. By noting the difference in time of arrival, he can localise the direction from which the sound came. Squirt then waits for a pattern of a sharp noise followed by a few moments of silence. If this pattern is recognised, Squirt ventures out in the direction of the last heard noise, suppressing the desire to stay in the dark. After this ballistic straight-line motion times out, the lower level is no longer suppressed and the light sensor is again recognised. If it is light, the spiraling pattern kicks back in. The end result is that Squirt gravitates towards the centre of action. The entire control system for Squirt fits in 1300 bytes of code.

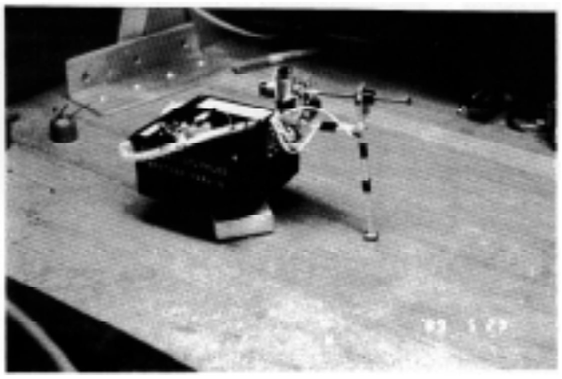

Fig. 3 A three- axis force controlled leg is the basis for a new six-logged rover. Each leg will have its own microprocessor for force servoing. Microprocessors will be connected together in a ring network. Total weight for the six legged walker will be 1.3 Kg. including batteries and solar cells for recharging. On Earth the robot will have a 10% working duty cycle during the day.

4. PLANETARY ROVER SCENARIOS

Genghis and Squirt show that it is possible to build small autonomous mobile robots. It takes only a small leap of faith to believe that such robots could be built to operate in the conditions found on at least some of the planetary bodies in the solar system. With Genghis and Squirt as models, the designers of planetary missions now have a new set of technologies available; small lightweight autonomous rovers. In the following subsections we outline some novel ideas for planetary exploration missions.

It is worth asking first though, whether small vehicles can traverse as rough terrain as large vehicles. The answer depends on the means of locomotion. On Earth, ants can traverse much wider varieties of terrain than humans or machines. Admittedly, they can not jump over large fissures, but over most of the Earth's surface these are rather rare. Thus size alone is not sufficient reason to dismiss small rovers as being unable to traverse rough terrain.

In fact, it was easier to make Genghis walk well than it is to make larger robots walk well. At a smaller scale, strength to weight ratio increases dramatically, as mass goes down by a cube law, while cross sections go down only be a square law. Getting a leg stuck in a crack temporarily does not mean disaster as it might for a horse-sized rover. Furthermore if a foot placement is missed, the distance to fall is shorter on a small robot so the impact velocity is much lower. In fact with Genghis we have found that we can simply ignore foot placement issues and rely on persistent oscillation of the leg to get the robot out of any troublesome situations.

4.1 Augmenting a Large Rover

There are major problems with planning a space mission which relies solely on one large planetary rover. If a mission is restricted to such a single large robot, there is a tremendous cost associated with losing the rover and thus a rash of conservatism will develop among the mission planners. There could be great trepidation in sending the vehicle into terrain that was unknown, rough, sloped with loose gravel or otherwise apparently dangerous, even though the area could be scientifically very interesting.

However, if the large rover carried a set of small potentially disposable I Kg rovers along, it could open up options available to the mission planners. There is much lower cost associated with losing one of the small rovers, and for sufficiently interesting sites one could, be sent off to carry out scientific tasks. These tasks might include

(1) relaying back TV images (a camera and transmitter sufficient to relay images to the large rover can be constructed in less than 50 grams),

(2) collecting small loose samples of soil,

(3) running simple chemical analyses using solid state silicon sensors,

(4) determining soil characteristics by measuring forces on a leg as it swings back and forth in the dust,

Adding such small rovers to an existing large rover would be a very small incremental cost but small rovers can vastly increase the scientific payback at the most critically interesting sites.

4.2 A Single Small Rover

An intriguing possibility is to consider sending just one I Kg rover to the Moon, an asteroid or Mars. If the total on-surface payload is small enough the mass of a vehicle needed in low Earth orbit to initiate the mission could be low enough to be in the range where it could be piggybacked into orbit on some other satellite launch mission which happens to have some spare payload capability.

A single vehicle mission would be high risk as there would be only one rover, but the cost might be so low that it would still make sense. Given that we have had no mobile surface exploration of any body other than the Moon, the payoff from any data collected from multiple sites on another body could be enormous.

4.3 A Herd of Small Rovers

More radically, one can consider replacing a large rover by a collection of small rovers.

The cost per kilogram of the rovers would be greatly reduced from the economy of building multiple copies. Lower reliability for each individual rover would be acceptable, as failure of a single rover would not jeopardise the whole mission. Indeed the mission could be planned with a particular reliability expectation that was below 100%.

Upon landing either together or in smaller groups, the rovers would disperse covering wide ranges over the surface.

Not all of the small rovers need be alike. Different ones could be specialised to particular scientific goals by the selection of (small) instruments onboard. The overall science component of the mission need not be compromised if time is spent rethinking the size and type of instruments used. The possibilities arising from having multiple well separated rovers which can nevertheless communicate with each other might lead to new and better measurement techniques on some fields.

Fig. 4 Squirt, the smallest robot we have built to date, packs motor, batteries, microcomputer, interface electronics and three sensors into a volume slightly larger than one cubic inch.

4.4 Micro Rovers and Manned Missions

A different sort of mission could be in support of manned activity. A manned lunar colony might be planned using lunar soil as radiation protection mass. To avoid the high cost, fast paced soil moving operations required upon the first manned landing, a small troop of micro rovers (say 100) in the I Kg range could be landed many months or even years ahead of the planned manned landing to prepare the way.

The micro rovers would be totally autonomous and not even communicate with Earth, though a central station, might send back television pictures of the area for monitoring on Earth. The rovers would operate much as an ant colony and mine the soil, perhaps tunnelling, or perhaps just piling loose collections of dirt for later manned use. Because time would not be a pressing factor, the rovers could use very slow techniques such as surface grinding to break up the regolith. Multiple rovers would be required to provide redundancy as surely over a long term, some rovers would expire. The power source could be small solar cells used to recharge batteries for higher current drain activities.

5. EMERGING TECHNOLOGIES - GNAT ROBOTS

Although the idea of replacing one large robot with many small Genghis-sized rovers creates new opportunities for planetary exploration, we can advance technology one step further. By organising the intelligence system of an artificial creature in terms of a subsumption architecture, we have seen that its control system can compile down to a very small amount of silicon. The remaining weight and bulk of a mobile robot then, is dominated by motors and batteries; low-tech items that have never seen the drastic cost and size reductions that integrated circuits have demonstrated in the last few years.

As many jobs for planetary explorers consist primarily of collecting data, robots that carry around extra bulk and weight offer no benefits from their size. Oftentimes, a robot that begins as a chassis with a few motors and batteries grows larger merely because large motors draw hefty amounts of power, which call for large batteries. Since large batteries load down the chassis, the vehicle further requires even larger motors.

The whole escalating problem of large motors requiring large batteries, in turn necessitating Larger motors and so on, could be eliminated if we stepped in the reverse direction. By scaling down and using smaller motors which could make do with tiny power supplies, we could gain a tremendous advantage. As most of the componentry we are interested in on our rovers, the computers and sensors, can fit on small silicon chips anyway, (charged coupled device cameras are just silicon sensor arrays) we can envision scaling all the subsystems down and integrating an entire robot on a chip [16]!

Recently, several groups have actually begun to design and build motors onto silicon substrates. Through a technique known as silicon micromachining. originally developed for microsensors, it is possible to etch freely movable structures onto silicon wafers. These actuators are primarily electrostatic and often no more than a few hundred microns in diameter [17, 18 & 19]. Micromotors do not have to necessarily be based in silicon however, as [20 & 21] have shown with harmonic microactuators fabricated from a variety of materials. However, micromotors created with processes compatible with silicon integrated circuits hold the promise of integrating sensors and electronics along with the actuators on the same substrate.

The advantage of integrating an entire robot onto a single piece of silicon is that we could then print robots like we print integrated circuits - by the thousands. The problem with today's robots is that they are just too expensive for the level of intelligence we can endow them. One approach might be to concentrate on making them smarter, but on the other hand, we could focus on making them cheaper for the same level of competence we can attain today. By reducing cost per level of talent, through batch fabrication techniques available with silicon microelectronic processes, robots can become increasingly more useful [22 & 23].

Self-contained, completely autonomous chip robots (we call them gnat robots) give us a whole new image for robotics. At first it might be reasonable to ask what a motor with nano-Newton-metres worth of torque would be good for, but if the only requirement is to push the chip on which it is built, then there might be something worthwhile there. As many mobile robots are used solely to collect information, such as security robots or planetary explorers, there really is no advantage to lugging around extra bulk. A gnat robot would be perfectly sufficient since software and data (as compared to the motors and batteries on large robots) take up almost no space.

A complete robot on a chip would put an intelligent connection of perception to action in an extremely small package. The low mass of a gnat robot is ideal for launch conditions as thousands of small gnat robots could be incorporated into one payload. The inherent redundancy of many independent, autonomous machines increases the likelihood of acquiring large amounts of data and in general, of mission success. In addition, an integrated robot implies escaping the burden of having connectors anywhere on the robot. As connectors are most often the site of problems, their absence and the resulting simplicity of an integrated robot raises the likelihood of reliability.

Such a new look and feel for robotics of the future requires new perspectives on how we solve problems and put gnat robots to use. One good model to keep in mind is to think in terms of an analogy to parallel processing computers vs. traditional sequential uniprocessors. Programming an algorithm on a parallel computer requires standing on your head and thinking sideways in comparison to traditional ways of implementing algorithms, but if the algorithm solution is well matched to the structure of the parallel computer, then there can be tremendous advantages in speed. Lots and lots of very simple processors can work together to out perform a goliath uniprocessor.

Similarly, we can match gnat robots to many real world tasks and solve problems in better, albeit different ways. Gnat robots introduce two new concepts to robotics. First is the notion of massive parallelism. By using lots and lots of simple robots in place of one large complicated expensive robot, we can do work in the environment at a fraction of the cost. Second, with lowcost, low-intelligence creatures, we can envision cheap, disposable robots. There is no need to spend undue amounts of effort retrieving the robot after it has finished its task or run out of batteries. Instead, gnat robots are like Bic pens and we throw them away when they are done.

Flynn, Brooks and Tavrow [24] provide detailed proposals for avenues around some of the technology hurdles involved in creating gnat robots, including microactuators processed from piezoelectric materials which have the potential for delivering higher torques, integrated infrared and optical imaging arrays made out of pyroelectric materials, and some novel techniques for forming three dimensional chasses and assembling the appendages. It also gives examples of applications for gnat robots, from autonomous sensors to machines that get into hard to reach places and do useful work, such as cleaning lenses of space telescopes.

Many of the ideas for thinking about how to solve problems with societies of gnat robots come from ideas in earlier work on multiple agents within one brain communicating through the world to compete for the resources of the robots body [6]. One should not think of swarms of gnat robots as machines which are told what to do, but rather as autonomous creatures that when turned on, do what is in their programmed nature to do, in the spirit of [11].

5.1 New Vistas

With this new vision of robot technology, complete autonomy in a very small package at low cost, even more radical planetary missions can be considered.

The key is that although such tiny robots cannot maintain two way communications, they can provide one-way low bandwidth signalling. They can include tiny comer reflectors that can be rotated or uncovered. An orbiter scans the planetary surface with a laser. With one corner reflector, a gnat can single its position and its desire to communicate. With multiple corner reflectors tuned to different frequencies, a gnat can signal more bits, two or three perhaps.

One application for such gnats is to spread them out over a large area of the planetary body, and let them signal their position if and only if they find some condition is met locally. The orbiter then gets a density map of the likelihood of that condition by watching for signalling gnats. Small chemical field effect transistors could be used to detect specific compounds for instance.

But how should the gnats be spread out over the surface? On Mars they could blow in the wind. Alternately they could locomote themselves by hopping. They could use solar cells to collect energy and store it in a silicon spring. After a certain level of compression, a sensor fires and the spring is let go, and the robot goes flying. Wherever it lands, it checks for the desired compound. If it finds it, it anchors itself and puts up its corner reflector. Otherwise the robot continues its stochastic search of the planet, for years perhaps.

Similarly, imagine distributed seismeographic sensors created by millions of tiny gnat robots covering the surface of a planet at regular intervals. They have micro-accelerometers and vibration sensors onboard and they communicate very crude tremor magnitudes to the orbiter. Millions of such sensors could be placed all over the planetary surface at the same cost as one more traditional large sensor.

6. CONCLUSION

Exploration of the Earth proceeded by many small spontaneous sorties into the unknown. Small autonomous rovers give us the same opportunity for the rest of the solar system. Useful autonomous robots can be designed, bunt and tested on fast timescales. They are cheap because of their size and the ability to mass produce them. They are cheap because they reduce the required launch mass. They are cheap and reliable because they are out of the control of a large ground-based mission organisation. With imagination and nerve we can invade the whole solar system.

*Support for this research was provided in put by the University Research Initiative under Office of Naval Research contract N00014-86-K-0685, in part by the Advanced Research Pro" Agency under Office of Naval Research contract N00014-95-K-0124 and in part by a gift from Siemens.

REFERENCES

1. R.M. Jones, "Micro Spacecraft for Space Science", Workshop, JPL, July 1988.

2. R.A. Brooks, "A Robot that Walks: Emergent Behaviour form a Carefully Evolved Network", *Neural Computation* , 1:2, Summer 1989.

3. C.M. Angle, "Genghis, a Six Legged Autonomous Walking Robot", MIT S.B. Thesis in Electrical Engineering and Computer Science, March 1989.

4. C.M. Angle, "Attila's Crippled Brother Marvin", MIT Term Paper *in Electrical Engineering and Computer Science,* May 1989.

5. R.A. Brooks, "A Robust Layered Control System for a Mobile Robot", IEEE *Journal of Robotics and Automation,* RA-2,14-23, April 1986.

6. J.H. Connell, "A Colony Architecture for an Artificial Creature" MIT PhD. Thesis *in* Electrical Engineering and Computer Science, June 1989.

7. R.A. Brooks and J.H. Connell, "Asynchronous Distributed Control System for a Mobile Robot", SPIE Vol. 727, Mobile Robots, Cambridge, MA, 77-84, November 1986.

8. J.H. Connell, "Creature Building with the Subsumption Architecture", IJCAI-97, Milan, 1124-1126, August 1987.

9. R.A. Brooks, J.H. Connell and P. Ning, "Herbert: a Second Generation Mobile Robot", MIT Al Memo 1016, January 1988.

10. J.H. Connell, "A Behaviour-Based Arm Controller", MIT Al Memo 1025, June 1988.

11. R.A. Brooks and A.M. Flynn, "A Robot Being", NATO Workshop on Robotics and Biological Systems, Tuscany, Italy, June 1989.

12. I.D. Horswill and R.A. Brooks, "Situated Vision in a Dynamic World: Chasing Objects", AAAI-88, St. Paul, MN, 796-800, August 1988.

13. K.B. Sarachik, "Characterising an Indoor Environment with a Mobile Robot and Uncalibrated Stereo", Proceedings IEEE Robotics and Automation, Scottsdale, AZ, 994-999, May 1989.

14. R.A. Brooks, A.M. Flynn and T. Marill, "Self Calibration of Motion and Stereo for Mobile Robot Navigation", MIT AI Memo 984, August 1997.

15. A.M. Flynn. R.A. Brooks, W.M. Wells, and David S. Barren, "The World's Largest One Cubic Inch Robot", Proceedings IEEE Micro Electra Mechanical Systems, Salt Lake City, Utah, 99-101, February 1989.

16. A.M. Flynn, "Gnat Robots (And How They Will Change Robotics)", IEEE Micro Robots and Teleoperators Workshop, Hyannis, MA, November 1987.

17. S.F. Bart, T.A. Lober, R.T. Howe, J.A. Lang, and M.F. Schlect, "Design Considerations for Microfabricated Electric Actuators", Sensors and Actuators, 14(3):269-292, July 1988.

18. H. Fujita and A. Omodaka, "Electrostatic Actuators for Micromechatronics", IEEE Micro Robotics and Teleoperators Workshop, Hyannis, MA, November 1987.

19. Y-C. Tai, L-S. Fan, and R.S. Muller, "IC-Processed Micro-Motors: Design, Technology and Testing", Proceedings IEEE Micro Electro Mechanical Systems, Salt Lake City, UT, 1-6, February 20-22,1989.

20. W. Trimmer and R. Jebens, "An Operational Harmonic Electrostatic Motor", Proceedings ME Micro Electro Mechanical Systems Salt Lake City, UT, 13-16, February 20-22,1989.

21. S.C. Jacobsen, R.H. Price, J.E. Wood, T.H. Rytting and M. Rafaelof, "The Wobble Motor: An Electrostatic, Planetary-Armature, Microactuator", Proceedings IEEE Micro Electra Mechanical Systems, Salt Lake City, UT, 17-24, February 20-22,1989.

22. A.M. Flynn, "Gnat Robots: A Low-Intelligence, Low-Cost Approach", IEEE Solid-State Sensor and Actuator Workshop, Hilton Head, SC, June 1988.

23. R.A. Brooks, "Micro-Brains for Micro-Brawn: Autonomous Microbots", IEEE Micro Robots and Teleoperators Workshop, Hyannis, MA, November 1987.

24. A.M. Flynn, R.A. Brooks and L.S. Tavrow, "Twilight Zones and Cornerstones: A Gnat Robot Double Feature", MIT Al Memo 1126. July 1989.