Robotic Comfort Zones

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ABSTRACT

This paper investigates how the psychological notion of comfort can be useful in the design of robotic systems. A review of the existing study of human comfort, especially regarding its presence in infants, is conducted with the goal being to determine the relevant characteristics for mapping it onto the robotics domain. Focus is placed on the identification of the salient features in the environment that affect the comfort level. Factors involved include current state familiarity, working conditions, the amount and location of available resources, etc. As part of our newly developed comfort function theory, the notion of an object as a psychological attachment for a robot is also introduced, as espoused in Bowlby's theory of attachment. The output space of the comfort function and its dependency on the comfort level are analyzed. The results of the derivation of this comfort function are then presented in terms of the impact they have on robotic behavior. Justification for the use of the comfort function in the domain of robotics is presented with relevance for real-world operations. Also, a transformation of the theoretical discussion into a mathematical framework suitable for implementation within a behavior-based control system is presented. The paper concludes with results of simulation studies and real robot experiments using the derived comfort function.

Keywords: Comfort zones, Comfort function, Attachment theory, Discrepancy theory, Behavior-based robotics

1. MOTIVATION

We all feel comfortable in some cases and uncomfortable in others. We act self-confidently, without looking for help from elsewhere, when we feel comfortable. On the other hand, when we have a strong feeling of discomfort, we act with considerable thoroughness, are resistant to explore new things and new places, and look for support in order to increase our level of comfort. Our behavior is strongly influenced by our level of comfort. Somehow, the external conditions of the environment we find ourselves in and our own internal state determine this level of comfort. Moreover, as the paper shows later, most of the features that affect the level of comfort are such that they reflect our perceived degree of safety in the current environment and the degree of normal functioning of our internal system. In the first case, these are exogenous variables and include such things as the degree of familiarity with a current environmental state and the pleasantness of past experiences in this state. In the second case, the variables are endogenous since they describe the internal state of the system and include such features as hunger, body temperature, pain, etc. Thus, a comfort level describes both the internal needs of a system as well as the safety of the surrounding environment.

This paper models a comfort function for use in robotics. But what would an autonomous system gain by having a comfort function model? First, a truly autonomous system should be capable of recognizing its own internal needs and modifying its behavior appropriately[19]. It cannot and should not act identically when it has a full fuel tank and a nearly empty one. The world is not deterministic, however, and we cannot foresee all the events that may occur to a robot. Many of these unforeseen situations could be critical and a robot must act quickly with little or no time for deliberation. The internal needs for a robot can be represented through a level of comfort, and a robot can use it in adjusting its behavior with minimal delay. This paper studies the effect comfort has on human behavior and attempts to model parts of it in a robot. Via the comfort parameter, the behavior of the behavioral control system is connected to the internal needs of the system.

Secondly, the numerous papers in psychology showed that familiarity with an environment and past experiences in it drastically affect the behavior of many natural systems[1, 2, 6, 17]. In effect, these features represent the safety of the environment, and our behavior, especially exploration behavior, is strongly influenced by the safety of the current environment. The comfort function reflects the degree of environmental safety and allows an autonomous system to quickly react in unsafe environments. If a robot is in a room where it was many times before and everything is as the robot always saw it previously, the robot should act with more confidence than if something in the room is significantly different from the robot's expectations or when in a complete novel environment.

Thus the model of a comfort function is directed toward the increase of the survival chances of the autonomous system. The comfort function can even be used more generally to drive a system towards maximizing its personal comfort level. Just as animals seek for a more comfortable state within the constraints of their environment and their goals, a robotic system should also maintain a notion of its own comfort level. A robot should operate in such a way as to achieve its goals while maintaining the maximum possible level of comfort, and as a result, increasing its own chances of survival.

2. RELATED WORK

Currently, no work on modeling a comfort function for robots is known to the authors of this paper. However, as there is a substantial research on modeling emotions in robotic systems, it might be worthwhile to explain how the present work is different from it.

It was suggested in numerous publications that emotions are one of the mechanisms that help natural systems cope with the world. As Darwin noted, one of the main functions that emotions carry is to increase the survivability of a system[7]. The emotions trigger corresponding reactions in a system in response to critical environmental events. These reactions typically act in manner that assists in surviving the crisis. Often a critical situation does not allow time for deliberation, and emotions modulate the behavioral response directly. Many AI researchers agree that an autonomous system has to possess some degree of emotions and a number of emotional intelligent systems were built[8, 9, 11, 12, and 13.] Pfeifer, who built the autonomous agents called "Fungus eaters", capable of emulating basic emotions, argues that for the successful performance of an autonomous agent requires that it have some emotions[8]. Moffat et al also argue that emotions are important for autonomous agents living in an uncertain world with bounded resources[9], as emotions are crucial for handling these limitations. This work actually goes even further and defines a set of emotional requirements that an emotional autonomous agent should possess. One of several properties they define is that emotions should react very quickly within a given environment.

One of the other reasons why emotions appeal to many AI researchers is that they make the system look more natural to humans, more human-like. There is much more in emotions than just an increase of survivability and the performance in a goal-achievement behavior. According to discrete emotion theory[10], there exists a set of primitive emotions. Their number varies from one theory to another, but usually it is assumed to be from six to twelve. Some of these emotions are: joy, happiness, sadness, shame, anger, disgust and fear. Depending on a robot's task in its world, often the full set of primary emotions is more than what a robot needs in order to improve its coping with the world strategies. Hence, instead of modeling a full set of primary emotions, the notion of robotic comfort is introduced in this paper. The comfort level characterizes what a robot feels regarding its ability to cope with the world. The more the robot is sure of its capabilities, the more comfortable it should feel. In contrast to full emotion modeling the smaller input domain for the comfort function provides a simpler mechanism for improving robot survival strategy. It also provides a secondary goal to a system - to try to maximize its personal comfort level or, in other words, to seek a more comfortable state. This strategy fits very well within many existing behavior-based robotic frameworks.

3. PSYCHOLOGICAL MODELS OF COMFORT

There are a number of questions that have to be answered creating a robotic comfort function. First, it is necessary to identify the input features that affect the comfort level. Second, the relationship between the comfort level and these features has to be studied. Third, the range of the comfort function has to be identified. Lastly, the actual relationship between the comfort level and motor output has to be determined. To answer these questions, the study of psychological comfort was reviewed. It is important to note that the psychological study of comfort that the model in the paper is based upon does not fully describe the notion of comfort in humans. Comfort as a subject is too vague and complex, and moreover, little psychological research on this topic was uncovered. Thus, the model presented here is preliminary in the sense that as comfort is studied more in psychology their results can be incorporated into the currently proposed model of robotic comfort.

One of the main sources of insights into the notion of comfort provided the book "Distress and Comfort" by Judy Dunn[1] that studies comfort and distress in infants. The fact that it was done on infants had its own advantages. In the early years of a child it might be easier to recognize the relationship between the internal and external factors and the degree of comfort or distress. In infants, supposedly, this relationship might be less complicated and less affected by other factors than in adults whose perception and understanding of the world are far more developed than in human infants.

3.1. Input domain of the comfort function

Dunn[1] states that the input features of comfort can be broken into two components. The first component of comfort results from satisfaction of the infant's primary needs. For example, comfort is most apparent when an infant is provided with warmth and food immediately after the infant was hungry and cold. All of the input are internal and constitute the endogenous component of the comfort function.

The second component of the comfort function comes from the external information of the infant's world. It arises from the interpretation and understanding of the current situation. For example, a child in a strange place might feel uncomfortable than in a familiar one. On the other hand, if a familiar person (e.g., a parent) is present with the child, he/she might feel much more comfortable. This component is the exogenous component since the information comes from external sources.

Dunn identifies endogenous factors such as hunger, body temperature, pain, and violent or sudden stimulation received by any of the infant's sensors such as eyes, ears, balance and others[1]. It is interesting to note that constant, slow, or rhythmic change in the stimulation results in greater comfort, whereas sudden, unexpected, or rapid stimulation results in discomfort. The above list of input features clearly does not present all the possible factors, and should be extended as more studies become available.

Factors affecting the exogenous component of comfort are slightly more difficult to characterize. One major factors, as mentioned above, is familiarity – the familiarity with a place a person is in, the familiarity with the people that are around, the familiarity with the events that are currently happening. According to Hebb's Discrepancy Theory[2], derived for animals, fear and as a result, discomfort, are evoked by events that are very different or discrepant from previous experiences. As an extension, Dunn suggests that not only is familiarity with the current situation important, but also whether the past experience with the current situation was a pleasant, neutral or unpleasant one[1]. A well-known state that consistently brings unpleasant experiences to a person causes strong discomfort by virtue of being in that situation again. The state as used here is not necessarily a spatial state, but includes all the relevant environmental characteristics.

According to Stroufe[3], an infant brings to the evaluation of any situation a predisposition threshold on whether to react with pleasure or fear. This threshold is influenced by many factors such as body temperature, familiarity with the people around and a situation and others as discussed above. One can suggest that it is equivalent to combining the two components of the comfort function into one threshold value: the comfort level.

Research indicates that the comfort function changes in children with their development[1]. In the early stages of life, immediate changes in an infant's physical state play the major role in the overall degree of comfort. However, as the child grows, the causes for comfort and the degree to which they affect the child usually change. This phenomena, perhaps in part, can be explained by the growth of familiarity with the world. As a child develops, more and more of the world become familiar to him/her. The situational states where some primary needs are left unsatisfied also become more familiar. This higher degree of familiarity with a variety of external and internal states causes an overall increase in comfort.

3.2. The objects of attachment or places of the greatest comfort

Bowlby created a theory of attachment[4] in which he points out that infants associate certain individuals with security and comfort. They use these people as sources of comfort. In their early years, children want to maintain close proximity to these people, and the degree to which they want to maintain this proximity depends on the circumstances. As Ainsworth and Bell expressed it[5]: "the behavioral hallmark of attachment is seeking to gain and to maintain a certain degree of proximity to the object of attachment, which ranges from close physical contact under some circumstances to interaction or communication across some distance under other circumstances." A good example of an object of attachment might be a mother to a child. Very often a child wants to be near his mother in his early years. He uses her as a source of comfort in dangerous situations and as a base for further exploration in normal situations. As Ainsworth points out, there is a difference between the expression of an attachment and the actual attachment bond. The former may vary depending on the situation while the later is not dependent on any stimulus but rather describes the true bond between a child and its object of attachment. As Bowlby suggested, the strength of an attachment between a baby and its mother is mainly dependent on the kind of care that the mother gives to her baby[4]. Thus, every object of attachment is associated with an attachment bond between itself and the child, whereas the force of the attachment is situationally dependent and is directed toward decreasing the distance between the child and its object of attachment.

The following presents a modification to the above theory. A mother for an infant provides not only a feeling of security. She also provides a source of primary needs fulfillment. An infant gains both maximum exogenous and maximum endogenous comfort components by being physically colocated with its mother. It can be viewed as if the object of attachment brings great comfort to an infant. Thus, the force between an object of attachment is a function of several variables: the attachment bond that corresponds to the object, the level of overall comfort in an individual, and the distance between the person and the object.

3.3. The range of the comfort function

This section attempts to identify some of the effects that the comfort level has on human behavior. Note that the identified effects only constitute a partial extent to which a comfort affects a person. In the future, as more psychological data becomes available, additional effects can be taken into account.

People try to maximize their level of comfort within the constraints and goals that they need to achieve. Every state in the world can have an exogenous comfort component associated with it. When all other properties of states are equal, people usually choose a state that brings the highest comfort level. All animals obviously seek to fulfill their internal needs as well. An increase in the endogenous component of the comfort function is sought. Actions are chosen that maximize the endogenous component of the comfort given all else being equal.

Attachment behavior can be viewed as a specific case. Instead of associating every state in the world with some exogenous comfort values and identifying which actions maximize endogenous component of the comfort function, the objects of attachments can be used to define those rare states in the world that bring maximum overall comfort. Thus, the current comfort level should affect the magnitude of the attachment force. It can be postulated that when comfort is at its maximum, the attachment force has the lowest possible level, whereas as the comfort level diminishes, leading to strong discomfort, the attachment force increases becoming one of the dominant forces in a person's behavior.

The control of the comfort level on the attachment force magnitude can also be viewed from a different perspective. It is well known that it is very important for any creature in this world both to find about the world it lives in and to avoid the world's dangers. And so it is for humans. "Balance between exploring the world and maintaining safe contact is obviously one of great importance to the child."[1]. The force of attachment attempts to maintain this balance. As comfort level decreases, the dangers become stronger since either the current state is unfamiliar, or past experiences that this state brings were unpleasant, or some of the crucial primary needs are unsatisfied possibly leading to a dysfunction in an organism.

Using the attachment force to control the exploration process correlates with the observation made by Ainsworth[7] that a child uses its mother as a base from which to explore. Ainsworth and Wittig performed a series of experiments in which one-year old children were left in a new room they had not previously encountered. When the children were with their mothers, they began to explore the room, whereas if left alone they immediately ceased the exploration process and tried to follow their mothers exit. This demonstrates that as an object of attachment moves away leaving a child in an unfamiliar situation, the attachment force on the child increases and becomes a dominant force in the determination of the child's overall behavior.

4. COMPUTATIONAL MODEL

This section brings the psychological features described above into the world of robotics, starting with the mapping of the salient features in the comfort function for humans onto autonomous robot systems. Afterwards, the output space of the comfort function is developed. Finally, a mathematical framework is provided for computing the comfort level. The relationship between the input space features and comfort function is not presented in this paper and is currently still under investigation.

4.1. Input domain of the comfort function for robots

It is first necessary to identify salient features that define the input space for the endogenous and exogenous components of comfort. The endogenous comfort component in infants is affected by such internal characteristics as hunger, body temperature, pain and violent or sudden stimulation received by any of the infant's sensors such as eyes, ears, balance and others[1] as described in the previous section. Most of these factors can be mapped directly onto corresponding features in a robot's world. Hunger can be mapped onto the level of energy remaining for the robot. Temperature can be mapped onto the internal temperature of the robot. Pain can be mapped onto the external and internal damage in the robot as a result of a physical assault, robot actions, or malfunctioning in the robot's internal circuits. Finally, violent and sudden stimulation can just be mapped onto the degree of the change in the external stimulation where constant, slow, or rhythmic changes in stimulation result in greater endogenous comfort, whereas the sudden, unexpected, or extreme change in stimulation results in discomfort. The overall amount of information a robot receives may also play into the stimulation factor. These suggested factors do not present the complete list of the possible features that affect the endogenous comfort component but are sufficient for the initial study.

Similarly, the input features for the exogenous comfort component for infants can be mapped onto the input space for a robotic autonomous system. The exogenous comfort experienced by a robot should be dependent on the robot's familiarity with its current state or situation. A state is not necessarily only a spatial location but contains other relevant situational context. If the robot is familiar with its current state, then it should know how to respond and should feel comfortable. If the current state is very new to the robot, then it should feel at least somewhat uncomfortable in this state. As with infants, the past experience should matter. A well-known state that consistently brings unpleasant experiences to the robot (e.g. damage, failure to achieve goals and etc) should cause strong discomfort in the robot. Ideally, every state in the robot's world should be associated with some exogenous comfort level. This comfort level should be a function of all the factors affecting it such as familiarity with the state, past experiences and any other relevant features. When the robot enters a new state, it assumes the corresponding exogenous comfort level. However, as time passes, the exogenous level of comfort changes. If no negative experience happens while in this state, the robot's comfort should rise. If the state brings a negative experience, the comfort should decrease, resulting in the sense of overall discomfort.

As the psychological model of comfort suggests, the two components of comfort, exogenous and endogenous, can be brought together to evaluate a single threshold - the comfort level - that can be used to define robotic comfort-based behavior. The robotic comfort function can be dependent on ontogenetic development. As the robot "lives" in its world, it develops. Not only can it get familiar and collect experiences regarding different world states. A robot can learn, for example, what are easier and more difficult resources to obtain. If energy for recharging is in abundance in the robot's world, then, perhaps, the amount of remaining energy should be less significant to the endogenous comfort component of the robot than other factors.

4.2. The objects of attachment or places of the greatest comfort for robots

According to attachment theory for infants the objects of attachment that cause the greatest comfort in infants are usually people. But what can such objects be in the domain of robotics? One possible answer is that such sources of attachment might be caregiving people or certain places where robots can fulfill their needs. At these places, robots can potentially attain their maximum degree of comfort. When all their primary needs are fulfilled, this results in maximum endogenous comfort. The robots are also in a safe place where they have been many times and experience was always positive. Thus, they gain a maximum exogenous comfort. This means that the level of overall comfort is at its maximum in such places.

An example of such an object of attachment might be a home base for a military robot. For a pet robot, such source of attachment might be its master.

The objects of attachments can be identified for a robot beforehand by a human, or potentially the robot can find it autonomously by exploring the world and monitoring for a state which maximizes its comfort level. The second approach involves learning the most comfortable places in robot's world.

Either way, every object of attachment should be associated with an attachment bond between itself and the robot. As Bowlby suggested that the strength of an attachment between a baby and a mother is dependent on the kind of care that the mother gives to her baby[4], the degree to which a robot feels a bond to a certain object of attachment is dependent on how its needs are fulfilled by that object and the level of comfort the robot can achieve with that object.

The attachment function has the same character as the one discussed in Section 3. The more discomfort the robot experiences, the stronger it should attempt to return to a known comfort source. The robot's behavior determines the proximity to its object of attachment. The attachment force is a vector directed toward the object of attachment, and the magnitude of the vector is a function of (1) the attachment bond that corresponds to the object, (2) the level of overall comfort in a robot and (3) the distance between the robot and the object.

4.3. The range of the robot comfort function

The effect of the comfort level in a robot should be similar to a human's. Drawing from psychological studies, each possible world state is associated with an exogenous comfort factor, and the robot is biased toward states with the higher. The comfort level is one of the variables in the attachment behavior. Comfort controls the proximity of the robot to its source of attachment. Since a high comfort level corresponds to familiar states, the effect is that the attachment behavior regulates exploration by controlling the distance of the robot to the source of attachment. As the environment becomes more and more familiar and seems safe, the robot increases its exploration range.

4.4. The mathematical framework of the model

The mathematical formulation of the theory given below is by no means the only one or, perhaps, might not be even completely correct when considering human comfort. Rather, it presents a mathematical model that fits into the theoretical discussion of the comfort function discussed above. As more constraints or factors affecting the comfort function are identified in the psychology research the mathematical model may change. But not necessarily as we are really interested in robotic comfort level representation and not human level.

A mathematical model is given for the relationship of the comfort level and its output. How the input space of the comfort function is related to the comfort level itself is still currently being investigated. Thus, for this paper, it is assumed that the value of the comfort level is determined a priori. Depending on the mission and the environment a robot can be more or less comfortable, but its comfort level stays constant throughout its mission in this early work.

The attachment theory does not say that there can be only one attachment object and it is common for humans to have more than one such object. However, most of the time the primary caregiver becomes the first and the most important figure of attachment for infants. Thus, for now it is sufficient to define the attachment behavior that only works with one object of attachment. Currently this object is defined by a human for the robot and can be, for example, a home base, a person, or another robot capable of servicing other robots.

According to attachment theory, the outcome of the attachment behavior is an action directed toward the increase or maintenance of the proximity with the object of attachment[17]. Thus, at any point of time, the output of the attachment behavior is a vector directed toward the object of attachment. That is, the robot experiences an attractive force toward its attachment object. The magnitude of this vector, on the other hand, varies and, in effect, represents the intensity of the attachment. As described in the section on the attachment theory the intensity of the attachment is the following function:

$$A = f(C, \alpha, d), \tag{1}$$

where A is the intensity of the attachment or the magnitude of the attachment vector, in other words; C is the overall comfort level of a robot; α is the attachment bonding quality between the robot and the particular attachment object in question, and d is the distance between the robot and the attachment object.

The function is defined as the product of the normal attachment maximum level N, quality of attachment α, and the amplification of the comfort component in the function by a proximity factor D:

$$A = N * \alpha * D * \varphi(C), \tag{2}$$

The normal attachment maximum level N just defines the maximum magnitude of the attachment intensity when the object of attachment is a normal "mother", so to speak. All the other factors in the function are normalized.

The attachment bonding quality (α) should be dependent on the quality of care that the caregiver attachment object provides for the robot. Since the current model is only defined for one such figure of attachment, then we can make the parameter α to be non-adaptive but rather configurable by a user. Setting the attachment quality α to 1 corresponds to a "normal mother" attachment object. Increasing the quality of attachment over 1 corresponds to "over-caring mother", whereas decreasing the quality of attachment below 1 corresponds to "under-caring mother". A case when the quality of attachment is set to 0, corresponds to "no-care mother" which results in the absence of attachment behavior in a robot.

The relationship between A and C expressed in the comfort component φ(C) is drawn from a couple of sources. First, the work by Feeney and Noller on attachment in adults[18] presents the comfort-seeking intensity as a function of anxiety and fear. The function is shown to be linear for secure subjects of the experiments. Since this work models secure robots rather than insecure ones, the relationship is also considered to be linear. In addition, as Colin[17] points out, there are two levels of activation for the attachment behavior. There is a low level of activation of the attachment behavior, at which the behavior has almost no effect but only monitors the proximity. There is also a strong activation level of the attachment behavior, at which the outcome of this behavior overrides almost completely any other behaviors in the system. Thus, based on these studies, in Figure 1 we propose one possible form of the relationship between A and C.

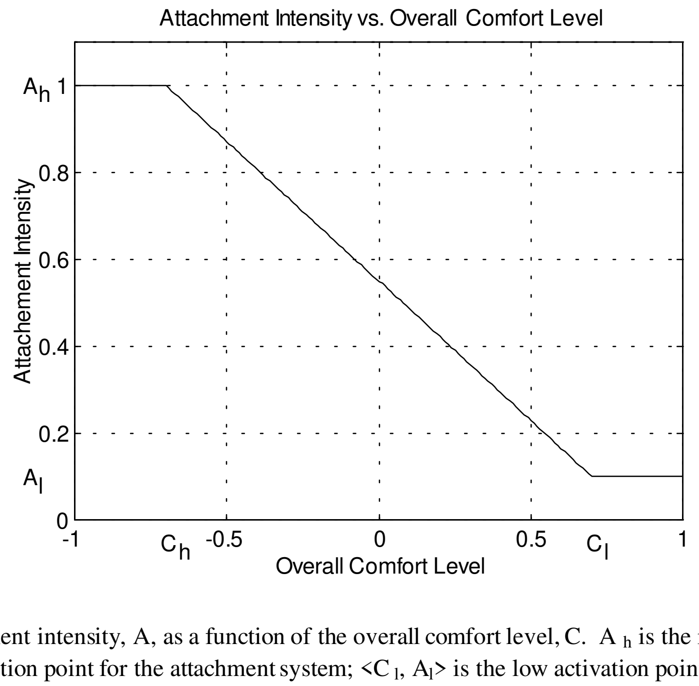

Figure 1. The attachment intensity, A, as a function of the overall comfort level, C. A_h is the maximum magnitude of the intensity; <C_h, A_h> is the strong activation point for the attachment system; <C_l, A_l> is the low activation point for the system.

Mathematically the relationship can be described as follows:

$$\varphi(C)=\begin{cases} A_l & \text{if } \; C > C_l \\ \dfrac{A_h - A_l}{C_h - C_l} * C - \dfrac{A_h - A_l}{C_h - C_l} * C_h + A_h & \text{if } \; C_h < C < C_l, \\ A_h & \text{if } \; C < C_h \end{cases} \qquad (3)$$

where C_l and C_h define low and high comfort activation level, respectively; and A_l and A_h are corresponding intensity levels for the low and high activation levels.

The last factor in the function is D, the proximity factor. It is a function of the distance d from the robot to the attachment object. The proposed function is similar to φ(C). When a robot is close enough to the object of attachment the proximity factor should be set to 0, in effect zeroing the attachment force since the robot is already nearby its object of attachment. This circle where the attachment force disappears can be called a *Safe Zone* since it constitutes a secure area where a robot receives that maximum level of comfort. As the robot moves away further from the safe zone the proximity factor grows, increasing the overall attachment force. At some distance the proximity factor reaches its maximum. The area between the safe zone and the distance where the proximity factor saturates can be called a *Comfort Zone*. This is the main zone where a robot operates and its behavior is influenced by the robot's comfort level along with the distance from the attachment object. Outside of the comfort zone the attachment force is quite large and should be one of the dominant forces in the robot's overall behavior forcing it to stay within its comfort zone. The idea is graphically displayed in the figure 2.

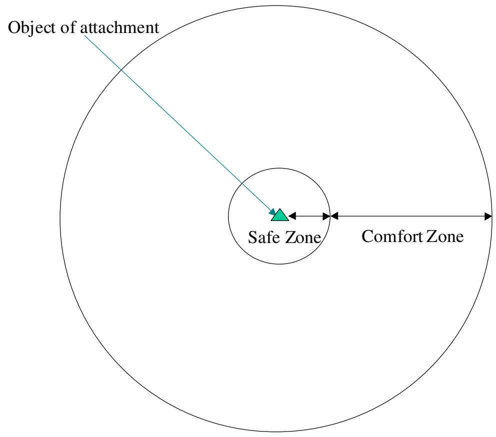

Figure 2. The safe and comfort zones of the robot around the object of attachment. These zones define the proximity factor in the attachment force function.

Mathematically the function is described below:

$$D=\begin{cases} 0, & \text{if } d < d_s \\ \dfrac{1}{d_z} * d - \dfrac{d_s}{d_z}, & \text{if } d_s < d < d_z + d_s \\ 1, & \text{if } d > d_s + d_z \end{cases} \qquad (4)$$

The distance of the robot and its object of attachment is represented by d. The parameter d_s is the radius of the safe zone. The parameter d_z is the size of the comfort zone as shown in the figure 2.

5. SIMULATIONS

The first part of the section goes briefly over the framework and how the comfort model was incorporated within it, whereas the second part shows the actual results of the simulations. The experiments on real robots are presented in the following section.

5.1. Integration within AuRA architecture

The framework chosen for the integration is the *MissionLab* system[21], which is a version of AuRA[22]. The overall architecture is a hybrid of a low-level reactive system with a high-level planning system. The lowest level, where this research was conducted, consists of sets of primitive behaviors (motor schemas[23]). At any point of time, a particular set (assemblage) of primitive behaviors is chosen to control the robot. Each individual primitive behavior is driven by its perceptual input (perceptual schema) producing its own motor response. The responses from each of the active schemas are added together resulting in an overall behavior output. Thus, each motor control schema produces a vector to drive the motor. The weighted sum of the vectors, after normalization, defines the final vector that is sent to the motor actuator. Thus, each motor schema affects the overall behavior of the robot and the degree of its effect is dependent on the environment the robot is in.

Within *MissionLab*, a finite state automata defines the high level plan of a robot's mission. Each state in the plan is a behavioral assemblage with the parameters of the behaviors set depending on the kind of a mission and environment the robot is expected to work in. The transitions between states are triggered by perceptual inputs called triggers.

Since the output of the comfort function is a behavior, specifically, the attachment behavior, the integration into *MissionLab* was very natural. The attachment behavior defines an additional schema in the overall behavioral assemblage, called the Attachment Schema. Figure 3 shows the simple behavioral assemblage for an exploration behavior that includes the attachment schema.

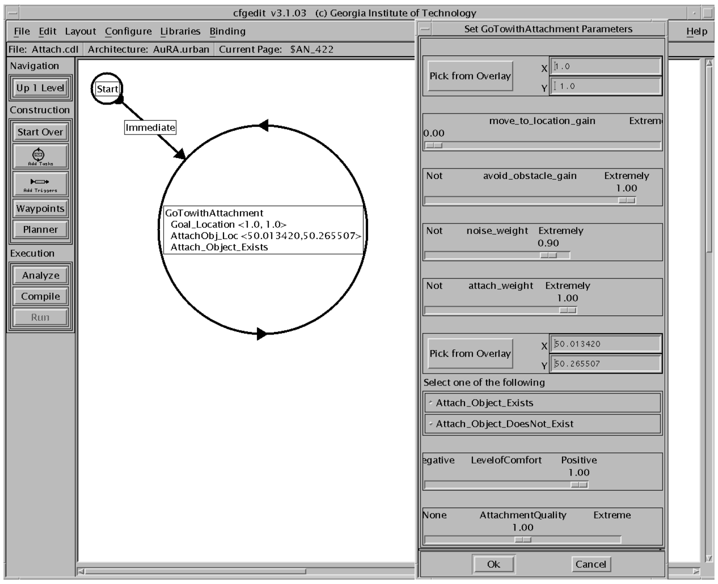

Figure 3. The exploration state with the parameter controlling the primitive behaviors that constitute the assemblage.

This assemblage consists of a number of primitive behaviors. These include the *move-to-goal* behavior with its weight set to 0 effectively disabling it; the *avoid-obstacle* behavior for a robust navigation in a cluttered environment; the w*ander* behavior which, essentially, defines the exploration process in a random manner; and the *attachment* behavior with its weight set to maximum, 1.0. The parameters controlling the attachment behavior are level of comfort (set to 1.0 for these studies), maximum comfort; attachment of quality (set to 1.0 corresponding to normal attachment quality); and whether the attachment object exists or does not. If the attachment object does not exist, then the attachment force is always zero.

5.2. Simulation results

Figure 4 shows runs of 3 minutes of exploration behavior. The attachment object is the home base located in the center of the circle representing the comfort zone of the robot. Figure 4a shows the run with the attachment behavior disabled (by setting the attachment object existence parameter to false). The robot's exploration is totally random and has no respect for the proximity to the home base. The robot goes on exploring without first exploring nearby regions. Figure 4b shows the exploration of the robot with the attachment behavior enabled. The comfort level in this case is set to 1.0, representing the state of most comfort for the robot. The robot explores the environment with confidence but concentrates mostly in its comfort zone. Figure 4c shows a run with attachment behavior enabled and comfort level set to 0.0, a neutral comfort level. In this case, the robot's security decreased and its exploration behavior is more biased toward the robot's object of attachment. The robot is less willing to explore farther areas and instead concentrates on areas close to the safe zone. The last figure, Figure 4d, shows a run with the attachment behavior enabled and comfort level set to –1.0, maximum discomfort. In this state, the robot's exploration is highly concentrated close to its safe area, the only area where the robot can feel secure and gain comfort.

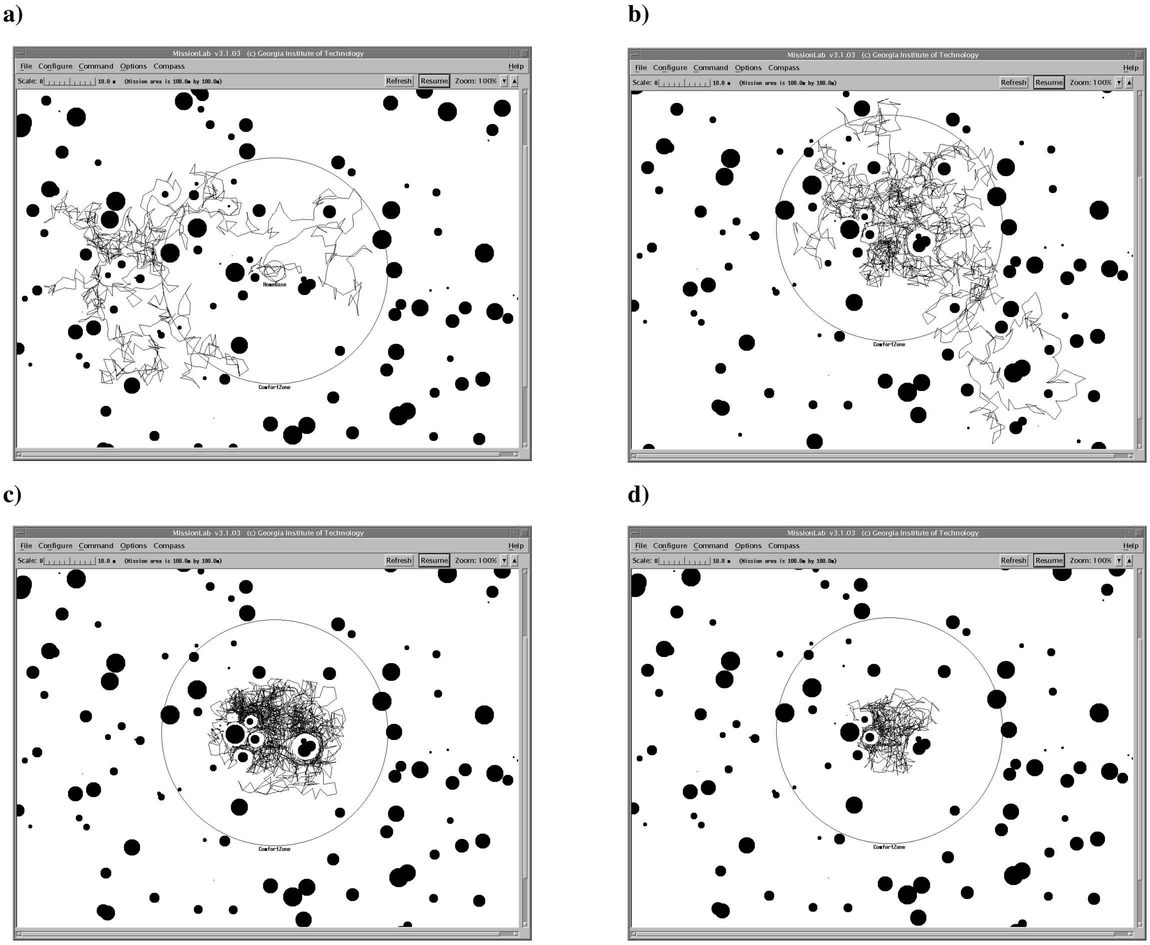

Figure 4. Examples of 3 minutes runs of exploration behavior. The object of attachment is the home base situated at the center of the circle. The circle defines the comfort zone. The figures are: a) no attachment behavior; b) attachment behavior with comfort level set 1.0 (maximum comfort); c) attachment behavior with comfort level set to 0.0 (neutral comfort); d) attachment behavior with comfort level set to -1.0 (maximum discomfort)

Figures 5-7 show statistical analysis of the simulations. Figure 5 shows how the average distance to the object of attachment changes as comfort level changes when the comfort zone is set at 20 meters. From the graph it can be seen that the average distance from the robot to its home base is beyond the comfort zone when the attachment behavior is disabled, whereas the average distance is within the comfort zone and increases as comfort level increases when the attachment behavior is enabled. Similarly, the figure 6 shows the variance of the distances from the robot to its object of attachment. The variance is much larger in the case of the behavior without the attachment schema showing that the exploration process is not concentrated within a circle around the object of attachment.

Figure 7 shows the distribution of explored area as a function of distance from the object of attachment. The graph shows that the percent of area explored close to the home base (the attachment object) of the robot without the attachment behavior is less than the percent of the explored area with attachment. On the other hand, for the distances beyond the comfort zone (20 meters) there is more explored area without the attachment behavior than with it. Also, as the comfort level decreases, the near area is explored more thoroughly, reducing the explored area farther away. This shows that as the robot starts the exploration of the new environment, its comfort level is low since the environment is unfamiliar. As a result, the exploration is concentrated nearby its home base where it can get quickly into safety. As the environment becomes more and more familiar, the comfort level increases and the robot starts exploring farther areas. Thus, the exploration process slowly grows depending on the perceived hostility of the environment rather than being purely random as it currently is when the attachment behavior is disabled.

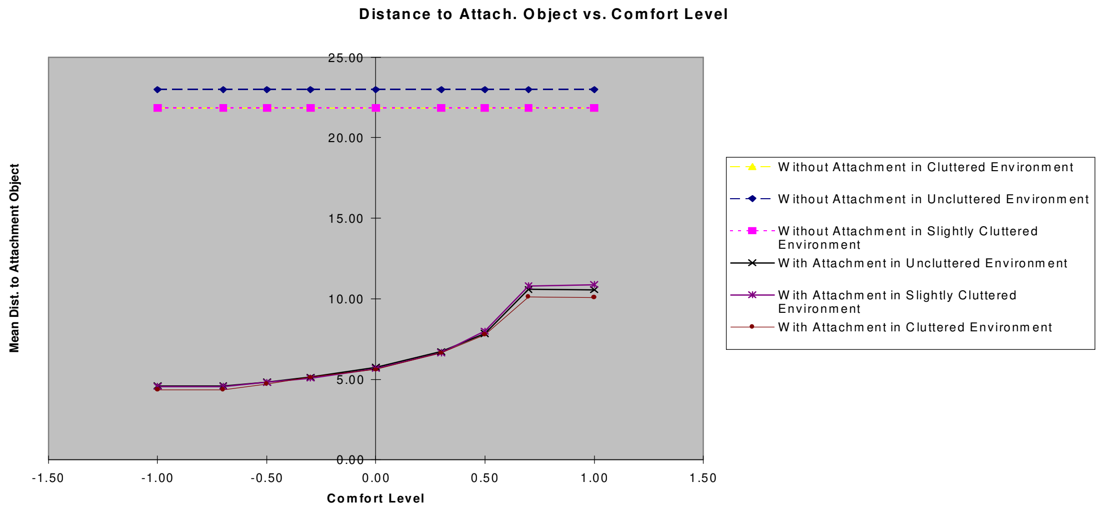

Figure 5. The average distance from the robot to its object of attachment without the attachment behavior (top horizontal lines) and with the attachment behavior enabled (bottom non-linear curves) in obstacle-free, slightly cluttered and significantly cluttered environments.

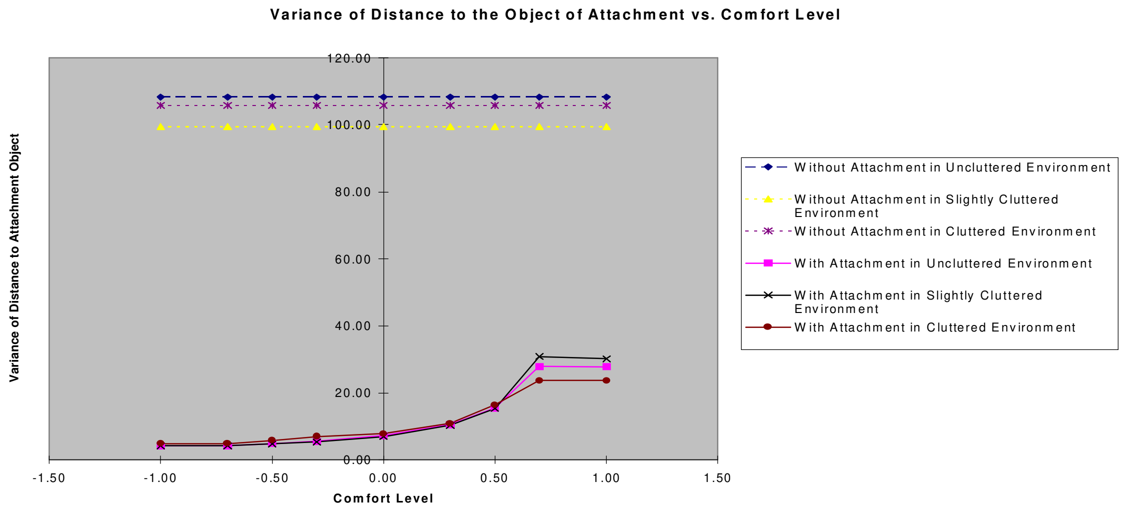

Figure 6. The variance of the distance from the robot to its object of attachment without the attachment behavior (top horizontal lines) and with the attachment behavior enabled (bottom non-linear curves) in obstacle-free, slightly cluttered and significantly cluttered environments.

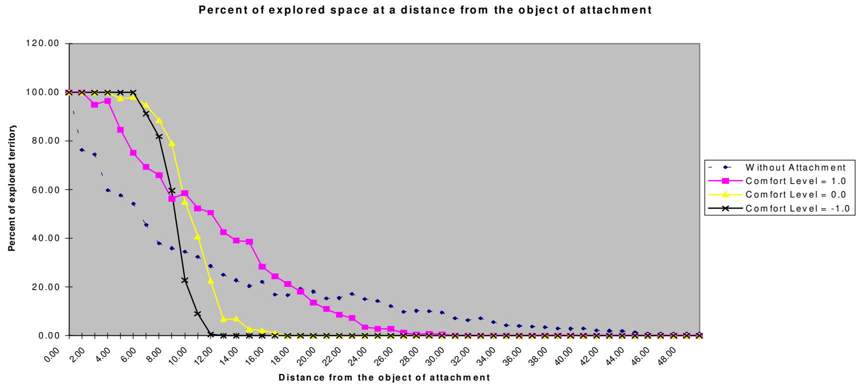

Figure 7. The percent of explored area at different distances from the object of attachment after 3 minutes of exploration behavior without attachment (the least steep curve) and with attachment for comfort level at 1.0, 0.0 and –1.0.

6. ROBOT RESULTS

The real robot experiments were conducted on a Nomad 150 series robot. The robot has 12 sonar sensors evenly placed around it. The information from these sensors was the only perceptual input driving the behavior of the robot. The *MissionLab* system described above provides a simulation environment as well as has a support for real robotic systems including the Nomad 150 robots. Thus, exactly, the same framework as for the simulations was used for the real robot experiments.

Figure 8. The environment for the real robot experiments. The image on the left shows the overall environment. The object of attachment is the tree in the white vase in the center of the picture. The photograph on the right is a close-up showing the robot and its object of attachment (the tree).

The environment for the real robot experiments is shown in Figure 8. The chairs were used to introduce additional obstacles in the environment. The tree in the white vase shown in the center of the picture represents the object of attachment for the robot. Each experiment consisted of a five minute run of an exploration behavior. Five minutes of actual robot time allow for a much smaller amount of exploration than in simulation since simulations are performed at a significantly faster speed. To help in comparing these results to the simulations given the limited time for each robot run, the comfort zone was decreased to 3 meters. When the comfort level was set to 1.0, during the exploration process the robot reached as far as the tables shown on the right of both photographs. When the comfort level was set to –1.0, the robot never even reached any of the chairs shown.

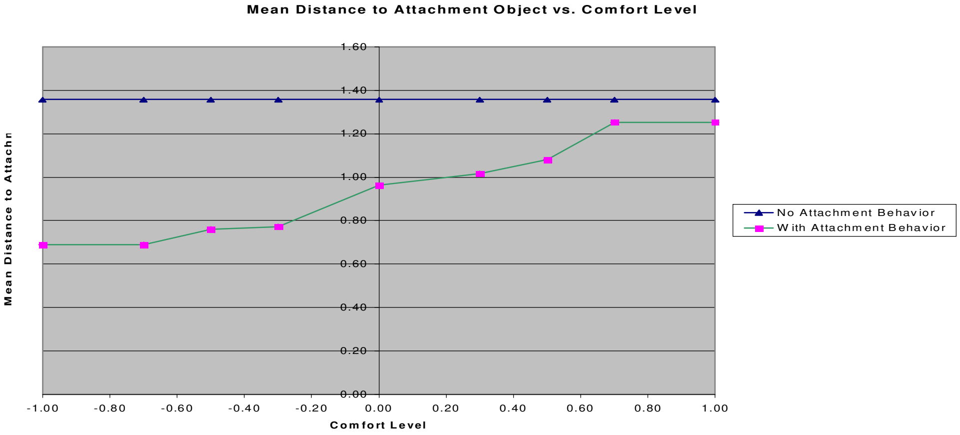

Figure 9. The average distance from the robot to its object of attachment without the attachment behavior (top horizontal line) and with the attachment behavior enabled (bottom non-linear curve) for real-robot experiments.

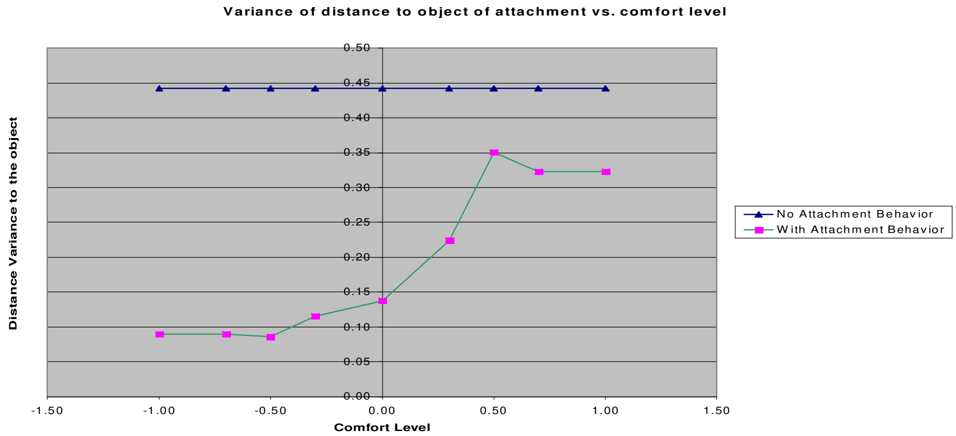

Figure 10. The variance of the distance from the robot to its object of attachment without the attachment behavior (top horizontal line) and with the attachment behavior enabled (bottom non-linear curve) for real-robot experiments.

The formal results of the experiments are represented in the figures 9 and 10. As for the simulations, the exploration behavior without an attachment schema is independent of the comfort level and, as a result, its mean distance to the object of attachment and variance of the distance are constant in the graphs. Whereas when the attachment schema is enabled, the mean distance and variance decrease as the comfort level decreases.

7. SUMMARY

This paper introduces the notion of comfort into the domain of robotics and shows the benefits of modeling the comfort function. These benefits include the ability of a comfort function to permit a robot to adjust its behavior in response to its internal needs and safety of the current environment it is in. It is also suggested that, the comfort function can be used in a more general sense - to bias the behavior of the robot into maximizing its level of comfort.

The proposed model of the comfort function is primarily based on existing research in psychology in related areas. Specifically, one of the main sources for the derivation of the model was the study of comfort in infants by Dunn[1]. In brief, the proposed model of comfort for robots includes the following concepts: the comfort level consists of the two components, exogenous and endogenous. The exogenous comfort component is a level of comfort that is dependent on external stimuli such as the familiarity with the current state and the past experiences in this or similar state. The endogenous comfort component is a level of comfort that is dependent on internal stimuli such as the level of available resources (e.g. energy), internal temperature, and the level of normal functioning of the robot. The two components define a single threshold called a comfort level. The behavior of the robot is to attempt to maximize the comfort level while pursuing the achievement of its designated goal. The paper presents and implements a simplified model that incorporates important phenomena that was studied extensively in psychology – attachment behavior. The attachment behavior has been shown to be crucial for the normal development of infants and adults, and therefore there are good reasons to believe it to be beneficial to the performance of robots as well. The paper introduces and connects two important notions into the field of robotics – the notion of comfort and the notion of objects of attachment. The results in both, simulation and real robot experiments, show their effect on the behavior of the robot, and in particular, how the exploration process is regulated by the comfort function.

Future work includes finalizing the mathematical relationship between the input features of the comfort function and the level of comfort itself. Also, the extension of the current attachment behavior to multiple objects of attachment might be very beneficial. The multiple objects of attachment would allow the robot to travel in its world through these objects of attachment creating overlapping comfort zones. Finally, additional analysis of the work in psychology can inspire additional ideas as to what other input features can influence the comfort level in a robot.

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REFERENCES

1. J. Dunn, *Distress and Comfort*, Harvard University Press, Cambridge, 1977.
2. D. O. Hebb, "On the Nature of Fear," *Psychological Review,* **53**, pp. 259-276, 1946.
3. L. A. Stroufe, E. Waters, and L. Matas, "Contextual Determinants of Infant Affective Response," *The Origins of Fear*, M. Lewis and L. A. Rosenblum, Wiley, New York, 1974.
4. J. Bowlby, *Attachment and Loss, I: Attachment*, Hogarth Press, London, 1969.
5. M. D. S. Ainsworth and S. M. Bell, "Attachment, Exploration and Separation: Illustrated by the Behaviour One-Year-Olds in a Strange Situations," *Child Development,* **41**, pp. 49-67, 1970.
6. M. D. S. Ainsworth and B. A. Wittig, "Attachment and Exploratory Behaviour of One-Year-Olds in a Strange Situation," *Determinants of Infant Behaviour IV*, B. M. Foss, Methuen, London, 1969.
7. C. Darwin, *The Expression of the Emotions in Man and Animals*, University of Chicago Press, Chicago, 1965.
8. R. Pfeifer, "The "Fungus Eater Approach" to Emotion: a View from Artificial Intelligence," *COGNITIVE STUDIES: Bulletin of the Japanese Cognitive Science Society,* **1(2)**, pp. 42-57, 1994.
9. D. Moffat, R. H. Phaf, and N. H. Frijda, "Analysis of a model of emotions," *Prospects for Artificial Intelligence*, A. Sloman, D. Hogg, G. Humphreys, A. Ramsay, and D. Partridge, IOS Press, Oxford, 1993.
10. C. E. Izard, "Organizational and Motivational Functions of Discrete Emotions," *Handbook of Emotions*, M. Lewis and J. M. Haviland, The Guilford Press, New York, 1993.
11. J. Bates, "The Role of Emotion in Believable Agents," *Communications of the ACM,* **37(7)**, pp. 122-125, 1994.
12. J. D. Velasquez and P. Maes, "Cathexis: A Computational Model of Emotions," *Proceedings of the First International Conference on Autonomous Agents*, pp. 518-519, 1997.
13. C. D. Elliot, The Affective Reasoner: A Process Model of Emotions in a Multiagent System, Ph.D. Thesis, Northwestern University, 1992.
14. G. Foliot, "An Algorithm Based on an Appraisal Theory to Control a Khepera Robot," *Emotional and Intelligent: Tangled Knot of Cognition*, pp. 82-83, 1998.
15. R. L. Solomon, "The Opponent-Process Theory of Acquired Motivation," *American Psychologist,* **35(8)**, pp. 691-712, 1980.
16. T. Bastick, *Intuition How We Think and Act*, John Wiley & Sons, New York, 1982.
17. V. L. Colin, *Human Attachment*, McGraw-Hill, New York, 1996.
18. J. Feeney and P. Noller, *Adult Attachment*, SAGE Publications, London, 1996.

19. R. Arkin, “Homeostatic Control for a Mobile Robot: Dynamic Replanning in Hazardous Environments,” *Journal of Robotic Systems,* **9(2)**, pp. 197-214, 1992.
20. D. Mackenzie, R. Arkin, and J. Cameron, "Multiagent Mission Specification and Execution," *Autonomous Robots*, **4(1)**, pp. 29-57, 1997.
21. R. Arkin and T. Balch, "AuRA: Principles and Practice in Review," *Journal of Experimental and Theoretical Artificial Intelligence*, **9(2)**, pp. 175-189, 1997.
22. R. Arkin, "Motor-Schema based Mobile Robot Navigation," *International Journal of Robotics Research*, **8(4)**, pp. 92-112, 1989.