Reactive Inclinometer-based Mobile Robot Navigation

Ronald C. Arkin and Warren F. Gardner

Mobile Robot Laboratory
School of Information and Computer Science
Georgia Institute of Technology
Atlanta, GA 30332-0280

Abstract

Outdoor navigation requires traversing terrain that contains a wide range of topographic features: hills, valleys, ridges, etc. Certain missions (e.g., surveillance) need information regarding the terrain's features for successful completion. One way to obtain this data is through the use of inclinometers: devices which measure the pitch and roll of the robot relative to gravity.

We have developed reactive motor behaviors (schemas) which exploit inclinometer data. Using this information we have literally implemented artificial intelligence "hill-climbing" techniques as well as valley-finding and iso-contour following. All of these schemas are integrated with the other schemas present in our system (AuRA - the Autonomous Robot Architecture) and can be used concurrently with obstacle avoidance, goal seeking, and other motor behaviors. Simulations studies illustrate the utility of these methods using actual terrain data.

1. Introduction

An understanding of the underlying terrain for a mobile robot can be extremely useful for a wide range of tasks. It is certainly essential for the maintenance of a stable pose on undulating ground. It can also provide valuable data for navigational purposes.

Inclinometers are devices which return the position of the robot relative to gravity. This data reflects directly the underlying surface patch of the terrain. Certain reactive motor behaviors can exploit knowledge of this local surface feature to the advantage of a mobile vehicle. Activities such as hill-climbing, valley-locating and iso-contour following can be implemented using this data.

Typical applications for this form of navigation are in unknown or partially modeled worlds; terrestrial or otherwise. For reconnaissance missions, a robot might be dropped into an unknown and potentially hostile environment and be given the task of finding a high-point from which it can observe. The low-cost sensing technique proposed in this paper can solve this problem. If partial world knowledge is available, adding an altimeter can confirm the attained position as a solution. This same type of hill-climbing behavior is also useful for the positioning of repeaters for communications systems (e.g., packet radio) without requiring manual intervention.

Movement along contours of constant altitude or lurking and moving in low-lying valleys can also assist in the prevention of detection in threatening environments, when such behaviors are important for the survival of the robot. When coupled with goal-seeking, obstacle avoidance, and other low-level behaviors, complex mission scenarios can be envisioned which are built entirely around reactive navigational techniques.

As in any artificial intelligence "hill-climbing" algorithm, one must be capable of dealing with local minima and maxima. Certain techniques can be used to address this particular problem and assist the robot during its navigation. Proper inclinometer design can minimize the effect of small local pitfalls (e.g., effective sensor damping). The judicious use of a random noise motion vector can also assist in wandering out of local maxima, minima, or plateaus (Sec. 4). Finally, utilizing *a priori* world knowledge when available can also guide the robot to reach global solutions while still reacting to the immediacy of its sensor data. Although world knowledge is important when available, this paper largely focusses on the combination of primitive motor activities to yield intelligent emergent behavior for outdoor navigation.

1.1 AuRA

The Autonomous Robot Architecture (AuRA) [2] is the framework within which our experiments in intelligent navigation are conducted. This system incorporates both a hierarchical planner and reactive control system [6]. *A priori* world knowledge is embedded in a meadow map [4] and is used by the hierarchical planner for the formulation of plans and selection of reactive behaviors (motor schemas [7]) necessary to satisfy the current mission's constraints.

Perceptual schemas provide the sensory information needed by each motor schema. This task-dependent expectation-based approach [3,8] has utilized computer vision, ultrasonic sensors, and shaft encoders as input devices to control motor action.

AuRA is designed to perform over a multiplicity of navigational domains. Successful navigational experiments have been conducted with our mobile robot (*George* - a Denning Mobile Robot) in the interior of buildings, in outdoor campus settings, and in manufacturing environments. Simulation results have demonstrated the extension of these techniques in three-dimensional domains such as aerospace or undersea environments [5,20].

The simulation studies in this paper show the application of these methods to unstructured and topographically interesting outdoor domains, using inclinometers as the prime source of sensory data.

1.2 Inclinometers

Inclinometers have been used for a wide variety of applications. Some of the less obvious include measuring the creep of polar ice [19], detecting changes in the seabed for earthquake prediction [21], dentistry [11], and medicine [1]. They also are important devices for measuring balance (posture control) in humans [18] and maintaining balance in robots [9,16].

CH2876-1/90/0000/0936$01.00 © 1990 IEEE

Multiple axis inclinometers are readily available commercially in a wide range of sensitivities. They are also listed under a wide range of aliases: slope sensors, precision pendulums, directional gyroscopes, tiltmeters or tilt sensors, and clinometers. The inclinometer systems required for the techniques described in this paper require two orthogonal axes and are capable of measuring both the pitch and roll of a mobile vehicle. Significant damping is also a necessity to prevent wild fluctuations in the readings as the robot moves over rough terrain.

2. Reactive Navigation

Reactive navigation is a relatively new approach. These control techniques are based upon the immediacy of sensory information and generally rely on little or no *a priori* world knowledge. They are principally used for plan execution [6]. Reactive navigation is in marked contrast to global path planning techniques that rely on world models to construct a path and then require that the robot adhere to it. The advantages of reactive control lie in its ability to operate in unstructured environments and to obtain real-time response to dynamic events.

The general characteristics of reactive control can be summarized as follows:

- It is typically manifested by a decomposition into primitive behaviors.
- Global representations are generally avoided.
- Sensor decoupling is preferred over sensor fusion.
- It is well situated for dynamic changes in the world.

Brooks' subsumption architecture [10], a layered behavioral approach, is an early example of this technique. Other representative examples include: Firby's reactive action packages (RAPs) [12]; Payton's reflexive behaviors [17]; Kaelbling's reactive architecture [13]; and Arkin's motor schemas [7]. These methods differ in their means of behavior integration, selection and control, but share the philosophy of decomposition into primitive behaviors that are intimately tied to incoming sensory data.

Motor schemas, as used in AuRA, are multiple active concurrent behaviors that are instantiated based upon the robot's current needs and intents and the environmental conditions. *A priori* world knowledge, if available, is used to guide the selection of the schemas that are necessary for successful completion of the robot's mission. The advantages schemas offer include their suitability for distributed processing, their modular construction geared to support incremental growth and development, their responsiveness to environmental sensing, and their ability to reflect uncertainty in perception within the motor behavior of the robot.

Schemas are distinguished from other reactive navigational techniques as follows:

- No hard-wired layering is present, rather a dynamic network of behaviors.
- High-level planning selects and parameterizes the behaviors based on the mission, environment, and internal state of the robot.
- Although potential field techniques are used, the entire field is never generated, only each behavior's individual contribution.
- Summing the contributions produces the gross behavior.
- Each schema is an independent computing agent.
- Perceptual strategies (both external and internal) are embedded within the motor schema.
- Perceptual uncertainty is readily reflected in the motor schema output.
- Their use is motivated by neuroscientific and psychological studies of behavior.

Each motor schema generates a vector reflecting the reaction of the robot to its perceived world from the standpoint of each of its current behaviors. It is repulsed by obstacles, attracted to goals, channeled onto paths, etc. Although the figures in the following sections illustrate the entire potential fields produced by both individual schemas and combinations of schemas for the reader's convenience, it should be remembered that the robot does not compute the entire field. Only the vector where the robot is currently located needs be computed. This makes for extremely fast computation. Of course any potential field methodology is subject to certain pitfalls (local maxima and minima, cyclic behavior) and when these events are detected the hierarchical planner within AuRA is reinvoked to adjust or reinstantiate the behavioral set based upon the newly received information [6].

3. Inclinometer-based behaviors

Three basic behaviors using inclinometer data have been implemented:

- **Move-up** schema: Moves in the direction of maximum increase of altitude based on current location (climbs uphill). This schema literally implements artificial intelligence "hill-climbing". The schema can be modified to put a limit on the maximum possible incline allowable to ensure robot stability on sloping surfaces.
- **Move-down** schema: Moves in the direction of maximum decrease in altitude based on current location (climbs downhill).
- **Maintain-altitude** schema: Moves in a direction that maintains current altitude. In general, at any point there are two directions which satisfy this criteria. Arbitrarily either the left-hand direction or right-hand direction when facing uphill is selected consistently to avoid cyclic behavior.

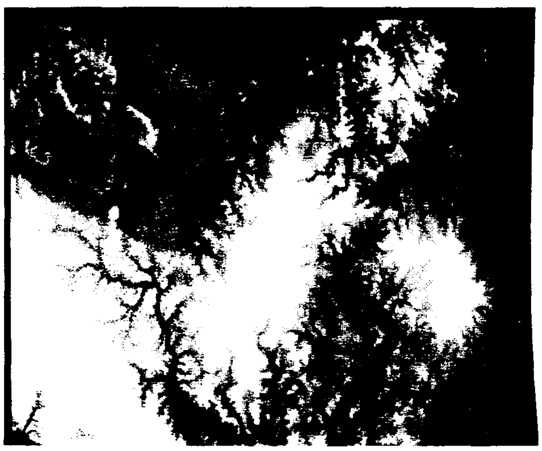
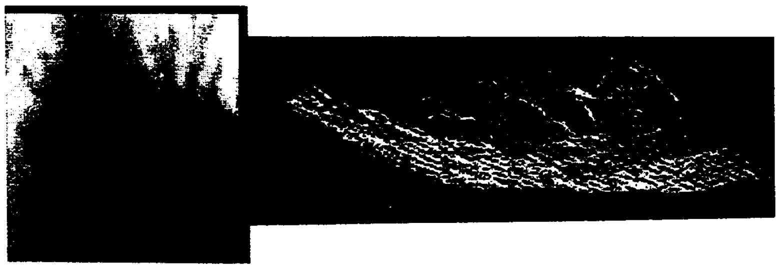


Figure 1: Image of DMA data of North Georgia region used as data source for simulation studies. Bright intensities indicate higher elevations. Resolution of map is 30 meter^2 per pixel.



(a) (b)

Figure 2: Terrain patch used for simulation studies.
a) Intensity image of 64 x 64 area.
b) Surface plot of the same region.

Our test data is derived from DMA data of the North Georgia Region (Fig. 1). A small area (64 by 64) was chosen to give a representative sample of the terrain. Unfortunately, the resolution of this data is still coarse (30 meter^2 per pixel) but still yields good results. Figure 2 shows both the coarse terrain patch and its surface plot.

In order to use this data, a tilt-slope plane was made by computing the local slope at each point in the map with a 3x3 mask. A plane is fit to the nine points under the mask using a least-squares method. The resulting plane representing the incline at each pixel is stored and used as input to the motor schemas in lieu of actual inclinometers.

Using digitized data such as this introduces problems that would not be found otherwise. The major difficulty is that the robot has only 8 possible directions to move towards from any given location on the map (the 8 neighboring elevation pixels). This digitization bias actually proved to be of little hindrance in the simulation studies that follow.

The first behavior, hill-climbing using the **move-up** schema is illustrated in Figure 3. Reiterating, the potential field which is shown in its entirely is never completely computed by the robot. Only the point where the robot is currently located needs to be determined to give reactive impulse to the vehicle. This is distinguished from global path planning methods that could be performed on this data assuming the world is known in its entirety. The global terrain data set is unavailable to the reactive control system. Observe how the robot's path makes its way uphill and then stops. Figure 3b illustrates the step versus altitude plot. Note the monotonicity of the hill-climbing behavior when instantiated as the sole primitive behavior.

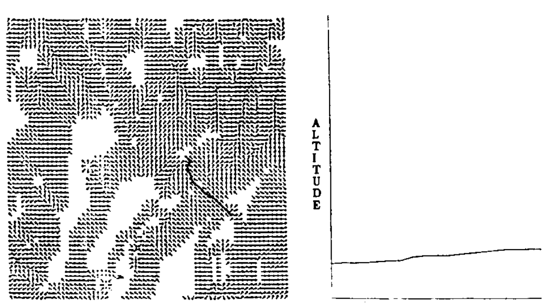
The **move-down** behavior is illustrated in Figure 4. Note that the potential field is equal in magnitude but opposite in direction that of the **move-up** schema in Figure 3. Here the robot seeks out valleys and low spots. The right-hand plot in the figure again shows monotonicity in the downward direction.

Perhaps the most interesting behavior is the **maintain-altitude** schema (Fig. 5). Iso-contour following is implemented with this technique producing long, winding paths following the lay of the land. The altitude plot shows some variance from actually maintaining the initial altitude (which ideally should be a flat line). This is due to the digitization bias described earlier. Nonetheless, it can be seen that the altitude is maintained quite effectively despite this artifact due to the nature of the input data.

4. Complex Behaviors

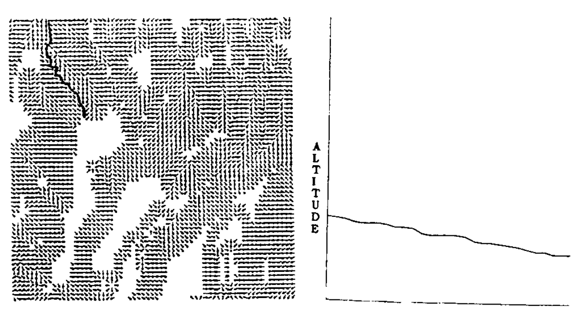
As described in earlier work [7], complex behaviors can be built up out of collections of concurrently active motor schemas. The potential fields used to describe these schemas have a basis in techniques developed by Khatib [14] and Krogh [15].

Some schemas available in our library of behaviors that are used in combination with these new inclinometer-based techniques include:



(a) (b)

Figure 3: Hill-climbing (**move-up** schema).
a) The potential field generated by the **move-up** schema when applied at all points. Note the path through the region as the robot moves to a position of high altitude.
b) Plot of altitude versus step number for the robot's path. Note the monotonic progress upwards (from 29 to 41 units).



(a) (b)

Figure 4: Valley-seeking (**move-down** schema).
a) The potential field generated by the **move-down** schema when applied at all points. Note the path through the region as the robot moves to a position of low altitude.
b) Plot of altitude versus step number for the robot's path. Note the monotonic progress downwards (from 70 to 41 units).

- **Move-ahead**: The robot is commanded to move in a particular specified direction from wherever it happens to be located. This schema is analogous to a tilted plane, upon which wherever the robot is placed it would roll in the same direction.
- **Avoid-static-obstacles**: A repulsive disk encircles any detected obstacle. The repulsive force drops off linearly up to a certain distance from the robot (the *sphere of influence*). The repulsion is infinitely high within the diameter of the obstacle itself. The gravitational analog can be viewed as a mountain whose slopes depend upon the certainty of detection.
- **Move-to-goal**: The robot is directed to move in the direction of a detected goal. This schema is analogous to the goal being located in a pit whose sides slope gently towards the center.
- **Stay-on-path**: The robot must strive to be in the center of a path. If the robot is on the path the force exerted drops off linearly from the border of the path towards the center. If the robot is off the path, a higher gain value is used to push the robot onto the path rapidly. A valley serves as the gravitational analog of this motor schema.
- **Noise**: A random velocity vector is generated. This behavior is particularly useful for handling local maxima [7] and can also be used for handling small local minima (described below).

In the simulation studies involving obstacles, the certainty of the presence of an obstacle is related to the distance of the robot from that obstacle. A certainty threshold for detection must be exceeded before *any* repulsive force is felt by the robot. This certainty value is also proportional to the repulsion generated by the detected obstacle.

Figure 6 shows the path of the robot when influenced by a combination of **Move-up** and **Move-ahead** schemas. Observe how the robot continues to move in the general direction towards the top of the figure while simultaneously satisfying the behavioral constraint to move upward. When compared to Figure 3, it can be seen that the robot no longer stalls out when a local peak is reached. Downward motion can occur if the gain on the **move-ahead** behavior is sufficiently strong to over-ride the pressure to **move-up**. A general description of this behavior is that the robot proceeds in a general compass direction all the while attempting to maximize its altitude (ridge-following).

Another example of complex behavior can be seen in Figure 7. Here the robot is striving to maintain a constant altitude while also avoiding obstacles. This will require deviations from the specified altitude when necessary. The presence of three obstacles causes an entirely different path to be taken than the one shown in Figure 5 (both have the same starting points). A snapshot of the potential field is also shown. Remember that the obstacles' presence is detected only when within a certain range of the robot, and the repulsive field is proportional to its perceived certainty. Thus only two obstacles can be seen in the field shown (the robot's position at this point is distant from the third obstacle).

As only inclinometer data is used, the robot has no memory of what its original altitude was. Thus when the robot gets pushed away from the original altitude it assumes that this new altitude is the one that needs to be maintained. By using altimeter data in conjunction with the inclinometers, a new behavior could be specified that pushes the robot downwards when it exceeds a certain altitude, forces it upwards when below that level, and uses the standard iso-contour following behavior when at the correct level. This is left for future work.

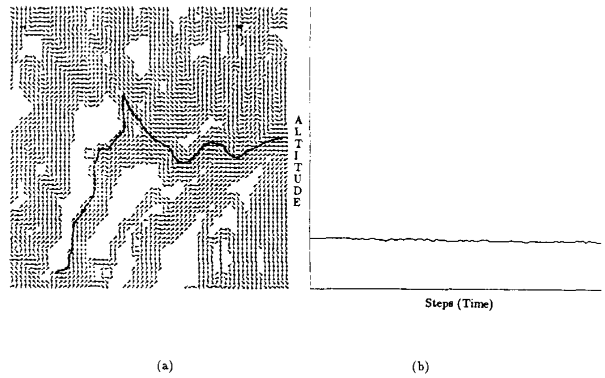


Figure 5: Iso-contour following (**maintain-altitude** schema).
a) The potential field generated by the **maintain-altitude** schema when applied at all points. The robot winds through the region maintaining the same altitude while following the terrain contours.
b) Plot of altitude versus step number for the robot's path. Note the slight deviation from the flat line predicted due to digitization bias of the input data. (The altitude started at 41 units and ranged between 38-41).

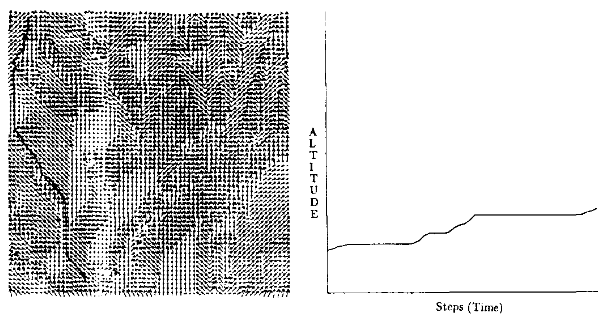


Figure 6: Path generated by a robot subject to the **Move-up** and **Move-ahead** schemas. (The altitude ranges from 36 to 69 units).

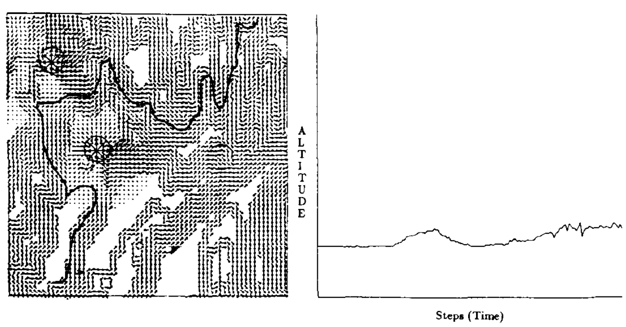


Figure 7: Path generated with **Maintain-altitude** and **Avoid-static-obstacles**. Three obstacles are embedded in the course. (The original altitude is 41 units, and ranges from 40 to 61).

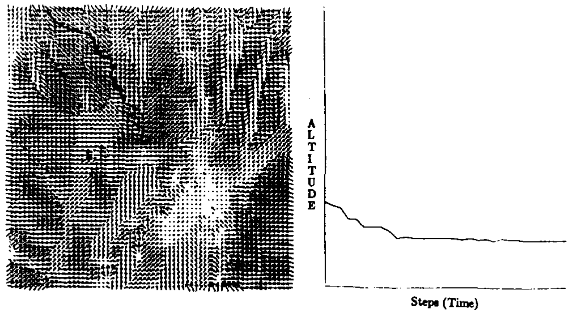


Figure 8: Path generated for **Move-down** and **Move-to-goal** schemas. Note how the robot overcomes local maxima due to the pressure exerted by the goal. (The altitude ranges from 70 to 39 units:)

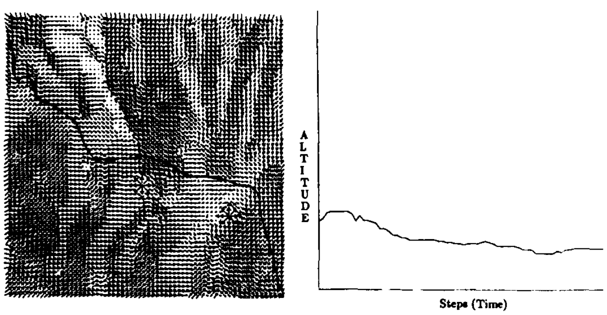


Figure 9: Path generated by robot for **Maintain-altitude, Move-to-goal, Stay-on-path,** and **Avoid-static-obstacle** schemas.

Goal-seeking behavior over complex terrain is illustrated in Figure 8. In this case, a combination of **Move-down** and **Move-to-goal** schemas lead the robot down the hillside until the goal is encountered at which point the robot stops its motion. Comparing this to Figure 4, which has the same starting point but only the **move-down** behavior, it can be seen that the robot extends its path to the goal, moving over local maxima as the robot seeks out its target destination.

The most complex example in this paper appears in Figure 9. A combination of **Maintain-altitude, Move-to-goal, Stay-on-path,** and **Avoid-static-obstacles** is used. There are 5 obstacles present and the goal is in the lower right-hand corner. The center line of the path is from the upper left-hand corner to the lower right-hand corner and is 20 units wide. The goal is acheived while simultaneously avoiding all obstacles, maintaining the position on the path, and trying as best as possible to follow an iso-contour.

The final examples show the importance of random noise as a means for overcoming local pitfalls that can occur when using the potential fields methodology. Figure 10 presents a **Move-up** schema combined with two different levels of the **Noise** schema. The paths shown have the same starting point as the no-noise version shown in Figure 3. The paths get consistently longer (and also a bit more haphazard) as the **noise** schema's gain (influence) increases. With no noise, the maximum altitude attained is 41 units. With a noise gain of 10% of the **move-up** schema a maximum altitude of 64 units is reached. With a noise gain of 30%, a maximum altitude of 78 is reached, almost twice that of the no-noise version. The altitude traces show that the robot is rocked out of local minima, knocked off of local maxima, and wanders successfully across flat plateaus in its quest for high ground.

5. Summary

A means for reactively navigating a mobile robot over rough, outdoor terrain has been developed based on the use of inclinometer data. Three new behaviors **move-up, move-down,** and **maintain-altitude** produce useful behavior for this domain. These motor schemas are readily integrated with the already existing schemas and other future behaviors yet to be developed.

Applications for this type of navigation include reconnaissance and surveillance missions. The low cost of inclinometers makes this method particularly attractive. These techniques are also extensible to any other sensor capable of providing surface normal information.

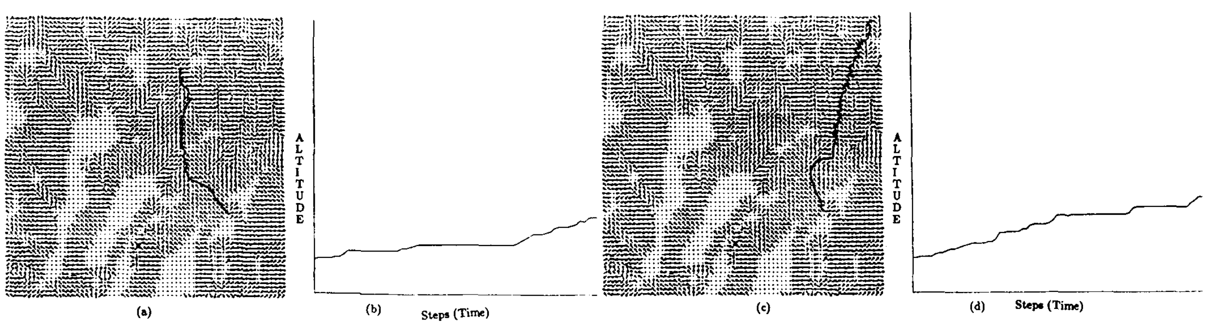


Figure 10: Paths generated by a combination of **Move-up** and **Noise** schemas. (See text for explanation).
a) Path for 10% noise. b) Altitude trace for (a).
c) Path for 30% noise. d) Altitude trace for (c).

As mentioned earlier, altimeters can also be integrated to provide additional input to the **maintain-altitude** schema. In the future, we hope to fit our Denning mobile robot with inclinometers and conduct outdoor navigational experiments in the wild.

REFERENCES

[1] Adams, M.A., Dolan, P., Marx, C., and Hutton, W.C., "Electronic Inclinometer Technique for Measuring Lumbar Curvature", *Clinical Biomechanics*, vol. 1, no. 3, pp. 130-134, August 1986.

[2] Arkin, R.C., "Towards Cosmopolitan Robots: Intelligent Navigation of a Mobile Robot in Extended Man-made Environments", *Ph.D. Dissertation*, *COINS TR 87-80*, , Univ. of Massachusetts, 1987.

[3] Arkin, R.C., Riseman, E. and Hanson, A., "Visual Strategies for Mobile Robot Navigation", *Proc. IEEE Computer Society Workshop on Computer Vision*, Miami Beach, pp. 176-181, 1987.

[4] Arkin, R.C., "Navigational Path Planning for a Vision-based Mobile Robot", *Robotica*, Vol. 7, pp. 49-63.

[5] Arkin, R.C., "Three Dimensional Motor Schema Based Navigation", *Proceedings of the NASA Conference on Space Telerobotics*, Pasadena, CA, Jan. 1989.

[6] Arkin, R.C., "Towards the Unification of Navigational Planning and Reactive Control", *AAAI Spring Symposium on Robot Navigation*, March 1989.

[7] Arkin, R.C., "Motor Schema-Based Mobile Robot Navigation", *Int. Journal of Robotics Research*, Vol. 8, No. 4, August 1989.

[8] Arkin, R.C. and Murphy, R.R., "Autonomous Navigation in a Manufacturing Environment", to appear in *IEEE Transactions on Robotics and Automation*, 1990.

[9] Brooks, R.A., "A Robot that Walks: Emergent Behaviors from a Carefully Evolved Network", *Proc. 1989 IEEE Int. Conf. on Robotics and Auto.*, Vol. 2, pp. 692-694, Scottsdale, May 1989.

[10] Brooks, R., "A Robust Layered Control System for a Mobile Robot", *IEEE Jour. of Robotics and Auto.*, Vol. RA-2, No. 1, pp. 14-23, 1986.

[11] Deane, E., and Rosenstiel, S., "Handpiece Alignment in Tooth Preparation - A New Approach", *Med. and Biol. Eng. and Comput.*, vol. 25, no. 4, pp. 478-80, July 1987.

[12] Firby, R.J., "Adaptive Execution in Complex Dynamic Worlds", *Ph.D. Dissertation*, Yale University, CSD/RR #672, 1989.

[13] Kaelbling, L., "An Architecture for Intelligent Reactive Systems", *SRI Technical Note 400*, Oct. 1986.

[14] Khatib, O., "Real-time Obstacle Avoidance for Manipulators and Mobile Robots." *Proc. IEEE Int. Conf. Robotics and Automation.* St. Louis,, pp. 500-505, Mar. 1985.

[15] Krogh, B., "A Generalized Potential Field Approach to Obstacle Avoidance Control", *SME - RI Technical Paper MS84-484*, Society of Manufacturing Engineers, Aug. 1984.

[16] Larimer, S., Lisec, T., and Spiessbach, A., "Simple Autonomous Mars Walker", *Proc. SPIE Mobile Robots III*, Cambridge, MA, pp. 98-102, Nov. 1988.

[17] Payton, D., "An Architecture for Reflexive Autonomous Vehicle Control", *IEEE Conf. on Rob. and Auto.*, pp. 1838-1845, 1986.

[18] Phillips, C.A. and Buhrman, J.R., "A Mathematical Model to Analyze Control of Upright Posture and Balance: Verification and Implications for Sensory Feedback Systems with an FES Orthosis", *Proc. 9th Annual Conf. IEEE Eng. in Medicine and Biology Society*, Vol. 2, pp. 609-610, 1987.

[19] Pimienta, P. and Duval, P.,"Rate Controlling Processes in the Creep of Polar Glacier Ice", *J. Phys. Colloq.*, Vol. 48, no. C-1, pp. 243-8, March 1987.

[20] Rao, T.M. and Arkin, R.C., "3D Navigational Path Planning", *Proceedings of the SPIE Conference on Mobile Robots IV*, Philadelphia, Nov. 1989.

[21] Sasaki, K., Kawasoe, T. and Fujisawa, T., "Seabed Sensors and their Applications to Earthquake Prediction", *Journal of Inst. Electron. and Commun. Eng. Japan*, vol. 69, no. 8, pp. 842-5.