A Biologically-Inspired Wolf Pack Multiple Robot Hunting Model

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Abstract - **A great amount of work has been made in biologically-inspired robotic systems on single and multiple animal behavior models. These studies have advanced the understandings of animal behavior and have provided at the same time inspiration in the design of single and multiple robotic architectures. Additionally, applications in the real word domain have benefited from such work, like exploration, surveillance, etc. In this work we present a multi-robot architecture based on wolf packs studies showing different formations during prey hunting and predator avoidance. The model has been developed and tested using the NSL/ASL, MIRO systems, and Sony AIBO robots. Results from real robot experimentation are discussed.**

Index Terms - **Autonomous Robots, Wolf Packs, Hunting Model.**

I. INTRODUCTION

Many living organisms have served as inspiration to robotic systems. Animals such as frogs [1], praying mantis [2], and rats [3] have helped inspired an extensive number of robotics architectures [4][5][6]. These studies and corresponding robotic architectures vary in the level of detail being studied, from very high level behavioral descriptions all the way to very detailed neural circuitry that can explain mechanisms involved in adaptation and learning.

Behaviors are not limited to single animals but also groups of them, such as ants, fish, and bees, in trying to understand *swarm* behaviors such as flock, disperse, aggregate, forage and follow trails [7]. Swarming and social behaviors in general have enabled such animals to minimize encounters with predators by organizing as large groups, such as bird flocks and fish schools. In these cases group behavior emerges from the desire to stay close together and at the same time, keep a certain distance with others members of the group. From these studies a number of distributed multi-robot architectures have been proposed [8][9][10].

In this paper we present a multi-robot architecture inspired on a wolf pack hunting behavior model. In a previous paper, Vallesa and Weitzenfeld [11] presented simulation only results from different wolf pack formations. These agent-based experiments evaluated position errors obtained while trying to maintain a formation in the presence of multiple preys and obstacles. There is related work in this area such as the work in multi agent formations by Balch and Arkin [12]. The current paper goes beyond this work by evaluating wolf pack behaviors in an embodied multiple robotic architecture.

The paper is organized as follows: Section II describes the wolf pack hunting model; Section III describes the robotic architecture used for developing and experimenting with the model; Section IV describes experiments and results obtained; and Section V provides conclusions.

II. WOLF PACK HUNTING MODEL

The model presented in this paper is based on a wolf pack hunting behavior [13]. The model considers a team of wolf predators, i.e. a wolf pack as the one shown in Figure 1, comprising an *alpha* wolf and several *beta* wolves. Studies have shown that wolves hunt in packs of about 5 to 20 members and keep a certain hierarchy while eating a captured prey with the stronger *alpha* wolf eating first. This organization permits the wolves to hunt animals that are even larger than their own size.

Fig. 1. Pack of wolves. Wolves hunt in small numbers, 5 to 20. A few such wolves are shown in the picture.

The wolf pack hunting model described in this work includes the following important assumptions:

a) Wolf teams are conformed by a group leader (*alpha* wolf) and at least one follower (*beta* wolf).
b) *Beta* wolves group around the *alpha* wolf keeping a certain distance from the leader and among themselves.
c) Wolves in the model receive only visual information from the environment, using this input to calculate their positions and distances. Any other type of communication between wolves is not allowed.
d) Visual fields are limited to a single camera recognizing objects by their colors. If alpha wolf is outside beta wolf visual field, then beta wolves loses track of leader.
e) Head direction is kept constant relative to body motions.
f) Walking speeds are kept constant for all wolves at all times.

In the following sections we describe the formation, hunting and avoidance model in more detail.

A. Formation Computation

Formations consist of one or more beta wolves following an alpha wolf. Beta wolves keep a radial distance r around the alpha wolf effectively forming a circumference centered at the alpha wolf as shown in Figure 2. Movement direction d is shown for all wolves. Lines in blue represent beta wolf visual field with angular size 2α. Beta wolves follow alpha wolf movement directions. If θ represents the angle between beta wolf moving direction and visual sight of alpha wolf; then when $\alpha < \theta$, beta wolf loses track of alpha wolf.
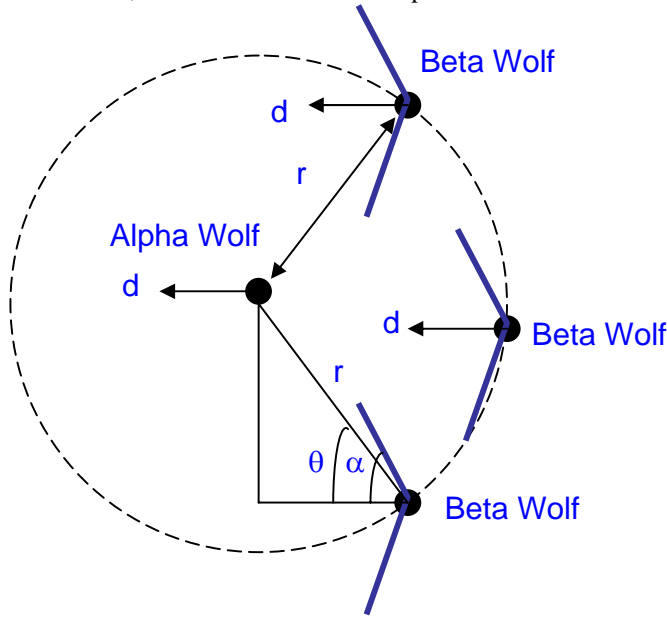

Fig. 2. Beta wolf pack formation. Wolves keep around a circumference centered at the alpha wolf and follow it by visually tracking their leader.

B. Hunt Behavior

In this section we describe the hunt behavior for both alpha and beta wolves.

Alpha Wolf. The *alpha* wolf behavior is determined by three states: *Wander*, *Stalk*, *Attack* and *Eat*, as shown in Figure 3:

- Wander. In this state the alpha wolf explores the environment looking for a prey to eat. When it detects one, the *prey_visible* condition is activated indicating a change to the *Stalk* state.
- Stalk. In this state two transitions can happen: one towards the *Wander* state in case the prey is outside its range of vision caused by the *prey_not_visible* condition; the other one occurs when the prey is detected close, activated by the *prey_near* condition continuing to the *Attack* state.
- Attack. In this state the wolf closes on the prey until catching it. When this happens the *prey_catch* condition is activated and the wolf changes to the *Eat* state. If the wolf suddenly loses control of the prey it goes back to the *Stalk* state activated by the *prey_not_catch* condition.
- Eat. In this state the wolf eats the prey. After that, the condition of *prey_not_visible* is activated indicating that the prey has been eaten. The wolf goes back to the *Wander* state.
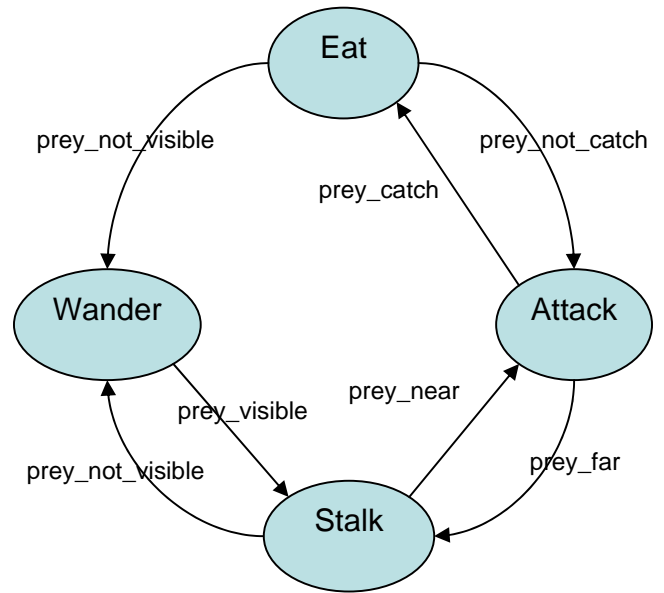

Fig. 3. Alpha wolf hunting behavior. Consists of four states: Wander, Stalk, Attack and Eat. Each state is activated by the corresponding conditions.

Beta Wolves. The *beta* wolf behaviour is described by five states, *Wander*, *Formation*, *Stalk*, *Attack* and *Eat*, as shown in Figure 4:

- Wander. The beta wolf searches the environment looking for the group leader or prey. If the wolf finds the leader, *leader_visible* is activated continuing to the *Formation* state. If the wolf finds the prey, *prey_visible* is activated continuing to the *Stalk* state. The wolf movement is similar to the alpha wolf in this state.
- Formation. As long as the beta wolf continues seeing the alpha wolf, it stays close to the leader. If visible contact is lost with the leader then the condition *leader_not_visible* is activated continuing to the *Wander* state. If the beta wolf detects a prey it moves to the *Stalk* state since the condition *prey_visible* is activated.
- Stalk. In this state three transitions can happen: one towards the *Formation* state in case the prey is outside its range of vision activated by the *prey_not_visible* condition; another one occurs when it detects the prey near, this activating the *prey_near* condition, continuing to the *Attack* state; and, in case the beta wolf loses track of the alpha wolf, it executes the *leader_not_visible* condition is activated, continuing to the *Wander* state. The objective of this state is to approach the prey without separating much from the group leader.
- Attack. The beta wolf considers itself sufficiently close to the prey although still taking into consideration the relative position to the leader. Yet, in this state the move to approach and catch the prey has greater priority than follow the group leader. Nevertheless, because the prey is in many cases faster the prey could escape. If this happens the *prey_far* condition is activated and the beta wolf returns to the *Stalk* state. If the wolves manage to catch the prey, the condition *catch_prey* is activated continuing to the *Eat* state.

- <u>Eat</u>. This state is similar to the alpha wolf although alpha wolves eat first.
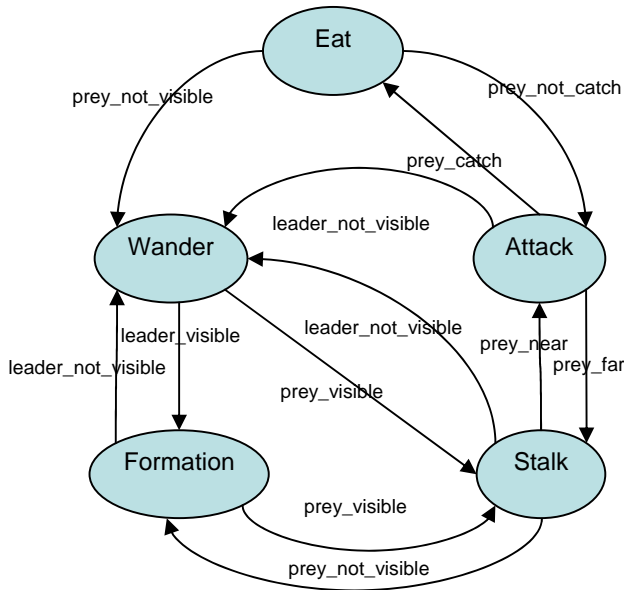

Fig. 4. Beta wolf hunting behavior. Consists of five states: Wander, Formation, Stalk, Attack and Eat. Each state is activated by the corresponding conditions.

C. Avoid Behavior

Although wolves are by nature predators, they can also be predated upon, e.g., by humans and other wolves. In Figure 5 we show a state diagram consisting of the previously described *hunt* behavior and a new *avoid* behavior that applies both to beta wolves as well as alpha wolves.

- <u>Hunt</u>. This behavior encompasses all behaviors previously described in Figure 3 and 4 for alpha and beta wolves, respectively.
- <u>Avoid</u>. At any time during hunting, the appearance of a predator will make the alpha and beta wolves run away in direction opposite to the predator.
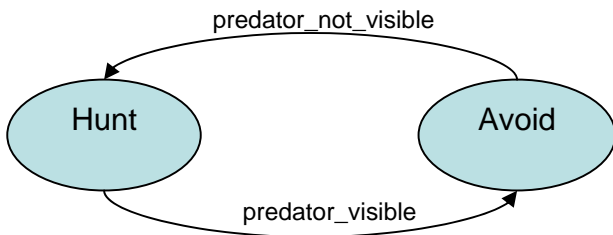

Fig. 5. Alpha and beta wolves avoid behavior. *Avoid* is activated by a *predator_visible* condition while in the Hunt state, and the other way with a *predator_not_visible* condition.

III. ROBOTIC ARCHITECTURE

Before testing the wolf pack model on real robots we designed and simulated it first in a computer. The initial simulation results were presented in Vallesa and Weitzenfeld [11]. Since then we have extended the model and tested them both in simulation and real robot experimentation. In this section we describe the extended model architecture and the robotic implementation where we are carrying out the experiments.

A. Model Architecture

We have developed the wolf pack model using a *schema* multi-level computational model representing units of brain processing [14]. The schema computational model enables mappings from higher level behavior to underlying neural structures in the brain representing perceptual, sensorimotor and motor areas. Higher-level schema representations and be decomposed and refined in a recursive fashion in such a way that complex behaviors can be described in terms of simpler ones [15]. We have previously used the schema computational model to describe prey acquisition and predator avoidance behaviors in frogs and toads [16], praying mantis *Chantlitaxia* ("search for a proper habitat") [2], rat explorations [3], among others.

The individual wolf model used for this work is based on a general prey acquisition and predator avoidance model inspired in our previous work in frogs and toads [17]. The corresponding schema model is shown in Figure 6. This single level schema model is divided in sensor schemas, at the left, actions or motors schemas at the right, and *sensorimotor* schemas coordinating among them, in the middle. The model represents sensorimotor integration in visually guided animals responsible for discriminating among preys and predators in prey acquisition and predator avoidance behaviors.
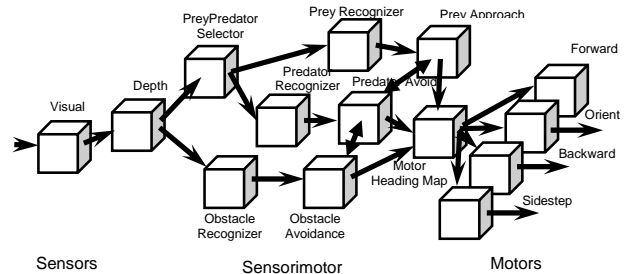

Fig. 6. Schema model corresponding to prey acquisition and predator avoidance behavior described in terms of sensors, motors, and sensorimotor schemas.

The wolf hunting model extends the original prey acquisition and predator avoidance model with additional behaviors such as animal formation. Note that *Prey Approach* schema in Figure 6 corresponds to the *Hunt* behavior previously described in Figures 3 and 4. The main sensor in the model is a camera represented by the *Visual* schema. *Depth* schema calculates distances to objects of interest from images obtained from the camera. Since we use a single camera for most of our models, depth computation is based primarily on the number of pixels of certain color segmented by the visual field. Processing continues with the *PreyPredator Selector* choosing among multiple preys or predators present. In the original frog model, obstacles corresponded to static objects while preys and predators had to move to be recognized as such. In the current model preys and predators are distinguished only by their color. Depending

on whether a prey or predator is selected, the corresponding *Prey Recognizer* or *Predator Recognizer* is activated, while static objects are identified by *Obstacle Recognizer*. If prey or predator is recognized, *Prey Approach* (*Hunt*) and *Predator Avoidance* (or *Obstacle Avoidance*) will be activated, respectively. Note that at any given time only one of these three schemas will be instantiated depending on the priorities given to the different stimuli. The *Motor Heading Map* schema is responsible for summing actions, i.e. motor actions, from the previous three schemas. Finally, depending on the output of the motor heading map, four motor actions will be activated, *Forward*, *Orient*, *Backward* and *Sidestep*. Note that actions can be combined, e.g. move diagonally equivalent to concurrent orient and move forward motions.

B. Robotic Implementation

The original wolf pack model was developed by Vallesa and Weitzenfeld [11] using the JavaBots simulator [18]. The current model described in this paper has been completely redesigned and implemented using the NSL/ASL [19] schema language and modeling environment. Robot implementation was done using the MIRO [20] system as shown in Figure 7. MIRO performs preliminary visual processing such as image segmentation from either a simulated or real camera, and also performs motor action generating simulation or real robot commands. Actual model processing is done by NSL/ASL in a remote computer.

The MIRO system supports connections to multiple robots each one connected to its own NSL/ASL instance in the remote computational system. Thus, processing is distributed between the robot and the remote computational system with wireless communication between the two systems. This *embedded* approach permits expensive computations to be done on the computer without having to port the model to the robot platform. For this particular work we have used the Sony AIBO ERS-210 four-legged robots having a local camera. The drawbacks are communication delays between robot and computer. Although such architecture would make it possible in principle to share robot "intelligence" among multiple robots, we keep fully autonomous robot processing.
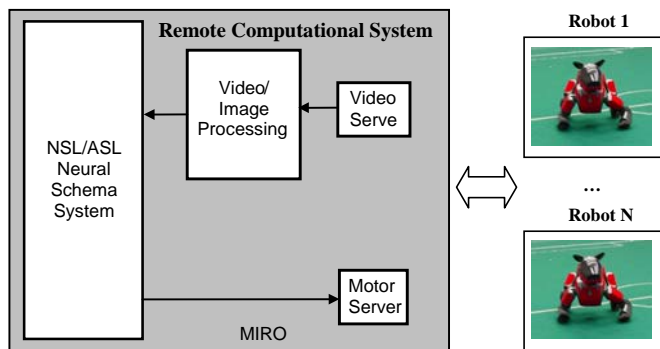

Fig. 7. MIRO embedded robotic architecture consisting of multiple autonomous robots linked to their own instance of the remote computational system. The remote computation system includes the NSL/ASL schema system, the video/image processing unit and the sensorimotor (video and motor) servers. Robot and remote system have wireless communication.

In Figure 8 we show a sample cycle of computation of the NSL/ASL/MIRO robotics architecture. The camera in the robot captures video and sends it to the remote computer for video processing by MIRO. Afterwards model processing is carried out in the computer by NSL/ASL using as input the processed images. NSL/ASL generates model output in the form of action control commands, i.e. robot walking, and robot and camera headings. These commands are sent by MIRO to the AIBO robots via wireless communication for execution. This cycle repeats itself indefinitely or until behaviors are completed.
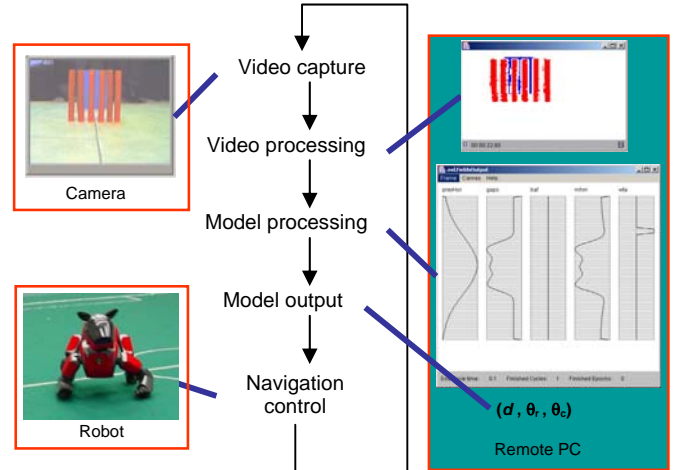

Fig. 8. NSL/ASL/MIRO computation cycle. Video is captured by the robot camera and sent to the remote computational system for processing. After the model is processed, model output is sent back to the robot for navigation control. These cycles continue indefinitely until the task is completed.

IV. EXPERIMENTS AND RESULTS

Simulation results for the original wolf pack model were presented by Vallesa and Weitzenfeld [11]. In the previous paper we evaluated different formations in a virtual world with varying number of preys and predators. In this paper we present more extensive behavioral experimentation of formations, prey acquisition and predator avoidance using a real robotic system composed of three robots.

Several robotic experiments were carried out using different scenarios to observe the behavior of multiple wolves and the state of their formation during prey hunting and predator avoidance. We evaluated model aspects such as if beta wolves were able to maintain formation even if leader of the group makes abrupt turns and if path followed by beta wolves would not interfere with the movement of the other wolves.

During experiments we used three robots as wolf pack. Prey was a blue cylinder, initially static and then manually moved. We added a green cylinder as an external predator to the wolves. All wolves moved at the same speed to facilitate pack formation. Alpha wolf and beta wolves were identified by different colors. Alpha wolf had to be in visual field of beta wolves at all times otherwise risking losing track of their leader and separating from the group. There were no obstacles in the field.

The following behaviors were tested: (a) alpha wolf stalk, (b) beta wolf formation and stalk, (c) alpha and beta wolves attack, (d) alpha wolf avoid, and (e) beta wolf avoid. Videos from all experiments can be downloaded from [21].

A. Alpha Wolf: Stalk

Our first experiment involves an alpha wolf stalk behavior. Referring back to Figure 3, when prey becomes visible, the alpha wolf switches from a *wander* to a *stalk* state until it is close enough to *attack* its prey and *eat* it. The experiment setup is shown in Figure 9 where an alpha wolf robot in red is in front of a blue colored cylinder corresponding to prey. Due to the absence of obstacles and the static nature of the prey, the robot directly moves towards the prey (stops before eating it).

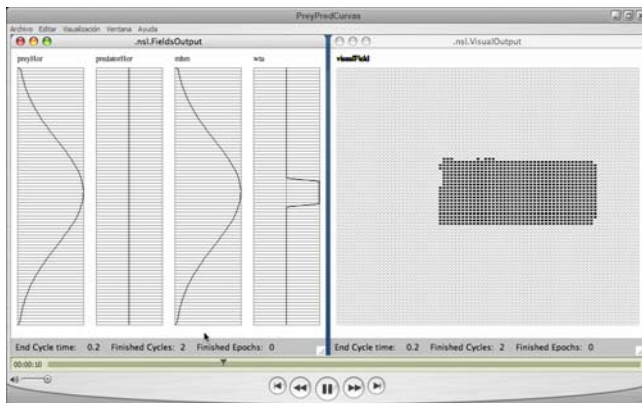Fig. 9. Alpha wolf in red in front of blue colored prey.

Fig. 10. Left: Prey, predator, motor heading map (*mhm*) and winner take all (*wta*) fields. Right: Alpha wolf segmented view of prey.

The alpha wolf recognizes the prey by its blue color producing a Gaussian where the prey is viewed as shown in Figure 10. The right hand side of the display shows the segmented prey, whereas the left hand side of the display shows four graphs containing two Gaussians and a resulting step function activation. The two Gaussians correspond to prey recognition and motor heading map activity (*mhm*), respectively, while the step function corresponds to a winner take all (*wta*) robot orientation field. The prey recognition field gets activated by the presence of the blue object in the

wolf visual field, while no predator activity arises due to the absence of a predator. Correspondingly, the *mhm* field receives input from the prey activation field and generates a *wta* maximum activity in the center of the Gaussian in correspondence with the prey location. Such a graph is computed every model processing iteration making it possible for the robot to always center on the prey after each step.

B. Beta Wolf: Formation and Stalk

Beta wolf behaviors have additional states from that of the alpha wolf. In addition to the basic alpha states, the beta wolf includes a formation state in response to the presence of the alpha wolf, as previously shown in Figure 4. While the alpha wolf only considers the presence of a prey (or predator), the beta wolf also responds to the presence of its leader, the alpha wolf. When neither leader nor prey is visible, the alpha wolf executes a *wander* behavior. When a prey becomes visible, the *stalk* state is triggered making the wolf close on the prey. Once the prey is close the beta wolf moves to the *attack* state. Finally, the alpha wolf proceeds to *eat*. In the *formation* state the pack moves as a group in search for the prey, while in the *stalk* state the beta wolf has both the leader and prey in sight. In the display shown in Figure 11, two beta wolves maintain a formation behind the alpha robot during *stalk* state. The alpha wolf is distinguished by its red uniform with the beta wolves in blue. They prey is a blue colored cylinder. Note that in the current experiments the beta wolves keep the same relative positions in both the *formation* and *stalk* states. Only when close enough to the prey they proceed to *attack* breaking up the formation.

Fig. 11. Alpha wolf in red, beta wolves in dark blue, all in front of the blue colored prey cylinder. Beta wolves maintain a formation behind their leader.

While the previous experiment was carried out with a static prey, in Figure 12 we show formation experiments after continuously moving the prey. In this particular experiment, one of the beta wolves lagged behind but eventually caught up with the other beta wolf and the leader. In some other experiments the robot would entirely miss the pack and end up wandering around.
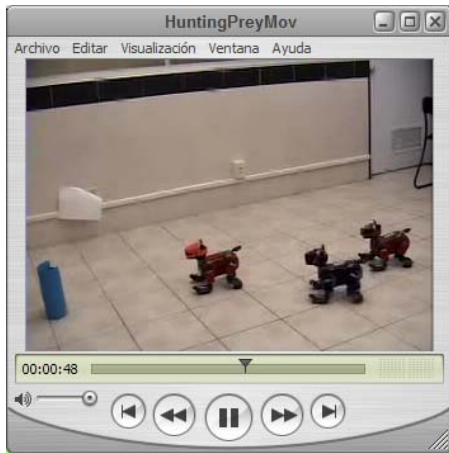
Fig. 12. Alpha wolf in red, beta wolves in dark blue, all in front of the blue colored prey cylinder. Prey is manually moved with pack tracking it. Beta wolves maintain a formation behind their leader.
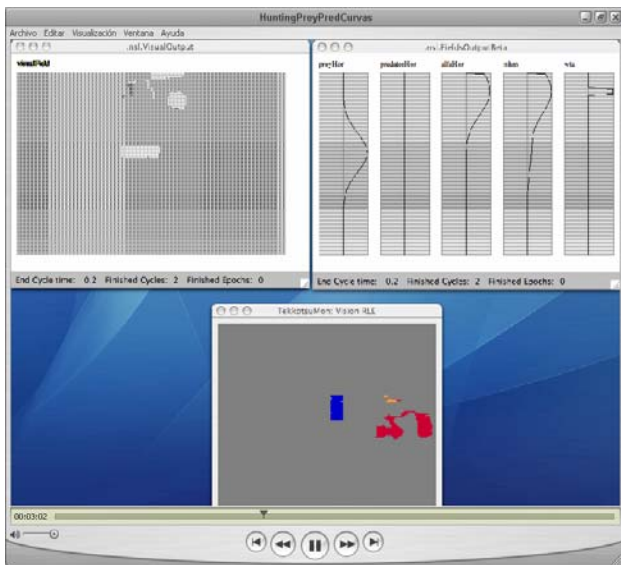

Fig. 13. Hunting model with prey in blue and alpha wolf in red. Upper graphs show segmented objects in gray (left) and recognition graphs (right). Upper graphs are rotated 90 degrees anticlockwise from lower graph.

The beta wolf recognizes the prey by its blue color and the alpha wolf by its red uniform. The model produces Gaussians in the graphs where preys are recognized, as shown in Figure 13. Note that the top graphs are rotated 90 deg anticlockwise from the bottom colored image. The top left display shows the segmented prey and alpha wolves in light gray, whereas the top right shows five graphs containing three Gaussians and a resulting step activation. The left three Gaussians correspond to the individual prey and alpha recognition maps with the resulting movement orientation shown in the motor heading map (*mhm*). Note that alpha recognition is stronger at this point than prey and thus the *mhm* graph receives stronger input from *alphaHor* than *preyHor*. The step activation graph corresponds to a winner take all (*wta*) robot orientation field. No predator activity arises due to the absence of a predator. Correspondingly, the *mhm* field receives input predominantly from the alpha activation field and generates a *wta* maximum activity in the center of the Gaussian in correspondence with the alpha wolf location. Thus the beta wolf will follow the

alpha wolf and not the prey. Note that by modifying weights in the model it would be easy to have the beta wolf change its behavior and follow the prey instead. In nature these kinds of situations occur due to varying drives, such as hunger, fatigue, etc.

C. Alpha and Beta Wolf: Attack

Once prey is near, alpha and beta wolves proceed to attack the prey. Beta wolves break formation in response to the presence of the prey as previously described in Figure 4. Both the alpha and beta wolves switch state due to the close presence of the prey. In Figure 14, the two beta wolves surround the prey with the alpha robot in front. Again, the alpha wolf is distinguished by its red uniform with the beta wolves wearing blue. They prey is a blue colored cylinder.

Fig. 14. Hunting model with one prey, an alpha wolf and two beta wolves. Beta wolves move ahead of the pack to attack prey.

D. Alpha Wolf: Avoid

Although wolves are natural predators, we tested the model in the presence of outside predators, such as humans or other wolves, as previously described in Figure 5. In this experiment, the outside predator is in green (seen as a second cylinder in front of the prey) with the prey in blue and wolf in red as shown in Figure 15. Once the prey predator is in sight, the alpha wolf turns around in a direction opposite to the predator location even if a prey is present.

The alpha wolf recognizes both the prey and the predator by their blue and green color, respectively. These recognitions produce separate Gaussians where the prey and the predator are viewed as two dimensional objects as shown in Figure 16. The right hand side of the display shows the segmented prey (lighter gray) and predator (darker gray), whereas the left hand side of the display shows four graphs containing solid Gaussians corresponding to prey (*preyHor*), a second curve (combination of Gaussians) corresponding to predator (*predatorHor*), a motor heading map activity (*mhm*), and a step activation function corresponding to a winner take all (*wta*) robot orientation field. The prey recognition field gets activated by the presence of the blue object in the wolf visual field, while the predator activity gets activated from the green cylinder. Due to stronger weight given to the presence of

predator, the *mhm* field receives input predominantly from the predator activation field and generates a *wta* maximum activity in the center of the Gaussian in correspondence with the predator location. The robot will avoid the predator in a direction opposite to that shown in the graph, i.e. a 180 degrees rotation.

Fig. 15. Alpha wolf in red with additional green colored predator in front of blue colored prey. Both prey and predator are shown as cylinders. Wolf gets away from outside predator.
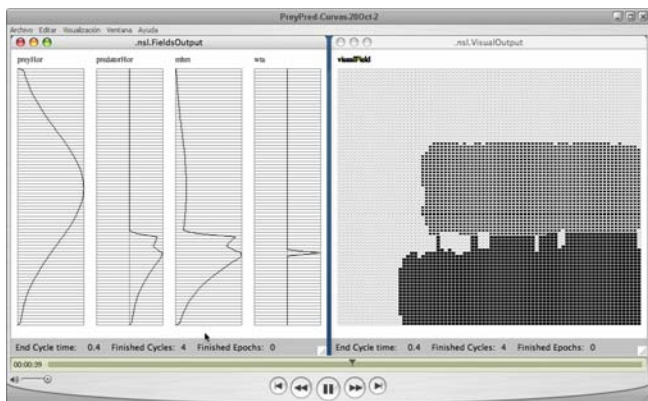

Fig. 16. Left: Prey, predator, motor heading map (*mhm*) and winner take all (*wta*) fields. Right: Alpha wolf segmented view of prey (light rectangle) and predator (dark rectangle).

E. Beta Wolf: Avoid

Similarly to the alpha wolf avoidance of a predator, the beta wolves break away from the pack and start retreating as well, as previously described in Figure 5. In this experiment, the outside predator is in green (seen as a second cylinder in front of the prey) with the prey in blue and wolf in red as shown in Figure 17. Once the prey predator is in sight, the beta wolves turn around in a direction opposite to the predator location analogous to the alpha wolf. This occurs even if a prey is present and without regards to the alpha wolf location.

Fig. 17. Alpha wolf in red with additional green colored predator in front of blue colored prey. Both prey and predator are shown as cylinders. All wolves are running away from predator.
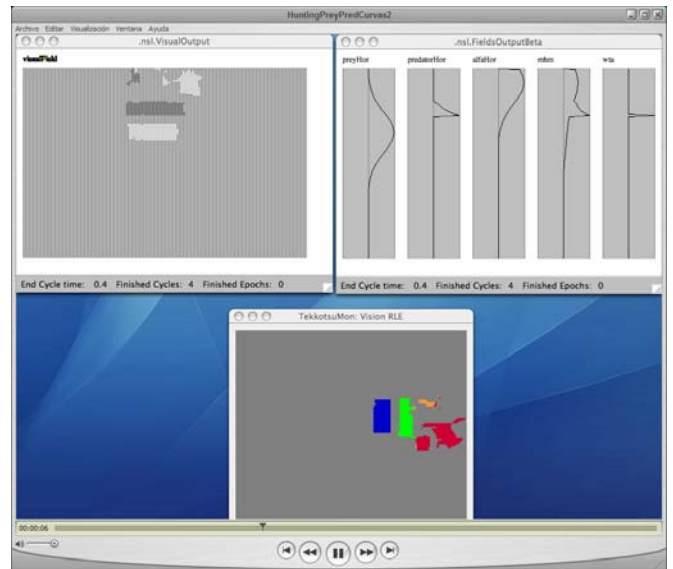

Fig. 18. Hunting model with prey in blue, outside predator in green, and alpha wolf in red Upper graphs show segmented objects in gray (left) and recognition graphs (right). Upper graphs are rotated 90 degrees anticlockwise from lower graph.

The beta wolf recognizes the prey by its blue color, the predator by its green color and the alpha wolf by its red uniform. The model produces Gaussians graphs representing object recognition as shown in Figure 18. Note again that the top graphs are rotated 90 deg anticlockwise from the bottom colored image. The top left hand side of the display shows the segmented prey with alpha wolves in light gray and predator in darker gray. The top right hand side of the display shows five graphs containing four Gaussians and a resulting step activation. The left four Gaussians correspond to the individual prey, predator and alpha recognition maps with the summed result appearing in the motor heading map activity (*mhm*). Note that predator recognition is stronger at this point than either alpha or prey and thus the *mhm* graph receives stronger input from *predatorHor* than *alphaHor* or *preyHor*. Correspondingly, the *mhm* field receives input predominantly from the predator activation field and generates a winner take all (*wta*) maximum activity in the center of the Gaussian in

correspondence with the predator location. The beta wolf will orient 180 degrees opposite the predator location. Again, note that by modifying weights in the model it would be easy to have the beta wolf change its behavior and follow either the alpha wolf or the prey. In nature these kinds of situations occur due to various drives, such as hunger, fatigue, etc.

V. CONCLUSIONS

The goal of this work is to develop a model inspired in real animals to investigate the concepts of team formation and cooperative tasks in robotic system. We extended the original agent-based model running only as simulation into a real robotic environment. We used the NSL/ASL and MIRO systems connected via wireless communication to three Sony AIBO robots. We performed various experiments to evaluate single and multiple robots behaviors including prey hunting and predator avoidance. Corresponding videos are included in the reference section.

In general, there are many factors that affect behavior results. These include aspects such as the existence of more than one prey, prey and predator mobility, wolf speed variations, unpredictable turns made by the alpha wolf, presence of obstacles, distances between wolves while in the pack, limited visual field affecting prey detection, among others. We have only experimented with few of these factors.

The model itself is limited in several aspects since wolf behavior can become quite complex. Here, wolves use only vision while in real life they also use sound and smell. The fact that the wolf only uses sight affects its hunting skills, for example, when it breaks away from the pack, limited visual field in the robot will not always enable the wolf to get back to the pack. Other aspects that will make behaviors more realistic are the inclusion of additional robots during experimentation, and the addition of motivational variables like fatigue and hunger.

Finally, we are planning to extend the previous experiments by adding additional robots, and by increasing the number of preys and predators while making them mobile using additional robots to further test pack formation and related behaviors.

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