Design of the "Army-Ant" Cooperative Lifting Robot

This new class of simple, inexpensive, interchangeable mobile robots are called "army-ants." They perform physical tasks and make cooperative decisions as a coordinated, homogenous team.

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The first-generation army ant was built by Richard Chen, Matthew DelGioro, Paige Detrick, Kyong Kang, and Robert Zacharias. The second generation robot was built by Henry Green, Troy Hille, Daniel Huff, Terry Lawrence, John Maushammer, Richard (Brendan) O'Connor, and Bryan Staats. Special thanks are due to Kimberly Sharman for her research assistance, contributions to the sensor construction, and advice in circuit design.

This paper describes the design and development of a new class of mobile robot. These small robots are intended to be simple and inexpensive, and will all be physically identical, thus constituting a homogeneous team of robots. They derive their usefulness from their group actions, performing physical tasks and making cooperative decisions as a coordinated team. All mechanical and electrical design aspects are decided with the group-dynamical behavior in mind. Because of their behavioral resemblance to their insect counterparts, they have been named "army-ant" robots.

While this robot was evolved as much as it was designed, the credit for realizing it rests with these people.

INTRODUCTION

Genesis

The "army-ant" robot system was originally envisioned as a flexible material-handling system. Under this scenario, many small robots would be deployed in large numbers to cooperatively lift and transport objects. As seen in Figure 1, the small tank-like robots would position themselves around the periphery of a large object, "squeeze" themselves underneath it, and then proceed to move in a coordinated way to transport their load.

In contrast, commercial robotic material-handling systems generally take one of two forms: either highly-constrained container-transfer devices, including gantry cranes and tracked automatic storage and retrieval systems (ASRSs); or automated guided vehicles (AGVs). Gantry cranes and ASRSs are widely used but restricted to highly structured environments, such as specially designed warehouses and libraries.

In less structured environments, AGVs are widely used. AGVs, though, are often constrained to following embedded cables, stationary markers, tape lines, or other navigation beacons. More intelligent AGVs can negotiate obstacles and plan alternate routes.

In both cases, AGVs and ASRSs are limited in the materials they can handle. Often, materiel to be transported must have dedicated,
standardized containers, or else they require human assistance to load and unload the payload. Furthermore, particularly in the case of the AGVs, they are often limited to handling payloads that are much lighter or smaller than themselves. Often, the payloads are considerably less costly than the robots themselves. AGVs employed in office buildings and hospitals, for example, may cost $75,000, but are relegated to delivering mail or trays of food.

The army-ant system was conceived to be more flexible and economical. Among its advantages over conventional material handling systems are:

- **Robustness.** Making the robots identical makes them modular and interchangeable. Because they always function in teams, failure of one or more individuals can be naturally and easily compensated for by other robots. It also greatly simplifies the programming and maintenance of the system.
- **Flexibility.** Rather than requiring palletized loads, the army-ant robots are designed to carry either palletized or unpalletized loads. Indeed, the original design was targeted to the military’s need for battlefield materiel handling and air-cargo handling.
- **Small Size.** In order to better scale to the size of the task, whether it is crawling through narrow passage-ways or handling pallets of odd size, we prefer small robots that are lightweight, easily stored, and highly maneuverable. For operations requiring more power, any number of additional robotic teammates can be recruited.
- **Low Expense.** A result of being small and identical, the robots would be well suited to mass-production for an economy of scale. The high cost of many of today’s mobile robots is arguably attributed to their manufacture in relatively small lots and their high degree of sophistication. Because of their robustness, the low expense of army-ant robots may make them expendable in military, space, or hazardous environments.
- **Simplicity.** A property equally compatible with size and manufacturability, low cost is a pre-requisite to deployment in large quantities. Simplicity is the necessary trade-off in order to achieve the economy of scale, because the cost of integrating many robots must be compensated by the cost of the individuals. Low cost is directly correlated with the technological simplicity of the devices.
- **Emergent Group Behavior.** It has been shown in very recent work that “group dynamics” may emerge in collections of autonomous individuals with rudimentary communication abilities. The study of this behavior as a large nonlinear dynamical system suggests that one can get “more than the sum of the parts” from the population [11, 12]. Again, the analogy is drawn to certain species of social insects, whose individual behaviors are sometimes detrimental to their individual survival, but beneficial to the population as a whole [5]. In addition to physical material handling tasks, distributed robotic systems such as these may have other applications, such as:
  - Nuclear and hazardous waste cleanup with robotic “swarms.”
  - Mining (including material removal and search-and-rescue), Mine sweeping (both land and water).
  - Surveillance and sentry.
  - Planetary surface exploration and excavation.
  - Microelectromechanical elements that are too small for on-board control.

Scope of the Paper

It is clear from the previous discussion that the “army-ant” robotic application is of enormous scale, involving complicated issues in mobile robot technology, decentralized control, distributed artificial intelligence, and communications. Most of these issues are yet to be addressed, while some have been discussed elsewhere [2, 14-17]. In this paper, we trace the design and development of the prototype robot.

Development of the first generation robot was written into the project budget in order to address an anonymous reviewer’s off-hand comment that “I doubt that it can be built.” As a proof-of-concept, two teams of robotics students (electrical, computer, and mechanical engineering), graduate and undergraduate, were tasked to implement the conceptual designs suggested by the research. They were to construct a small (about the size and shape of a toaster-oven), inexpensive ($<1000), mobile robot that, under computer control, could lift and crawl under an un-palletized corrugated cardboard box much larger than itself.

This paper describes the results and status of these designs. Admittedly, as the reader will surely notice, these robots do not have the full repertoire of abilities we are asking of the eventual design. Nevertheless, they represent significant steps toward a new approach to cooperative mobile robotics, and they have successfully demonstrated some innovative approaches to robot design.

**FIRST GENERATION ARMY-ANT**

The top priority in the production of the first generation robot was time (followed closely by cost). An absolute limit of one semester was allotted to five students to demonstrate a working system. As a result, it was decided that the physical structure would be adapted from off-the-shelf components to the extent possible.

Specifications for the design dictated that the vehicle have a low profile in order to minimize vertical lifting of the pay-
load. Furthermore, team transport necessitated a zero turning radius and, eventually, a swiveling, lazy-susan style top surface for the robot. In this way, several robots maintaining a friction-enforced contact with the underside of a rigid payload would not have to implement differential steering trajectories during turning maneuvers. In such a case, those robots on the outside of a curve would have to coordinate their trajectories with those on the inside of the curve, which in turn implies some a priori knowledge of the dimensions of the payload. While we are developing communications-based cooperative behaviors, the need for differential steering is completely circumvented with freely-rotating robots. In the end, the swivel mechanism was not installed, since only one vehicle was to be built in this generation and so multiple-robot cooperative turning would never be demonstrated.

Among the choices for zero-turning-radius configurations, treaded tank-like vehicles were chosen because they have simple kinematic models and are relatively easy to construct. Synchro-drive mechanisms are another good choice, but are more mechanically complex. Because it was desired that the actual transport mechanism should not be a research issue, but should be available in inexpensive off-the-shelf hardware, a radio-controlled tank-like vehicle was used. This provided the chassis-tray, together with drive axles and wheels, bearings, and a suitable gear train. All other components discarded, this base vehicle provided a handy mechanical substrate that would be easily customized.

Computer
The robot was required to operate autonomously under computer control, so the radio-joystick and receiver were never installed. Instead, a Motorola 68HC11 EVBU was selected to act as arbiter for sensor inputs in a stimulus/response scheme. This EVBU was essentially un-modified; i.e., no external memory or specialized interfaces were used. Instead, the EVBU's built-in RS232 port, small internal RAM, and I/O ports were directly connected to the necessary sensor and motor driver hardware. Because of the EVBU's small fan-out, only buffers were added to the wire-wrap area on the board.

Power
Power was supplied by two 6-volt, 4.2 amp-hour lead-acid batteries. For stability during the lifting of heavy objects, these were also considered as counterweights and were located in the bottom of the chassis tray, under all of the other circuit boards. The resulting inaccessibility prompted the placement of the recharging circuit adjacent to the battery terminals, with a 112-volt AC power cord routed through the body. The recharging board required little space and would then not have to be transported separately.

Two connections to the battery were made: one, across a single battery, to a five-volt regulator and filter board, and another, spanning both batteries, that would supply 12 volts to a relay and small air compressor that would be used for the lift mechanism. Such connections across the two batteries resulted in uneven current drain, power supply coupling, and subsequent loss of charging efficiency. This problem is addressed in the second generation robot by using completely distinct power sources for electronics and power devices such as motors.

Drive Train
The high-speed, low torque motors included in radio-controlled vehicle kits are clearly unsuitable for the army-ant robots. Instead, Barber-Coleman DC gearhead motors were retro-fitted to the gearbox. Their 300 RPM no-load speed was reduced by the combined 26:1 (approx.) reduction of the external gears and the tread to give 7.3 feet/minute speed.

The motors were bidirectionally speed-controlled with a pulse-width-modulated (PWM) H-bridge driver circuit consisting of Darlington-paired FETs for high current drive. The 68HC11 controller board, having little else to do in the simple sensor-based operation, provided direct output of the PWM signals, buffered for isolation.

Lift Mechanism
By far the most novel component of the robot design, the lift mechanism was required to support much more weight than the actual weight of the robot (a feat of some rarity in robotics), but not consume more current than the motor drivers could supply. Large work requirements therefore implied a large mechanical advantage from the mechanical lift.

A number of options were initially considered, including dual lead-screw driven scissors lift, and a geared lever assembly. Because the robot need only crawl under the object so that it would rest on its "back," complicated articulated linkages could be avoided. After the lifting maneuver, the weight of the load would be born by the axle bearing rather than the lift mechanism, so such a mechanism would not require continued holding power after the actual lifting maneuver.

The result of these factors was the choice of a pneumatic bladder. As shown in Figure 2, the bladder was housed in a "cow-catcher" tray mounted in the front of the robot. The tray has a false floor, under which is located the miniature 12VDC air compressor and solenoid valve. Above the bladder is the leading hinged lift-lever: a flat plexiglass sheet with a sheet metal front lip. This lift-lever is hinged to the top horizontal surface of the robot, much like the robots depicted in figure 1. Although the pump was capable of generating over 50psi, it was generally driven to produce only about 10 psi (at an unknown flow rate). Thus, with approximately 25 square inches of contact area between the inflating bladder and the hinged plexiglass, 250 pounds of lifting force could be generated. This contact area would increase under higher loads, and decrease with lower loads, making a self-regulating pneumatic lift.

Because the entire robot weighed less than twenty pounds, applying such vertical loads at the front extremity would easily tilt the treads off the ground. The front basket was therefore supported directly by the ground (floor) by attaching ball casters to its underside. Then the full weight of the batteries could contribute to the tangential ground friction necessary for pushing while the body of the vehicle was freed from the weight of the load during the lift. Of course, after the box was completely on the back of the robot, its weight would be totally supported by the axles and treads.

Sensors
Initially, the robot was incapable of navigation, having no goal-seeking or obstacle avoidance sensory apparatus. Our focus in
the first generation was demonstration of the mechanical lift. To this end, lever microswitches sufficed to trigger the lifting response, and to turn it off when lifting was complete.

One switch was mounted under the hinged lift lever, on the top surface of the cow-catcher. Small deformations of the plexiglass when the front lip made contact with a heavy object triggered the microcontroller to initiate the lift response. This involved only turning on the air compressor to inflate the bladder while slowing the forward progress of the treads. Lifting the edge of the payload (for demonstration, a large but empty corrugated cardboard box; supported from the back so that the robot did not push it across the floor) serves not only to raise it high enough to make room for the robot, but also to decrease the friction between the box and the lift edge.

A second microswitch mounted between the horizontal top surface of the robot and the rising lift lever, along the axis of the hinges, is activated when the lift lever is almost horizontal. At this point, the pump is turned off, but the treads continue to drive the vehicle forward, sliding under the box.

When the payload box has covered the entire top surface of the robot, it depresses a third switch, which has a number of functions. For demonstration with a single robot, it inflates the air bladder by opening a solenoid valve, and initiates backward robot motion so that the robot can execute whatever open-loop trajectories may be programmed into it. In its final implementation, where there will be other robots that themselves will be trying to crawl under the box, activation of the third switch stops all robot motion and puts the robot into a standby mode, prepared to emit a "ready" signal when: i) the payload is horizontal again, and ii) the force supported by the robot is below a threshold (strain-gage force sensors have been designed and built but not yet installed). Until this ready signal is emitted, the robot would transmit a "help" signal, effectively attracting more robots to the same payload. Simple tone decoders can be used to detect emitted signals with a priori known meanings.

Results
Shown in Figure 3 are still photos of the first generation army-ant vehicle lifting and supporting the cardboard box.

As we have mentioned, many of the intended functions of the robot (top swivel, signal emission, etc.) were not implemented because of the lack of teammate robots with which to coordinate. Many of these features are being implemented in the second generation army-ant, which improves on several deficiencies of the first. These will be discussed next.

SECOND GENERATION IMPROVEMENTS
The most egregious shortcomings of the first generation robot were mechanical. The off-the-shelf chassis was molded plastic, and the wheels within the tank treads ("bogeys") were attached with torsional springs as shock absorbers. Thus a vertical load resulted in excessive compliance, bottoming out the vehicle and exerting bending forces on the axles.

The top surface of the robot had been designed to be smooth enough to slide against the payload during the lift maneuver. This low friction force could be tolerated when the robots moved in unison, but it did limit the forces that could
be transferred to the load. When the robots were to crawl back
out from under the load, this same lack of friction could
result in undesired sliding of the load on the dwindling num-
ber of robots still present. It is unclear what would happen
when, during the drop process, only two robots remained,
each taking advantage of the low friction to back out.

In addition, of course, were the sensing and communica-
tions capabilities left unresolved from the first generation.
Beacon-seeking, range-finding, status signals, and closed-loop
motion feedback must all be implemented. In addition, the
swivel-top must be installed and the force sensors attached
and interfaced.

The second-generation robot design addresses most of
these concerns, as well as many improvements on the more
basic capabilities. Unlike the first generation, it is built
entirely from the ground-up. Figures 4 and 5 show the layout
of the mechanical components. It is still a two-tracked tank-
like vehicle, but major changes have been made to most
other systems.

Computer

More optimistic expectations required a more capable com-
puter in the second generation. Expanded sensory capabilities
and robot autonomy necessitated considerable improvements
on the 68HC11 EVBU, which is now operated in expanded
mode in order to access the address and data bus.

First, 32K of external non-volatile static RAM was added.
Second, I/O ports were mapped to external memory and a sep-
ate I/O board was constructed, connected to the main board
through a 50-pin connector. This I/O board also contains the
motor driver circuitry, the voltage regulators, decoding logic,
and a connector to an optional external LCD display to be
used for debugging. Also on the I/O board is space for a 9-volt
battery dedicated to powering the logic functions only, but
later longer-life 4 amp-hour rechargeable NiCd batteries are
to be used as space allows.

Power

Ideally, the same lead-acid batteries used in the first robot would
also be used in the second. However, space considerations led to
the choice of 2 volt D-size sealed lead-acid "gel-cells." These are
required in larger numbers but have the advantage of being dis-
tributed throughout the available space in the chassis.

It was found that in the first robot, using the same power
source for the high-current actuators, especially the air com-
pressor, introduced intolerable noise into the power bus. Volt-
age regulation and buffering could not completely isolate
these noise sources from the sensitive digital circuits, so it
was decided to use completely distinct power sources: two
separate banks of batteries. Only the power sources for the
digital electronics need be regulated. The other 12-volt source
is switched across the motor terminals by the PWM H-
bridges, and therefore need not be a "clean" source.

Drive Train

The drive mechanism remains largely unchanged from
the first design. In this case, though, material had to be selected
and assembled, rather than relying on manufactured chas-
sis, wheels, and treads.

The tread material is made from nylon reinforced rubber
conveyor belting, stitched and glued together to form a closed
loop. These treads will ride between edge flanges on rein-
forced PVC wheels. On the wheel axles are quadrature
encoders for position and velocity control of the treads.

High-torque DC gearhead motors were again selected for
the drive train, with 1:1 external gearing. These motors oper-
ated at 25 RPM and produced a peak torque of 20 in-lbs, while
consuming 1.3 amps.

The motors are again driven by PWM signals, but this
time the PWM logic-level source is not the 68HC11 itself,
but National Semiconductor LM629 motor drivers. The
68HC11 can read from and write to these drivers, which
assume all motor control responsibilities from the main
processor.

Lift Mechanism

The second-generation robot uses a lift mechanism consisting
of a single movable flat top platform. Instead of the air com-
pressor and bladder, it requires two lift motors, each with a
large gear reduction. The motors actuate a twin jack-screw
mechanism similar to the robots pictured in the original con-
ceptual diagram of Figure 1, but mounted in the front and
back, instead of on each side.
Twin jack-screws give the top platform two degrees of freedom: vertical (both jack-screws moving in the same direction), or tilt (one raising, the other lowering). The cost of the second degree of freedom, of course, is that the second actuator must be driven.

Even twin jacks like this do not compare to the mechanical advantage of the pneumatic lift, so high reduction gearhead motors (582:1) were chosen to drive the screws. The turning threaded rods produce linear actuation through recirculating ball bearings in a closed guide—a "ball" screw. Recirculating balls are considerably more efficient that a simple lubricated threaded guide. For the threaded guide, the motor would be required to produce 1.14 in-oz of torque for each pound of axial load on the shaft. Ball-screws, by comparison, require only 0.354 in-oz per pound of axial load. Analysis with a worst-case assumption of 200 lb applied to the leading edge of the robot results in over 485 lb of axial load on the screws, so the improved efficiency of the ball screws saves almost 24 in-lbs of torque demand on the motor.

As the drawings in Figure 5 illustrate, this motorized screw drive requires that the motors themselves be free to move within the robot body; an arrangement that wastes valuable space and requires the new robot to be wider than the old (approximately 19 inches versus 13 inches).

The advantage of the two-degree-of-freedom platform is three-fold. First, it makes the entire top platform a lifting wedge, instead of the shorter hinged portion of the first design. This reduces the angle between the platform and the ground when the platform is lowered to the lifting position. Lower friction and a sharper approach angle result.

Second, the platform is free to move in a purely vertical direction, which will facilitate cooperative transport of a single payload on uneven terrain, or on slopes.

Finally, the single platform greatly facilitates "backing-out," since the down-tilt maneuver can be performed while the robot is in place under the payload. Tiltling the platform down will not only reduce the contact friction, but will cause the weight of the pallet to actually exert a force with a horizontal component, helping to force the robot out.

Sensors
The second generation army-ant is equipped with many of the same sensors employed by other researchers: infrared for beacon and direction-finding, as well as obstacle detection, ultrasonic for range-finding, and whisker-type contact switches for collision detection. The use of these sensors is unique mostly in the types of information gathered from them.

The materials-handling scenario, as well as many of the other envisioned applications, requires that the ants be able to detect the range and direction to a stationary beacon attached to a potential payload. Robots are thus "attracted" to the payloads that must be moved. Destination information can be encoded such that it modulates the emitted beacon signal, or otherwise mounted on the payload itself (barcode, perhaps). We also require that the robots be able to locate each other, in order that they can perform most of the spatial self-organization tasks we have generated [17].

These range and direction-finding sensors are mounted on a 360° motorized scanning head, to be mounted on a rear-mounted mast, not shown in the figures. This mast is not retractable and thus prevents the robots from crawling completely underneath an object. An alternative mount was considered under the front lifting edge of the robot, which could, of course, only operate when the edge is elevated. Such a sensor, though, would not have a 360° scanning range.

The ultrasonic range sensors, now standard equipment on mobile robots, are gold-foil capacitive transducers, using time-of-flight range measurements. It has driver electronics that send high voltage pulses (400V) to the transducer, filter the echoes, and count the time until the return.

Robots recognize each other through infrared (IR) signals. Ultrasonic measurements of another robot's range will only be triggered when a detector signals the CPU that the sensors are pointing at an IR emitter. Each robot has a ring of beam-focused IR transmitters mounted on the scanning sensor head. These emitters are driven much like the emitters described in [10]. To avoid interference with ambient light, the IR signals are switched at 40KHz and further modulated by tones ranging from 100Hz to 1000Hz. Inexpensive off-the-shelf devices can decode these signals.

In order to distinguish other robots from the fixed payload beacons, an identical IR detection scheme is used. Payload beacons are constructed as small modules that adhere to the sides of the payload, with 9-volt batteries for power. Payload "beacon-buttons" are fixed to modulate the 40KHz emitted IR signals at 200Hz. Thus, simple tone decoding distinguishes a beacon from another robot.

For obstacle detection, the ultrasonic range sensors can be triggered when the IR detector does not point to an IR source. However, because of the relatively slow motion of the robot, whisker sensors suffice to stop the robot without damage in the event of a collision, and are more efficient. All the controls algorithms being written as reactive stimulus/response pairs, we intend to do no world-mapping and therefore do not intend to scan the entire environment.

FEATURES FOR GROUP OPERATIONS

Group Operations
Many of the other sensor devices on the army-ant robot are used to facilitate group coordination. Our approach to multiple robot coordination is to make the population homogeneous; i.e., all robots are alike. This has the advantage that it makes the robots mass-producible, and removes any single point of failure. It does, however, require that each robot be equally capable with every other robot. Coordination, then, is somewhat more difficult because there is no supervisor or other fixed hierarchical command or communications structure. We ask that differing responsibilities among a team in cooperation emerge dynamically, so that a leader might be elected (see [13]), but could easily be replaced by another robot if it should fail.

In [14], a coordinated control system was developed that enables multiple robots to act in concert in the transportation of a pallet. The concept adopted was a leader/follower strategy, wherein one robot (presumably one that first senses a destination beacon), turns itself toward that beacon and applies a force. The others, with appropriate force sensors at their pal-
let interfaces, detect these forces and turn to align themselves with that direction. The treaded vehicles result in nonholonomic constraints, and can only travel in the direction in which they are pointed. They therefore can exert active forces only in that direction, but can support constraint forces in all other directions. During the turning maneuver, they exert interaction forces against each other, but successfully converge to a common direction. This strategy is implemented with a reactive “caster” response. In the same way that a passive caster aligns itself with the direction of travel of a pushed chair, the follower robots align themselves with force exerted by a leader (or externally).

When unconstrained, that is, when the robots are traveling independently in search of a load or for mere exploration, we have devised a number of reactive self-organization strategies. With simple rules, we can show that the sensor suite intended for the army-ant robots sufficiently facilitates the formation of regular geometric arrangements of robots, clustering, uniform coverage of an area, and navigation through arbitrarily obstructed regions such as warehouses and office buildings [18].

Group coordination and task decomposition in various tasks is an area of active research, and it is beyond the realm of this paper. However, there are certain sensor and hardware structures implied by some of these cooperation techniques, particularly during cooperative material handling, that warrant discussion.

Force Sensors
In much the same way that forces among multiple force generators must be equitably distributed in multi-fingered hands and multi-legged vehicles, we would prefer that the forces borne by each robot be equally shared when carrying a common load [6-7]. It can be shown that “equally shared” forces are impossible when one considers that the robots are subject to nonholonomic constraints and moment-balance equations, but nevertheless, we would like them to satisfy a constrained minimum-norm criterion.

With total force available to the 68HC11, vertical weight-bearing can be compared among several robots (the “pall-bearer” problem). We are investigating some novel reactive force-equalization techniques based on the entrainment of broadcast nonlinear waves, but if the force signals are available for transmission, a number of conventional control methods may be envisioned.

Equal force distribution implies both force-sensing and signal transmission. We have found that simple strain gages mounted on cantilever arms supporting the top platform provide sufficiently clean signals that signal-conditioned load cells are not necessary. As shown in Figure 6, strain gages are to be applied to loading points that support the top platform, cushioned by commercially-available rubber shock-mounts.

It is also necessary that horizontal forces be sensed, but unlike vertical force, they need not be transmitted in order to achieve cooperative transport (the “Ouija-board problem”). Instead, we have shown that if a leader is determined, the rest, the followers, can copy the leader’s movement by simply sensing the reaction forces applied to their top surfaces. The reactive caster emulation strategy already discussed is one realization of this approach [14-15].

The caster solution requires a series of reactions, passive and active, in response to horizontally applied forces. The passive reactions include a small horizontal displacement in the direction of the applied force, primarily for a compliance that aids stability, but also to create a small moment arm at the contact point. Sensing this displacement, the robots can turn to face this force, then begin moving so as to regulate it.

The displacement is accomplished with a large shock-mount whose center is also the center of rotation of the swivel bearing. A combination of a continuous-turn potentiometer and a linear potentiometer serve to sense the magnitude and direction of horizontal displacement, assuming known spring and damping constants for the shock-mount.

Software
Control code for the robot is currently written in 68HC11 assembly, but is now under development in C for convenience. Although it is desired that the code be reactive, thus conforming to our philosophy of simplicity, it is executed on a single processor board. It therefore cannot be described as a “subsumption” architecture [3]. Rather, we refer to it as “pseudo-subsumption” multitasking system. Because each of the sensor service routines is reactive, and hence, very short, it is inefficient to service them through interrupts. They would consume more time in overhead than in actual execution. Instead, individual behavioral modules, or functions, are executed in sequence during each cycle. Each routine produces a desired action without regard to the results of the other routines. The module consults a priority function and, as allowed by this priority function, places its results in a command register. This scheme allows the central controller to call each service module in any order, and allows for easy changes, additions, and deletions. After a cycle of these sensor service routines, the motor “server” reads all the desired commands from the command register, and performs any necessary logical operations on them before passing them to the motor drivers for execution in the actuators. This scheme is shown in Figure 7.
CONCLUSIONS: FUTURE IMPROVEMENTS AND FEATURES

At the time of writing, final assembly of the second-generation army-ant is underway. Thus, the performance of its software and hardware cannot be discussed. Most of the subsystems have been independently assembled and tested, and appear to work as intended. Simulation results have demonstrated the effectiveness of the newly-developed control algorithms, and a literature search of related systems validates many of the chosen sensor apparatuses [1, 4, 7, 8].

The robot will be constructed with very close to our original budget of $2000, but this includes hardware only; no labor, equipment, or overhead costs, and, of course, includes educational discounts on many of the parts. Given that a large task might require many such robots, it may be argued that even this relatively low cost would easily surpass conventional material handling systems when multiplied by 10, 20, 50 or more robots. In total, this is true. However, an advantage of army-ant robots over conventional systems is their modularity. They can be bought like building blocks, a few at a time. And when one fails, it neither deprives the rest of the team of its full functionality, nor does it cost too much to replace.

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