IEEE International Workshop on Intelligent Robots and Systems
IROS '90

AUTONOMOUS ROBOTS AND EMERGENT BEHAVIOR: A Set of Primitive Behaviors for Mobile Robot Control

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Abstract

Autonomy is desirable in tasks which involve manipulation and mobility but for which human intervention is difficult. We are interested in addressing the following question: How does one develop a robot which exhibits autonomy across a broad range of unstructured and dynamically changing environments, in support of many tasks which may have little in common with each other?

We have based our work on a fundamental assumption: In order for a robot to act autonomously over a wide range of tasks and environments, it must be capable of exhibiting a variety of different behaviors.

In this paper, we examine different types of behavioral patterns that can exist for a mobile robot when one is limited to constructing such behavior from computational devices which contain no internal state. We construct a set of primitive reflexive behaviors, each of which causes the robot to exhibit a specific behavioral pattern in response to external and/or internal stimuli. Each primitive behavior models a simple form of reflex behavior. In addition, we discuss how each primitive reflexive behavior results in motion of the robot, illustrate different types of primitive reflexive behaviors, and provide graphic representations of the resulting behavioral patterns.

1.0 Introduction

A review of the literature in mobile robot research provides an important observation: the primary goal of most efforts are directed towards the development of a mobile robot which is capable of a single task, navigation. We believe that there are many useful tasks besides movement between two places that are required of of robots. Furthermore, we believe that the many tasks required of such vehicles cannot necessarily be decomposed into only navigational subtasks.

In this section, we classify many of the approaches based upon a new method of classification: what types of tasks are the resulting systems capable of supporting? Or equivalently, what range of behaviors are possible for such a system?

1.1 Single Behavior Approaches

The most common behaviors found in the literature support the task of navigation [Miller, 85; Moravec, 84; Elfes, 86; Flynn, 85; Crowley, 85; Krogh and Thorpe, 86].

Much work has occurred in this area for both known and unknown environments. We can classify combinatorial and continuum based approaches to path planning as resulting in a single navigational behavior in which the collision avoidance behavior is coupled with the behavior of movement between two places in the environment. This coupling is so strong that once a robot reaches its desired location in the environment, no protection is provided from collisions with approaching objects (i.e., the only time which the robot is capable of avoiding an object is when the robot has been given the task of moving to a different position).

Single behavioral approaches to autonomy (i.e., navigation) tend to result in autonomous systems which perform reasonably well for a specific class of applications, but do not degrade gracefully when dynamic and highly unstructured environments are encountered.

1.2 Multi-Behavioral Approaches

While most research has been directed to supporting navigational tasks, there have been a number of investigations leading towards the development of a robot capable of exhibiting different types of behaviors which may support a variety of tasks.

One of the approaches to multi-behavioral autonomous mobile robot development is that of Brooks at MIT. Brooks' approach is aimed at developing a robot capable of exhibiting a wide range of different behaviors, among them "flee," "wall following," and "exploratory" behaviors [Brooks, 86a; Brooks, 86b]. His goal is to incrementally develop a robot with increasing levels of competence in achieving autonomy with the thought that such competence will eventually, lead to a complex form of intelligent behavior.

Other work reported by [Arkin, 87] incorporates the concept of multiple concurrent behaviors such as "avoid-static-object," "move-ahead," "move-to-goal," and "stay-on-path," however, each of these schemas are used to overcome unexpected situations which may occur as the robot is performing a navigational task. Similarly [Payton; 86] reports on a set of reflexive heuristic behaviors which when combined, form other types of behaviors such as "wander," "seek-heading," and "back-and-turn." However, as with Arkin's approach, such behaviors are intended to support navigational tasks and are implemented as parameterized procedures.

Our multibehavioral approach to robot control is based upon a vertical decomposition in which sensory data is processed concurrently by a set of primitive behaviors[1], each of which contributes to the overall motion of the robot, the *emergent behavior*. The approach has been empirically verified in a variety of two dimensional unstructured certain environments which consisted of static polygon representations of objects and and also by using a real untethered mobile robot, SCARECROW, with onboard parallel processing in an actual unstructured dynamic environment. We have previously introduced our approach to reflexive behavior in [Anderson and Donath, 88a] and its relationship to observed animal behavior in [Anderson and Donath, 90]. In this latter paper, we also

[1] This term was used by Brooks in the domain of mobile robots for describing the use of simple behaviors supporting desired behavior [Brooks; 1986].

described the results from simulation and actual experiments on SCARECROW moving about our laboratory. The architecture of SCARECROW is more fully described in [Talbott et al, 89], while a more complex approach based on reactive behaviors is described in [Anderson and Donath, 88b]. In this paper, we will focus on the primitive behaviors that are used in various combinations to form the emergent behaviors.

Our work departs from the more traditional combinatorial and continuum approaches to path planning but shares some similarities with the potential field approach to obstacle avoidance proposed by [Khatib, 85; Andrews, 83; Krogh, 86; Arkin, 87] and is influenced primarily by ethological observations of animal behavior [Manning, 79; McFarland, 87; Anderson and Donath, 90], the work of [Brooks, 86], and to a lesser extent to that of [Payton, 86].

In autonomous mobile robots, it builds upon and is most closely related to Brooks [Brooks, 86] in that complex behavior can be constructed incrementally by combining new types of primitive behaviors with existing ones. However, our approach differs in that each of the primitive behaviors which we construct models a simple stimulus/response behavior and does not incorporate such things as localized path planning or arbitrarily assigned time-outs to affect such behavior. Furthermore, our approach is based on the separation of the individual stimulus/response behaviors from the control mechanism which enforces temporal and spatial ordering of such behavior. Our approach is to construct a set of very simple, primitive nonheuristic innate behaviors. It is our thesis that such primitive behaviors can be combined to achieve other more complex behaviors through the spatial and temporal ordering of primitive behaviors. It is the consequence of the resulting complex behavior which supports the desired task of the robot. Specification of such ordering occurs as the result of a design process. We feel that our approach provides a consistent framework for such design and that such consistency is required when one desires to construct complex types of robot behavior.

2.0 Primitive Reflexive Behavior as a Concept

We begin with a fundamental assumption: in order for a mobile robot to act autonomously over a wide range of tasks and environments, it must be capable of exhibiting a variety of different behaviors. In this paper, we introduce some of the primitive reflexive behaviors which we have constructed for a mobile robot, providing a starting point for our investigations in how to achieve autonomy. We begin by investigating the degree of autonomy possible when the robot is limited to memoryless reflexive forms of primitive behaviors.

To provide the robot with reflexive behavior, we construct a set of *primitive reflexive behaviors*, each of which causes the robot to respond to a subset of the total stimuli present in the environment and internal to the robot. We refer to the resulting motion of the robot in its environment as a *behavioral pattern* and the processes which affect it as *behavior*[2].

Each primitive reflexive behavior which we construct is actually an assemblage of computational devices which interpret sensory data, process the data in some manner, and issue a signal which acts as a reference command to the robot actuators. Thus, each behavior is considered as separate from the robot control system. We limit ourselves to constructing behavior from computational devices which do not contain internal state. This results in the construction of behavior which may be characterized as *reflexive*[3]. Such behavior in effect contains no form of memory.

Each primitive reflexive behavior is defined as a transformational system in which the output at time t+1 is completely determined by the inputs at time t. Each primitive behavior acts to enforce a rigid relationship between its inputs and its output and as such, each behavior models a reflexive behavior which causes the robot to respond in a deterministic manner to its internal and/or external state.

Internal state of the robot is characterized by such quantities as position and orientation[4] but may also include quantities such as energy level. External state refers to the environment in which the robot exists. The environment is characterized by sensory data which may be provided by a variety of sensory devices. In this paper, where we focus on the primitive behaviors themselves, rather than on the higher level emergent behaviors that can be created, we will use simulations to demonstrate our results. The environment is modelled as a two dimensional world constructed from interconnected line objects. The state of the environment at each point in time is provided to the robot by a simulated ranging device which provides distance measurements to unknown objects in the environment. The robot does not construct nor maintain an internal map from these measurements.

Each primitive reflexive behavior interprets this sensory data as a *stimulus* which results in a *directed response* by the robot. The response may take the form of a directed motion which would cause the robot to avoid an environmental stimulus (e.g., an approaching object or an enclosed region of space) or the response may cause the robot to exhibit a directed motion towards an environmental stimulus (e.g. - a wide open region of space or a moving object). In addition, the response may be such that it is independent of the external environment and depends only upon the internal state of the robot (e.g. - maintain current direction of motion) or may be a goal directed response which causes the robot to move towards a desired location in the environment.

Many of the reflexive behaviors which we will present model very simple forms of stimulus/response behavior. Simple forms of reflexive behavior are of value when real time motion is desired since the amount of processing required by each behavior is considerably less than that required by traditional path planners.

2.1 Generation of Motion from Behavior

We use a summing device to combine the outputs of each of the primitive reflexive behaviors, resulting in a drive command which is then applied to the robot. The summing device acts as a behavioral fusion module which acts to combine the effects of each of the primitive reflexive behaviors. One perspective from which to interpret the generation of motion from behavior is based upon the use of potential energy fields[5] [Andrews, 83; Hogan, 84; Khatib, 85; Krogh & Thorpe, 86].

In the potential energy approach, one specifies a potential energy function which describes the desired potential energy of

[2] This definition of behavior is consistent with that presented by [Manning; 79] (note - replace the term animal by robot): "Behaviour includes all those processes by which an animal senses the external world and the internal state of its body, and responds to changes which it perceives." Thus, behavior is associated with internal processes where as behavioral pattern is associated with our observation and interpretation of physical phenomenon.

[3] We refer to a behavior as reflexive if it results in a fixed behavioral pattern in response to a set of external and/or internal stimuli. For such behavior, the response at time t+1 is completely determined by the stimuli at time t and is independent of other external/internal events. This definition is consistent with that presented in [McFarland 87]: "Reflex behavior is the most simple form of reaction to external stimulation. Stimuli such as a sudden change of tension in a muscle, a sudden change in the level of illumination, or a touch on some part of the body, induce an automatic, involuntary, and stereotyped response."

[4] Position and orientation require sensing devices which contain state.

[5] See [Andrews; 83] for a more complete presentation of potential fields.

the robot as a function of position[6]. By imposing a specified potential field upon the robot, it is possible to cause the robot to respond as if the robot were subject to an artificial force. The "artificial force"[7] which acts upon the robot as a result of an imposed artificial potential field is by definition, the negative gradient of the potential field function evaluated at the given point in the imposed field.

In our approach, each primitive reflexive behavior interprets sensory data and constructs a drive command equivalent to the force developed as a result of the robot's instantaneous location in the field. The resulting "artificial force" acting on the robot is equivalent to the negative gradient of the potential function evaluated at the specific point in two dimensional space.

Again, it should be emphasized that the potential field approach only provides one with a metaphor for interpreting the signals generated by each primitive reflexive behavior. Such signals do not in actuality correspond to any physical quantity such as force.

2.2 The Primitive Reflexive Behaviors

The following sections describe each of the primitive reflexive behaviors from a functional perspective. The graphic representation of the resulting behavioral patterns are based on a simulation of a robot, operating in an unknown environment (constructed of polygon objects), and subject to the various primitive behaviors. The robot detects the location of objects using simulated sensors, which provide exact measurements at fixed angular intervals. Each of the large circles represents a position of the robot at a given instance of time while the mark internal to the circle represents the current orientation and direction of motion of the robot. The diameter of the robot was fixed at 2.2 feet (the diameter of our real robot). The simulated sensing device provides distance measurements to unknown objects within its maximum range of 11.0 feet at each position of the robot. The measurements are provided at 6 degree increments. Each point detected on an unknown object is represented by the small dark circles (see Figure 2).

The primitive reflexive behaviors are of two distinct types: avoidance and attraction. Avoidance behaviors cause motion away from some stimulus while attraction behaviors cause motion towards some stimulus. Figure 1 shows each of the primitive reflexive behaviors from a functional perspective.

Avoidance Behaviors

Animals exhibit many different types of avoidance behavior. They avoid collisions with objects as they move through their environment, they avoid various predators and avoid environments which do not offer conditions optimal to their survival. Almost exclusively, the mobile robot research community has been concerned with the type of avoidance behavior known as collision avoidance (i.e. insure that the robot will not collide with any objects as it moves from an initial position to a goal position). We have defined two primitive reflexive behaviors which together form the basis of a collision avoidance behavior.

Passive Avoidance

The most fundamental method of avoiding a collision with an object is to halt the forward motion of the robot if a potential collision is detected. This is the purpose of the passive avoidance behavior. It is equivalent to the freeze or startle behavior which has been observed in many different animals. It acts as a reflexive type of behavior which protects the robot in those situations in which a meaningful response cannot be formulated due to limitations in the rate at which sensory data becomes available and the computational time required to generate a response.

The resulting behavioral pattern is the halting of the forward motion of the robot when an object appears within some region of safety and the allowance of forward motion when the object moves out of the region of safety. Rotation is still allowed and may occur if other reflexive behaviors are active.

The region of safety required for a mobile robot is a function of the speed at which the robot is moving, the maximum and minimum range of the sensor, its field of view, the dimensions of the robot and the overall bandwidth of this behavior.

For simulation purposes, the region of safety was defined to be equal in width to the diameter of the robot and extends to twice the radius of the robot, as measured from the center of the robot.

Active Avoidance

The purpose of the active avoidance behavior is to provide a directed response in order to avoid a collision with an approaching object. The term active is used to describe this type of avoidance behavior since unlike the passive avoidance behavior, active avoidance will continually issue commands directed at avoiding a collision with an approaching object. This behavior allows the robot to exist in dynamic environments[8].

The approach we have taken is to dynamically calculate a drive command based upon local sensory range data. Associated with each range measurement is a repulsive "artificial force" which acts to direct the robot away from the detected point on a given object. The vector summation of all of the repulsive "artificial forces" from all points on all detected objects at any given time causes directed motion which will move the robot in the direction of the local minimum of the field at that moment. The robot uses the available, sensory range data to calculate a two dimensional drive command vector based on the specified potential field which is a function of the detected objects at any given instance of time. By continually calculating new drive commands, the robot has the ability to react to dynamically moving objects. No assumptions are needed regarding obstacle motion.

The coordinate frame in which the potential energy function is calculated is polar, with its origin at the center of the robot. Since protection of the robot from collision with approaching objects was of extreme importance, a potential energy function with a nonlinear repulsive force was used. As the distance to an object decreases, the repulsive force acting on the robot approaches infinity. The potential energy function that we used is based on the natural logarithm of the range to an object. The resulting repulsive force function, the negative gradient of the potential function, is then inversely proportional to each range measurement.

By using a constant of proportionality equal to one in our simulations, we get the desired effect. As the distance to an object decreases, the repulsive force approaches infinity and as the distance from an object increases, the repulsive force approaches zero.

The resulting repulsive force vector associated with a given set of range vectors, is the vector summation of each of the individual forces.

[6]The potential field may also be a function of velocity, termed "generalized potential field" [Krogh & Thorpe; 86].

[7]As will be shown, the term "artificial force" is used since Newton's third law "to every action there is always an opposed and equal reaction" does not hold. Henceforth, we will use the terms "artificial force" and "force" interchangeably.

[8]There is a limit to the degree to which this behavior can avoid collisions with dynamic objects in the environment due to limitations in the ability to sense such objects, limitations in the rate at which such objects can be detected, and the limited power available to the robot for response. These limitations are limitations not in the approach but in the current state of technology.

The behavioral pattern which results from the active-avoidance behavior is illustrated in Figure 2 in which the robot is initially placed next to an object. This primitive reflexive behavior causes the robot to move away from the object until the object is no longer detected by the sensor. Note that if the object moved towards the robot, the robot would again actively move away to avoid collision.

Attraction Behaviors

The following sections describe the different types of attractive primitive reflexive behaviors which have been constructed.

Location Attraction

The purpose of this behavior is to provide the robot with location directed motion where the location is specified by a desired position of the robot in a global frame of reference.

A robot acting with this behavior will continually generate commands which result in motion in the direction of the desired location. This behavior provides no protection from objects which may block the path of the robot or any protection from approaching objects once the robot is at its desired location. It simply causes straight line motion from the current robot location to the desired location.

This behavior is similar to the goal oriented behavior observed in many different animals and has been shown to be a component behavior in migratory types of behaviors [Baker, 81]. During migratory types of behavior, when the animal is displaced from its current location, it has been observed to exhibit a directed motion which causes it to re-orient itself towards a goal. It is thought that migratory behaviors are a result of the animal's ability to sense its own orientation relative to the magnetic fields produced by the earth [McFarland, 87; Baker, 81].

One should note an important point regarding this behavior: (1) it depends upon external specification of the desired location at each step in the simulation since the robot has no form of internal memory, and (2) while the behavior itself contains no internal state, the stimulus to which it responds, does (i.e., the sensing device which maintains the robot's location in a global frame of reference). This supports the notion that some form of memory is required when we are constructing a device which fulfills a purpose which we desire (i.e., "imposed autonomy").

Forward Attraction

The purpose of this behavior is to provide the robot with forward directed motion. A robot acting with this behavior will continually generate commands which result in motion along the current orientation of the robot. In effect, this behavior results in a robot which sustains forward motion, regardless of detected objects in the environment. As with the location attraction behavior, this behavior provides no protection from objects which may lie in front of the robot. With the forward-attraction behavior alone, a robot would move along its current orientation until a collision occurs.

Object Attraction

The object-attraction behavior functions to generate motion in the direction of an object. The object is represented by its surface normal which is calculated from the range data obtained from the sensor (Figure 3). When an object is detected, an attractive force is generated to cause motion towards the object.

The object-detector upon which this behavior depends does not distinguish between different objects, it forms the surface normal based upon all of the objects detected at any given time. Figure 4 illustrates the surface normal as calculated by the object-detector when two distinct objects are present. Note that the output of this detector is not unique; the representation of the objects shown in Figure 3 is equivalent to that shown in Figure 4.

A robot acting under this behavior will exhibit no movement (i.e., response) unless an object is detected (i.e., stimulus). When an object is detected, movement will occur in the direction of the object.

Object Following CW

As with the object-attraction behavior, the object-following-cw behavior depends upon an abstract sensing device, the object-detector to generate a representation of the objects in the environment. In contrast to the object-attraction behavior which generated motion in the direction of the surface normal, this behavior generates motion in a direction perpendicular to the output of the object-detector such that motion occurs in a clockwise direction around the object.

Figure 5 illustrates the effect of activating this behavior. This behavior exerts no control over the distance with which it follows objects. Thus, the robot follows objects at varying distances due only to the geometry of the environment and its position in it.

The behavior is completely deterministic and it is possible for the robot to repeat the behavioral pattern given the same starting location for the robot and the same environment. (In reality, this is not likely.) In addition, this behavior does not provide for protection from collisions with objects in the environment (as will eventually occur due to interior corners of the room). As with the object-attraction behavior, this behavior will cause no response in the absence of stimuli. Thus, object following occurs only when objects are detected by the object-detector.

Object Following CCW

This behavior is identical to the object-following-cw behavior except that the attractive potential field associated with this behavior causes motion in a counter clockwise direction around the object.

Open Space Attraction Behaviors

The stimulus-response behaviors which we have defined thus far have been primarily concerned with the locations and shapes of objects in the environment. For example, passive-avoidance, active-avoidance, object-attraction, and the object-following behaviors each generated their response based upon detected objects in the environment. A group of primitive reflexive behaviors can be defined based upon the regions of space in which no objects are detected. Such regions are defined when a set of sensory measurements return no range value (i.e., no object detected). These regions indicate completely open regions of space which provide unobstructed travel. At any given position in the environment, multiple regions of open space may exist (e.g., corresponding to the case when multiple objects are detected) or a single region of open space may exist (e.g., when no objects were detected).

Each region of open space is characterized by a set of attributes. For each region of open space, such attributes are calculated and stored temporarily in a data structure. We refer to the instantiated data structure as an *open-space-object*.[9] The attributes associated with each open-space-object are listed in Figure 6.

Figure 7 illustrates graphically three open-space-objects as detected by the simulated sensors and the mobile robot. Figure 8 illustrates the computing element open-space-detector responsible for generating open-space-objects.

This is an abstract type of sensor which has as its inputs, the range data associated with a given scan of the environment, the current orientation of the robot in its environment, and the global location of the robot. The output of the open-space-detector is a list of open-space objects, each of which represents one of the detected open regions of space.

[9]Objects here refer not to objects in the environment but to computational objects which hold local state information in its instance variables.

This detector interprets range measurements as binary valued quantities: If a given range measurement has a value, it is equated to 1; if the given range measurement returns no value (i.e., out of range), it is equated to 0. This sensor device constructs open-space-objects from those sets of adjacent measurements which are equated to zero.

The resulting model of open spaces is a very simple one deriving its knowledge from an understanding of the arrangement of the sensor on the vehicle and its maximum range. From these two quantities, one can calculate the angular width of the open-space-objects, a value which allows one to differentiate between wide open regions of space and narrow open regions of space.

Note that such a sensor could be constructed using very crude approximates of distances to objects in the environment (e.g., a device such as a low resolution proximity sensor). The open-space-detector derives its power from many such sensors (i.e., high angular resolution), arranged in a radial manner around the robot.

The open-space-detector functions by examining the angular separation between each of the successive range measurements present on its sensory input wire, determining if the angular separation is greater than the angular resolution of the sensor. If this condition holds, then an open space must exist (assuming perfect sensory data) and the open-space-detector creates an instance of an open-space-object, setting its instance variables to the appropriate values. This process occurs recursively until all of the range data on its sensory input wire have been processed. The list of corresponding open-space-objects is then placed on its output wire and the open-space-detector awaits for new values to appear on its inputs. Thus, the open-space-detector functions as a new type of sensor, abstracting range measurements and creating open-space-objects. If no objects are detected by the range sensor, a single open-space-object is created, representing a completely open region of space. In this case, however, the global orientation to center is set to the current orientation of the robot.

Based upon this interpretation of range data, three different primitive reflexive behaviors are defined, each of which causes a different type of open space attraction.

Narrow Open Space Attraction

The purpose of this behavior is to provide the robot with open space directed motion such that attraction to narrow open spaces occurs. This behavior will generate an attractive force which results in motion towards the center of the open-space-object which possesses the smallest open angular width. If only one open-space object exists, no output is generated. This occurs if the robot is in completely open space (i.e., no objects detected) or if the robot encounters only one object. Thus, attraction to narrow open spaces occurs only when there are two or more open-space-objects from which to choose. This behavior provides protection from collision with objects in the sense that the behavior generates an attractive force in the direction of an open-space-object which by its very definition, contains no object. The ability of the behavior to avoid collisions is limited however in that for the case when only one open-space-object is detected, no action is taken.

Figure 9 illustrates the resulting behavioral pattern when this behavior is active. As can be seen, this behavior provides for limited collision avoidance. However, this behavior is useful for getting a vehicle to enter a corridor from a large open region. It may also provide a robot with a behavior which induces motion towards regions of space which provide natural protection from adverse environmental factors. It may allow the machine to 'hide'.

Wide Open Space Attraction

The purpose of this behavior is to provide the robot with open space directed motion such that attraction to wide open spaces occurs. This behavior will generate an attractive force which induces motion towards the center of the open-space-object which possesses the largest open angular width. Unlike the operation of the narrow-open-space-attraction behavior, action will occur for the case when only one open-space-object is detected. The action taken will depend on whether the open-space-object represents a space in which no objects are detected or whether it represents the detection of a single object. In the first case, no action occurs since the robot is in an open space where no objects are present (i.e., the robot is in the "most open space" possible). In the second case, an attractive force is generated towards the open space so as to the machine away from the object. Thus, the wide-open-space-attraction behavior results in a robot which constantly causes motion to occur in the direction of the largest detected region of open space. This behavior results in a robot which "seeks" regions of wide open space. If the robot, acting under this behavior reaches a region in which no objects are detected, it will remain idle. If an object approaches the robot, it will seek a new region of space in which no objects exist. As with narrow-open-space-attraction, this behavior provides protection from collision with objects, in the sense that the behavior generates an attractive force in the direction of an open-space-object which by its very definition, contains no object. This is a side effect of the implementation, however, and is not its primary purpose.

Such a behavior may itself prove valuable from the standpoint of sensory interpretation (e.g., landmark recognition) by causing motion which is directed towards regions of open space which provide a maximal view of the surroundings.

Figure 10 illustrates the resulting behavioral pattern which occurs when this behavior is activated. As can be seen, the robot moves until it either finds a region of space in which no objects are detected or until it finds a region of space which is locally "large". There may be larger open regions in the environment, but moving to them would require movement through "smaller" regions of space. However, the robot will continue to move, "seeking" a more wide open region of space than it currently occupies.

Location Directed Open Space Attraction

The purpose of this behavior is to provide the robot with a type of directed open space attraction such that motion occurs in the direction of regions of open space which lie in the direction of some specified location in the environment. This behavior will generate an attractive force which results in motion towards the center of the open-space-object which has its global-direction-to-center closest to that of the direction of the desired location.

If only a single open-space-object is detected, it is examined to determine whether it represents completely open space or the presence of a single object in the environment. In the first case, the global-direction-to-center is modified to point in the direction of the desired location. In the second case when the open-space-object occurs due to the presence of a single object, no action is taken.

Thus, the location-directed-open-space-attraction behavior results in a robot which constantly causes motion to occur in the direction of open regions of space which are most closely aligned with the goal direction. Figure 11 illustrates the resulting behavioral pattern.

3.0 Emergent Robot Behavior

In the multi-behavioral approach to autonomy, emergent behavior occurs as a result of the spatial ordering of behavior (i.e., the concurrent activation of a set of primitive reflexive behaviors); or through the temporal ordering of behavior (i.e., the sequential activation of different sets of primitive reflexive behaviors). Many emergent behaviors can be developed from the above set of primitive behaviors. Higher level behaviors take advantage of lower level emergent behaviors by simply adding on the appropriate behaviors. While we recognize that it is difficult to see the value of the primitive reflexive behaviors without examining the emergent behaviors in detail, it is difficult to do justice to both within the confines of one paper.

A brief summary of those emergent behaviors that we have investigated is presented in Table 1. Figure 12 illustrates the Location Directed Open Space Wandering behavior for a simulated robot whose goal location is not immediately accessible. It is important to note that each of the primitive reflexive behaviors, which we have constructed, models a simple stimulus/response mechanism which does not incorporate heuristics or localized path planning algorithms. Each behavior models a directional response to a specific stimulus.

Simulation and experimental results are both discussed in much more detail in [Anderson and Donath, 90].

Acknowledgements:

This work was supported with funds provided in part by the University of Minnesota Productivity Center, the CIM Consortium, CyberOptics Corp., and the Office of Naval Research under Contract N0004-85-C-0847. We also appreciate the loan of equipment by MTS Systems Corp.

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Emergent behavior:	**Component Behaviors:**
Object Avoidance	Passive Avoidance, Active Avoidance
Generalized Wandering	Object Avoidance, Forward Attraction
Simple Navigation	Object Avoidance, Location Attraction
Perimeter Following	Object Avoidance, Object Attraction, Follow Object (CW or CCW)
Wide Open Space Wandering	Generalized Wandering, Wide Open Space Attraction
Narrow Open Space Wandering	Generalized Wandering, Narrow Open Space Attraction
Location Directed Open Space Wandering	Generalized Wandering, Location Directed Open Space Attraction

Table 1 Emergent Reflexive Behaviors and their Component Behaviors

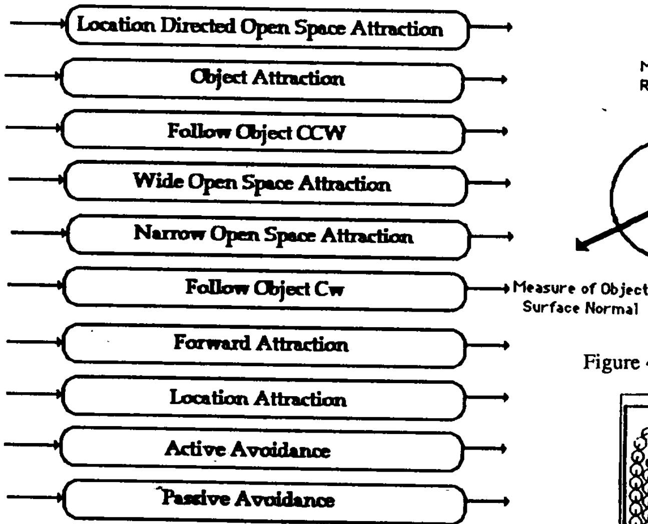

Figure 1 Functional diagram of primitive reflexive behaviors

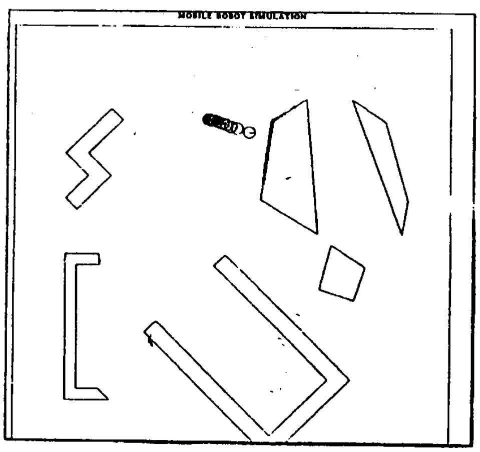

Figure 2 Behavioral pattern due to *active avoidance* primitive reflexive behaviors

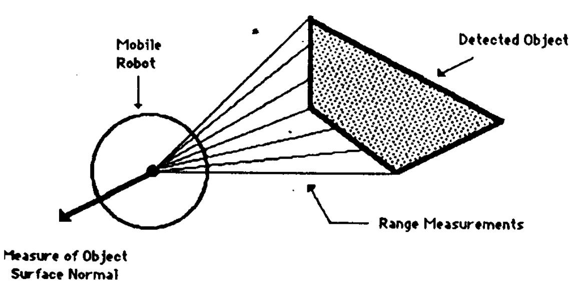

Figure 3 Surface normal taken as a measure of the local environment by object-detector device

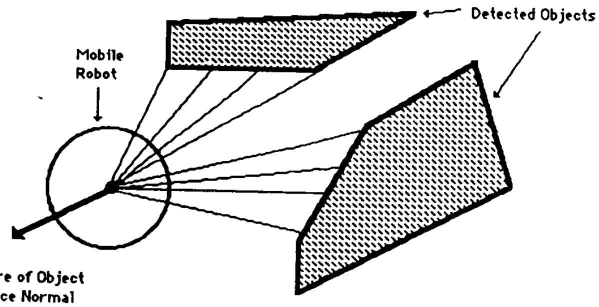

Figure 4 The output of the Object-detector device is not unique

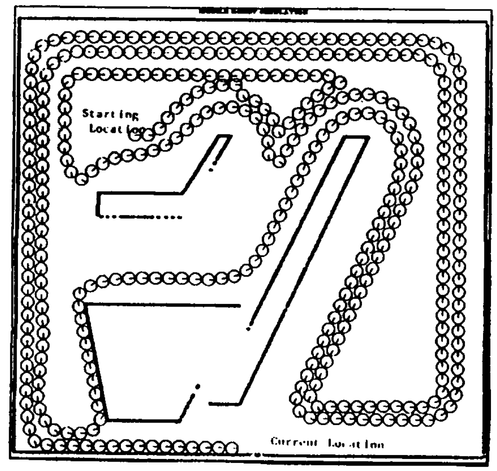

Figure 5 Behavioral pattern due to *object following cw* primitive reflexive behavior

Ω_c = Global direction to center of the open-space-object
ß = Angular width of the open-space-object
Xg, Yg = Global location of the robot
R_{max} = Maximum range of the sensor

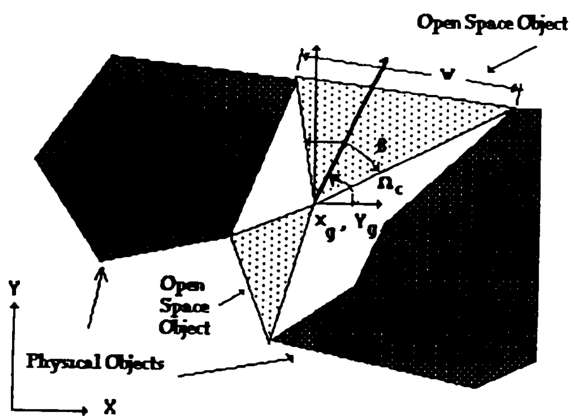

Figure 6 Two open space objects are detected by the open-space-detector device

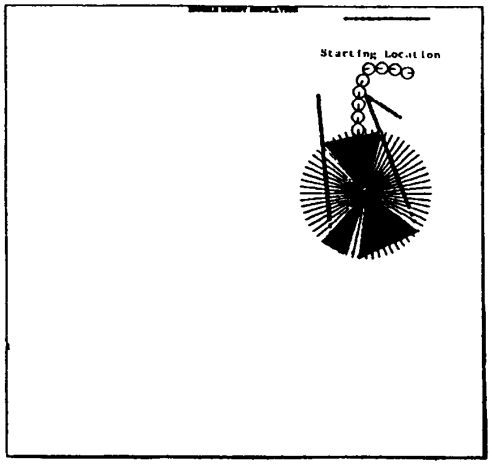

Figure 7 Graphic display of three open-space-objects as detected by the open-space-detector

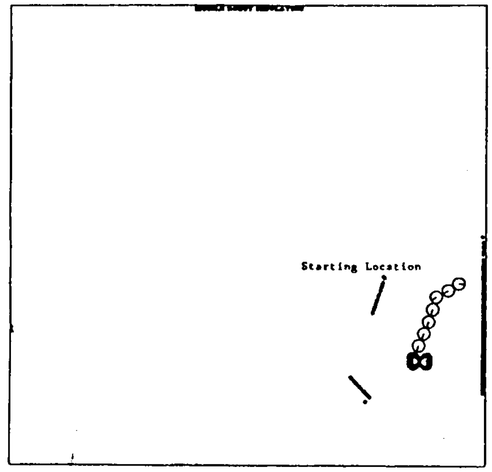

Figure 10 Behavioral pattern due to *wide open space attraction* primitive reflexive behavior

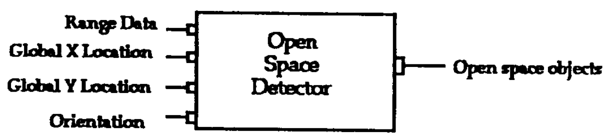

Figure 8 Open space detector

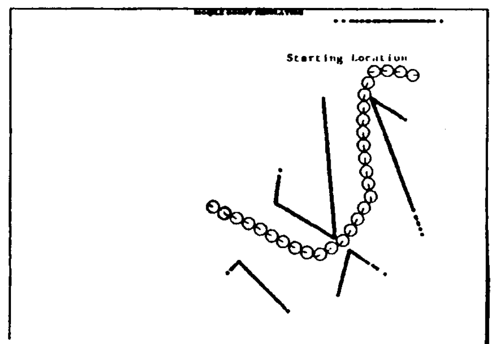

Figure 11 Behavioral pattern due to *location directed open space attraction* primitive reflexive behavior

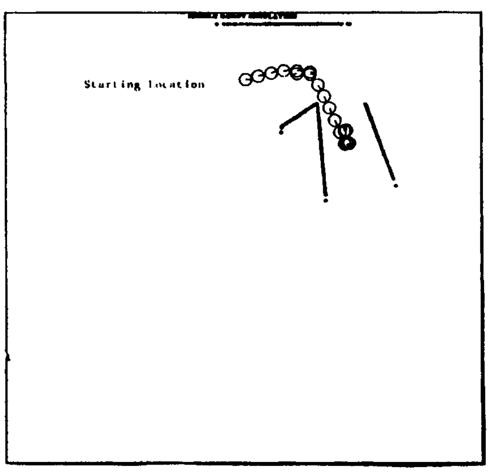

Figure 9 Behavioral pattern due to *narrow open space attraction* primitive reflexive behavior

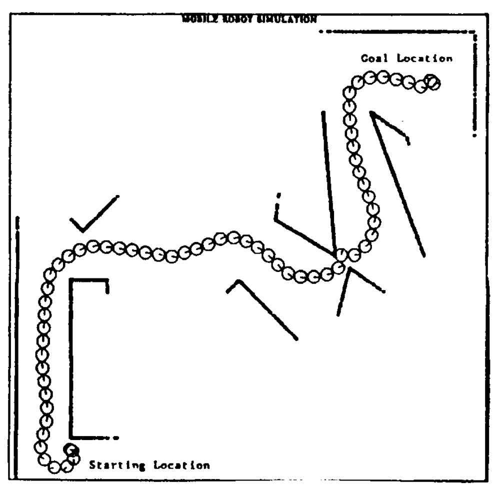

Figure 12 The *Location directed open space wandering* emergent behavior