Insect-Inspired, Actively Compliant Hexapod Capable of Object Manipulation

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Abstract

Insects, in general, are agile creatures capable of navigating uneven and difficult terrain with ease. The leaf-cutter ants (*Atta*), specifically, are agile, social insects capable of navigating uneven and difficult terrain, manipulating objects in their environment, broadcasting messages to other leaf-cutter ants, performing collective tasks, and operating in cooperative manners with others of their kind [9][12]. These traits are desirable in a mobile robot. However, no robots have been developed that encompass all of these capabilities. As such, this research developed the Biologically-Inspired Legged-Locomotion Ant prototype (BILL-ANT-p) to fill the void. This paper discusses the features, development, and implementation of the BILL-Ant-p robot, quantifies its capabilities for use as a compliant mobile platform that is capable of object manipulation.

The goal of this research [10] was to develop a robot that is power and control autonomous; capable of navigating uneven terrain, manipulating objects within the environment, and active compliance with the environment; very strong for its size; and relatively inexpensive compared to other similar robots. An investigation into existing hexapod robots [2] was conducted, such as Tarry I and Tarry II [4], MAX [1], Robot I [7] and Robot II [6], the TUM Walking Machine [11], the LAURON series of robots [8], and Genghis [3]. While each robot exhibited one or more of the above-mentioned traits, none were found that encompassed all of the desired aspects. As such, the BILL-Ant-p was designed, constructed, and evaluated.

Fig. 1. BILL-Ant-p robot (left) and *Acromyrmex versicolor* (Leafcutter ant found in Arizona, USA, ©Dale Ward) (right).

Based on abstracted anatomy from ants [9][12] and leg coordination from stick insects [5][6][7], the BILL-Ant-p robot (Fig. 1, left) is an actively compliant 18-DOF hexapod robot with six force-sensing feet, a 3-DOF neck and head, and actuated mandibles with force-sensing pincers for a total of 28 degrees of freedom [10]. The robot actively moves in a planar motion away from external perturbations applied to the body by measuring the shift in load on the six foot-mounted force sensors. Similarly, changes sensed by the pincer-mounted force sensors while grasping an object cause actively compliant movements in the neck and the body.

Mechanical System

The body is constructed from 6061 aluminum and carbon fiber sheets (Fig.1, left). During a neutral stance, the BILL-Ant-p is 47cm long, 33cm wide, and 16cm and 26cm tall to the top of the body and top of the head, respectively. It weighs 2.85kg.

Layout of the body and orientation of the body-coxa (BC) joints was based as closely as possible to the body segments of various ants (Fig. 2). While the ant body has a much more compact configuration, the mechanical design was limited by the constraints of function (housing batteries and servo controller) and the connecting elements (legs and head/neck). Leg placement and orientation was designed to accommodate 90 degrees of rotation for each BC joint (maximum range of motion for the joint motors) without interfering with other legs throughout the range of motion. Front and rear BC servos are splayed 60 degrees from the medial plane. The middle BC joint motors are perpendicular to the medial plane. This pattern is similar to the ant for the middle and rear legs; however, it is not biologically accurate for the front legs. While the front BC servo orientations were chosen to produce axially-symmetric body plates, the front legs are attached to their respective servos to roughly conform to the ant's anatomy with a starting position of 15 degrees from the medial plane. All legs have ±45 degrees of motion; however the front legs have +0/-90 degrees of forward/rearward motion from starting positions of 15 degrees off the medial plane.

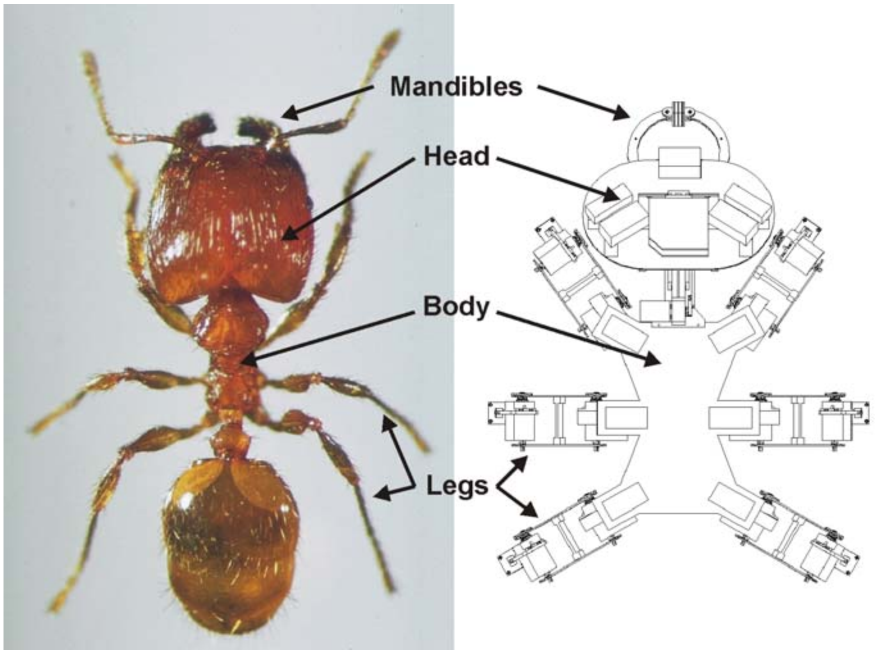

Fig. 2. Top-view body layout comparison of *Pheidole fervida* (left, found in Japan, ©Japanese Ant Database Group) and the BILL-Ant-p robot (right).

Each leg has three active degrees of freedom: a body-coxa (BC) joint, a coxa-femur (CF) joint, and a femur-tibia (FT) joint (Fig. 3). MPI MX-450HP hobby motors (Maxx Products, Inc., Lake Zurich, IL, USA) are used for the joints. These servos were chosen for reliability, high torque, and affordability. The MPI servos have 8.37kg-cm of torque, can rotate through a 60º arc in 0.18sec, and the small internal dc motor consumes 1125mW of power at stall torque. At the time of construction, similarly sized digital servos had slightly more torque (8.59kg-cm), but consumed much more battery power (over twice the current draw) and were three times the cost.

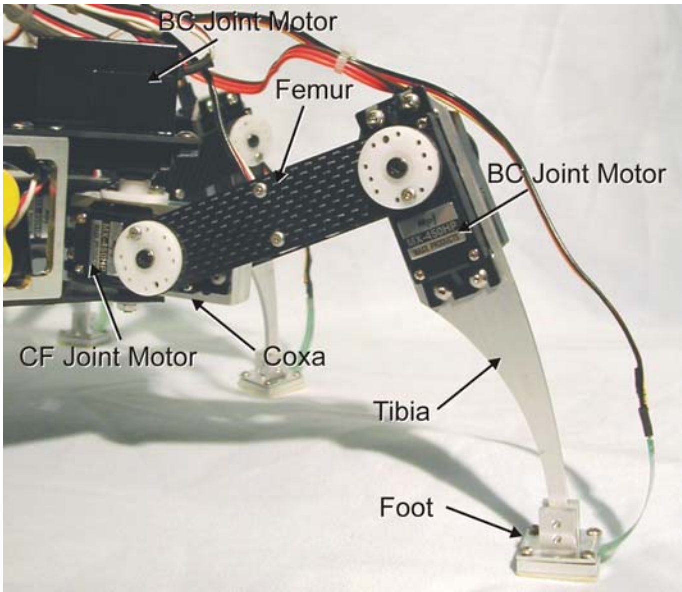

Fig. 3. Front left leg attached to the body.

Since both the CF and FT joints have the possibility of bearing the entire vertical load supported by the leg, depending on leg and joint positions, they each have the same high-torque MPI servo. The BC joint, however, did not necessarily require the same high amount of torque as that joint doesn't support the weight of the robot or any payload. But, to give the robot the greatest amount of pulling and pushing power possible, the same motors were used in the BC joint as well. Additionally, using identical servos allows for fewer unique spare parts to be kept on hand in the event of a joint failure within a leg.

Attached directly to the ends of the tibiae are the feet. The feet provide traction and measure the load along each leg. Each foot is comprised of an Interlink Electronics, Inc. (Camarillo, CA, USA) FSR 402 force-resistive sensor sandwiched between two flat plates (Fig. 4, left), which are 2.06cm square. A simple voltage divider with a 10kΩ resistor and the force sensor in series is used to measure force at the foot. Signals for each foot are connected to the IsoPod™ microcontroller ADC inputs.

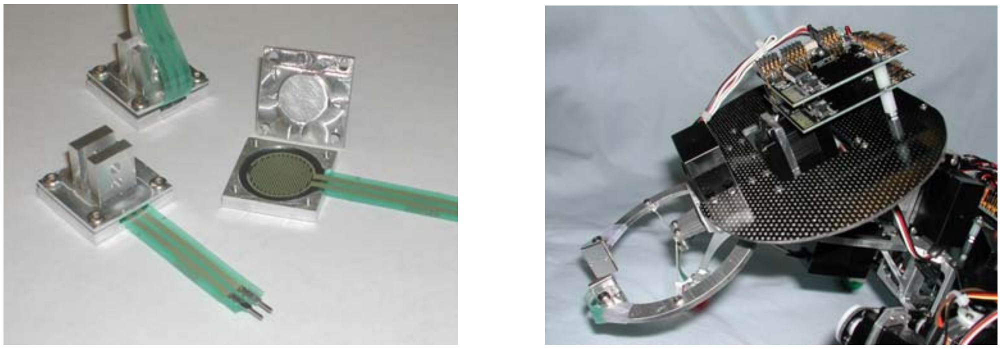

Fig. 4. Foot-mounted force sensitive resistors (left) and Head and neck assembly with the attached mandibles (right).

The foot-mounted force sensors are used to measure the load observed by each foot. These measurements are compiled to determine the total load on the robot, and where that load is centralized. By comparing the amount and location to initial values, changes in the load can be sensed. Since the robot is a raised mass, any perturbations to the robot's head or body will be exerted onto the feet. For example, pushing rearward on the head will cause greater force to be seen on the rear feet, and less force to be seen on the front feet. The shifts in load center are then used to create active compliance in the robot, where the robot's goal is to remain balanced and stable and will actively retreat from external forces. This allows the robot to take commands from the environment, enabling it to have coordinated movements with another robot through force measurements rather than transmitted communication.

The neck has three degrees-of-freedom, which allows for nimble manipulation of objects. Each degree is actuated by an MPI MX-450HP servo. At the base of the neck is the yaw servo, which is attached to the robot body. The pitch assembly is connected to the output of the yaw servo. Tilting motions are achieved by an aluminum push rod connected between the pitch servo and the roll servo housing. The roll servo attaches to an aluminum plate that is connected to the underside of the carbon fiber head. This plate is also connected to the mandibles servo housing to give the mandibles assembly a strong connection to the neck.

The oval-shaped carbon fiber head is 18.54cm wide and 12.19cm long at the extremes. Attached to the neck by the roll servo mounting plate, the head is not part of the load-bearing link between the mandibles and the neck. It supports the two BrainStem microcontrollers that are used to actuate the neck and mandibles, and range-finding sensors. Additional space is available for placement of future sensors, such as a miniature video camera.

Object manipulation is achieved by the twin pincer mandibles (Fig. 4, right). They are fabricated from aluminum and actuated by a single MPI MX-450HP servo. The mandibles are kept open by a lightweight spring and closed by Kevlar fiber cables attached to a pulley on the servo. The tips of the mandibles each hold twin Interlink Electronics FSR 401 force transducers. By using four sensors and having the head at an angle to the ground, mandible closing force and horizontal and vertical forces exerted by a grasped object can be measured. The pincer contact plates are mounted to allow slight movements when grasping an object (Fig. 5). These movements allow horizontal and vertical forces to be measured in addition to lateral forces.

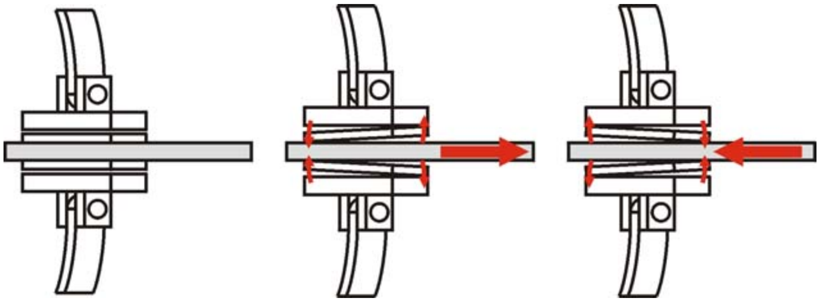

Fig. 5. Exaggerated movements of the pincer contact plates during perturbations of a grasped object.

Electrical System

The electrical system has two major components: control and power. Control consists of motor controllers (IsoPod™ and BrainStem microcontrollers) and a System Controller (laptop computer, 2.8MHz P4, 1GB RAM, 60GB HD). Power is supplied by on-board Li-ion batteries. A system connectivity diagram is shown in Fig. 6.

A New Micros, Inc. (Dallas, TX, USA) IsoPod™ V2 SR microcontroller is used to translate System Controller commands into leg joint servo signals and return foot-mounted force sensor values. This microcontroller was chosen for several reasons: programmability, the availability of floating-point math, the ability to control up to 26 R/C servo motors (with the attached daughter board), small footprint, two serial interface ports, and low cost. There are eight ADC inputs on the IsoPod™, six of which are used to measure foot-mounted sensor forces.

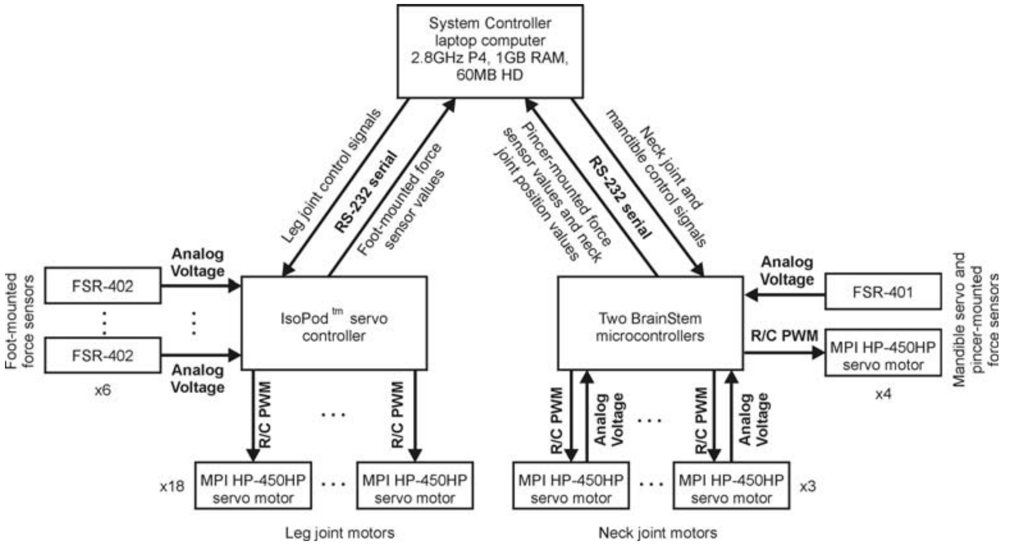

Fig. 6. Electronic and control system connectivity.

Two Acroname BrainStem GP 1.0 microcontrollers (Acroname, Inc., Boulder, CO, USA) are used in the head (Fig. 4, right). These PIC-based controllers have four R/C servo outputs, five 10-bit ADC inputs, five digital I/O ports, an RS-232 serial interface, I^{2}C interface bus, and a digital IR range finder input.

One of the BrainStem units controls the 3-DOF neck. Three servo output ports and three ADC input ports are used to actuate and sense the status of the neck servos. The additional two ADC inputs can be used for future expansion to connect with IR range finding sensors (such as the Sharp GP2D12 IR Sensor).

The second BrainStem unit controls the mandibles. The mandible servo is actuated through a servo output port and the four force transducer voltage dividers values are fed into four ADC input ports. The fifth ADC input is connected to the IR range finder (Sharp GP2D120 IR Sensor) located at the base of the pincers. Since these controllers have limited processing power and no capacity for floating-point math, they were not selected for use in controlling the legs.

Currently, the System Controller is a laptop computer running custom software that was written in Microsoft Visual Basic 6.0 (Microsoft Inc., Redmond, WA, USA). The System Controller has a user interface to dictate commands to the robot and remotely to view robot posture and status. It is connected to both the IsoPod™ microcontroller and the router BrainStem microcontroller by two RS-232 serial ports.

By using a computer separate from the robot, behaviors, parameter values, and system features can be tested more quickly and with the assistance of a user interface. The next design iteration will migrate the developed features onto the IsoPod™ and BrainStem microcontrollers, which will automate the robot and allow for faster responses since there will be no communication overhead. A main command system will still be required for user commands and behavior modes, however. This role will initially be filled by the remote computer currently in use, and later be replaced by an on-board personal digital assistant (PDA) located in the robot's abdomen (not currently part of the robot). Placing the PDA in the rear of the robot will provide additional balance while heavier objects are being carried.

The BILL-Ant-p robot is power autonomous, with four on-board 2400mAh, 7.4vdc Li-ion batteries from Maxx Products, Inc. (MPI, Lake Zurich, IL, USA). To limit the voltage to 6.0vdc, each of the batteries is connected to an MPI ACC134 6-volt Regulator. These units step the 7.2vdc (and higher when freshly charged) voltages down to 6.0vdc, which is the maximum safe voltage for use with hobby servos. Three of the batteries are connected in parallel to provide power for the servo motors. The fourth battery supplies power to the microcontrollers.

Software System

A Software Interface was created using Microsoft Visual Basic 6.0 (Microsoft Inc., Redmond, WA, USA). The interface allows the operator to command robot actions and view robot status. Basic commands on the interface allow the operator to: manipulate each leg joint; set foot position in body-centric x-, y-, and z- coordinates; initiate a standing routine; adopt a standing posture; adjust body height from the ground; adjust body roll and pitch; drive the robot using speed, heading, and rotation values; manipulate roll, pitch, and yaw of the neck; and adjust position and closing force of the mandibles.

Strafing (moving in one direction while facing another) (Fig. 7, center), walking (a type of strafing where the robot is facing the direction of motion) (Fig. 7, left), rotating (zero radius turn about the body center) (Fig. 7, right), or a combination of strafing/walking and rotating movements are possible. Each foot heading during stance and swing is calculated based on the heading and rotation values. For strafing/walking all feet move a uniform direction. Rotating assumes a zero radius turn and has each foot moves tangentially to the body center at a speed proportional to the distance from the foot to the body center. Vector sums of each foot's path for strafing/walking and rotating is normalized to the nominal step length to create combinations of movements (e.g. turning in an arc or rotating while moving along a straight line). An implementation of Cruse control for leg coordination is used to adjust stance length and set transition points between stance-swing and swing-stance phases [5][7]. A continuum of gaits from wave to quadruped to alternating tripod is achieved as speed is increased.

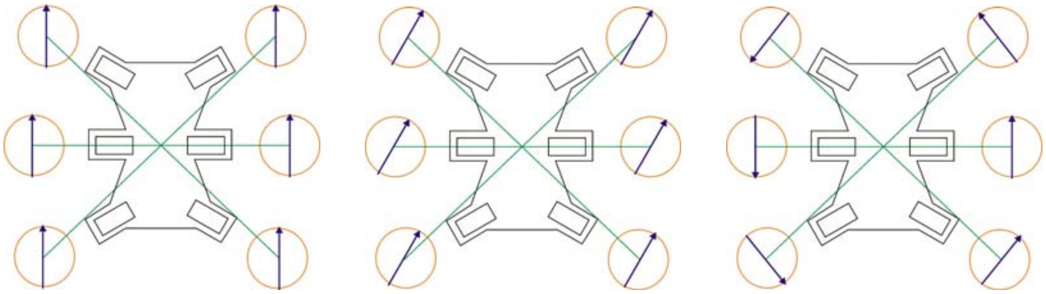

Fig. 7. Foot movements during the swing phase for walking (left), strafing at 330º (center), and rotating counter clockwise (right).

When employing an active compliance behavior, the BILL-Ant-p robot is programmed to maintain a neutral stance, where the legs are axially symmetric about the medial plane, and the neck motors are at the center of their ranges of motion. Perturbations applied to the body are measured by the foot-mounted force sensitive resistors (Fig. 4, left). External force amount and direction is calculated by summing the force sensor values in body-centric x- and y-coordinates based on the position of each foot relative to the body. Measured forces at each foot are converted to vertical forces (positive z) based on the angle of the foot with respect to the ground. The robot moves in a planar motion in the direction of, and proportional to, the force, as though attached to a virtual attractor by a virtual spring and damper (Fig. 8, left).

The BILL-Ant-p is also able to grasp objects with force-sensitive, servo motor-actuated mandibles (Fig. 4, right). Four force sensitive resistors, similar to those used in the feet, are mounted two-per-side in the tips of the pincers. Gripping force is user-defined and is essentially a stiffness setting. The pincers open and close to maintain the desired gripping force. Similar to the body movements initiated from the foot-mounted sensors, the neck and body responds to forces measured by the pincers (Fig. 8, right). The three degrees-of-freedom in the neck move within their ranges of motion to balance the forces measured by the pincer sensors such that the sensors values are all equal and at the desired gripping force. Each neck axis is divided into three 30º areas. When the neck is outside the central 30º area, movement commands are sent to the body to bring the neck toward a more neutral position. Body movements (planar and rotational) are initiated in response to lateral, longitudinal, and rotational forces. These commands continue until the neck is within the "body motion deadband", near the center of the ranges of motion.

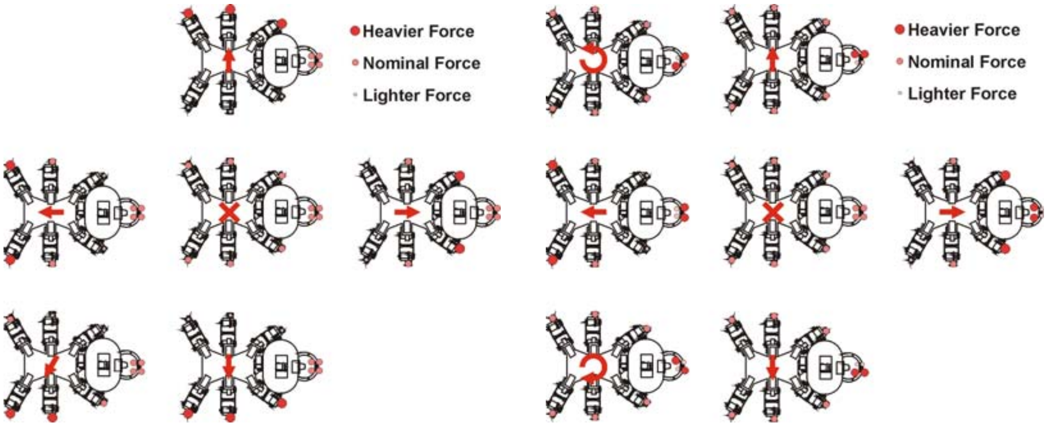

Fig. 8. Actively-compliant body movement based on foot-mounted force sensors (left) and pincer-mounted force sensors (right).

System Performance

With fully charged batteries, the robot is able to stand and walk at 0.72cm./sec (two body lengths per minute) with its 2.85kg body weight and an additional 3.18kg of payload, and can rotate at a rate of 6.9º/sec. While standing in a neutral posture, the BILL-Ant-p is able to support its body weight and a payload of up to 8.64kg. Motor batteries allow for approximately 36min. of normal operation, or about 25min. of heavy lifting. Weight lifting performance declines by up to 30% over 25min. as battery power is consumed.

When the body is perturbed, the BILL-Ant-p quantifies the amount and location of the force and moves away from the perturbation at a speed that is proportion to the force. This allows for robot strafing and walking movements to be initiated by pushing or pulling, rather than through the user interface. Speeds up to 0.72cm/sec were observed during several experiments including: pushing from behind, pushing from the side, pushing rearward on the head, pulling toward the head, pulling toward the rear, and pulling toward the side. Since the operator end of the attached string for pulling was raised above the robot body, the robot responded more quickly and smoothly during the pulling experiments. During pushing experiments the feet had a slight tendency to get caught on the ground.

Reactions while grasping an object were conducted by closing the mandibles on a solid block of Delrin® held by an operator. Movements of forward and backward walking, left and right strafing, and clockwise and counter-clockwise rotation were initiated by manipulating the grasped block. As expected, lateral movements and rotational movements of the block caused the neck to rotate in the direction of the applied force. Once the neck was outside the central 30º area, the legs began moving in the appropriate manner for the applied force: strafing for lateral forces and rotating for rotational forces. Forward and backward movements were observed when pulling and pushing the block. The neck rotated to equalize the forces sensed by the pincer contact plates; however the walking response was initiated regardless of the yaw motor position, as programmed.

Future Work

The next phase of development for the robot is to have the Cruse control implemented on the IsoPod™ microcontroller and move all active compliance control on-board the robot (in the IsoPod™ and BrainStem microcontrollers). This will allow the robot to be both power and control autonomous as an actively compliant agent. This, however, is not enough to achieve the goal of object searching, manipulation, and gathering.

To advance the functionality of the robot, on-board navigation and object recognition will be required. These features will allow the robot to autonomously navigate the terrain in search of meaningful objects for observation and/or collection. It is proposed that a personal data assistant (PDA) with wireless communication be added and interfaced with the IsoPod™ to set goals, navigate the terrain, and decide which observed objects are noteworthy. A vision system may be added to assist both in object recognition and navigation.

Making the robot part of a group of other robots will require communication. Based loosely on the leaf-cutter ant's event-based broadcast communications the robot will be able to send broadcast messages to other robots within range when significant events occur, such as "object found", "returning to home point", and "help required".

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