

Lek Behavior as a Model for Multi-Robot Systems

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Abstract— Lek behavior is a biological mechanism used by male birds to attract mates by forming a group. This project explores the use of a biological behavior found in many species of birds to form leks to guide the creation of groups of robots. The lek behavior provides a sound basis for multi-robot formation because it demonstrates a group of individual entities forming up around a scarce resource. This behavior can be useful to robots in many situations, with an example scenario the case in which robots were dropped via parachute into an area and then needed to form meaningful task-oriented groups.

I. INTRODUCTION

As part of a project for the Office of Naval Research, we are studying biological models of behavior as a basis for creating heterogeneous unmanned networked robots teams¹. Our research group is currently looking at models of deception, canid pack behavior, and political coalition formation as inspirations for such robotic systems. In addition, we have been working with an ornithologist at the University of Pennsylvania, Dr. David White, to assist us in applying a model of bird behavior found in nature, lekking (Fig. 1), as a basis for useful robot team activity.

Lekking is a group behavior that introduces some interesting possibilities for use in robot formations. It is based on proximity to other participants, traffic patterns, stability, and two different “classes” of participants. The addition of this heterogeneity in participants allows for multiple independent leks to be formed and used in different ways. Biologists have created models to explain this activity in nature. One such model, the “hot spot” hypothesis, allows these leks to be positioned based on the availability of resources and the possibility of detection, which can be mission-dependent. For example, stealth may be favored in certain circumstances (e.g., reconnaissance) as opposed to observability in others (e.g., search and rescue).

The computational implementation of this behavior is based on a parameterizable repulsion zone, an attraction zone, and a buffer between the two. The scale of these areas can be easily changed based on the mission-specific area that the leks are required to cover and the abilities of the specific sensors available to the platforms.

This work was supported in part by Office of Naval Research under MURI Grant # N00014-08-1-0696.

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Figure 1. A Prairie Chicken lek (reprinted with permission [1]).

Using this model, leks result in formations for evenly distributed robots, but in certain circumstance results in various configurations influenced by both parametric and environmental factors. Overall, this behavior appears useful for a range of robotic applications and has the potential to be widely applicable in multiple domains and missions.

II. LEK BEHAVIOR

A. Basic Behavior

The formation of leks in order to effectively share resources and to allow all parties to be more successful is a true testament to the intelligence of these bird species. Lek behavior is unique to each particular species of bird, but there are some common themes between all of the variations. All species of birds that lek do so because the primary responsibility for the males is to copulate with females with their goal being to obtain as many successful copulations as possible. Interestingly, copulation with one male does not serve to devalue the possibility of copulations with other males, even those in the same lek, during a breeding season [2]. The behavior of species that lek is determined by available resources, both female and natural, that cannot be monopolized by any one male [3]. The most successful male of a lek, around which subordinates often gather, is termed the “hotshot”. Thus males group into leks to become more successful as a group than would be possibly individually [3]. It is predicted that if the most successful males are removed from a lek, the female visitation will decrease, but if the lesser males are removed, the female visitation will remain the same [3].

Males in a lek often display their colors and announce their presence with mating calls. Where hotshots are located in a lek, their status is determined by differences in

¹ Project website: <http://www.seas.upenn.edu/~onrhunt/index.html>

attractiveness to potential mates or their dominance over the other males [3]. In general, our computational model will focus on male behavior in the lek. At this stage in our research, however, we are concerned solely with the spatial distribution and organization associated with this behavioral pattern rather than the intraspecies communication mechanisms.

Lek settlement appears to be based on minimizing interlek competition rather than maximizing proximity to females [2]. Individual lek location is related to the traffic patterns of females [4], but not on the locations of the nest. A possible reason for this is that leks are by their nature noisy due to the males' vocalizations, and thus should be located in more open areas, while nests should be in sheltered areas with less noise to avoid predation [2]. The number of males per lek and the amount of young males that joined the lek seems to be based on the female to male ratio throughout the season, although they also appear related to the amount of time that other males had been present in the lek [4]. This appears reasonable, since male fidelity between seasons is based on the harem size (number of females) that is encountered at a given site. Therefore, the number of established males is a good predictor of how popular a particular lek is. Since leks are located in the same area from year to year, they are not located near fruiting plains, which can be highly varied from season to season [5]. It was shown in simulation [6] that as male populations increased, the number of leks remained the same and the size of these leks increased. As evidenced by certain species, the average lek size for territorial males was between two to six males [5], but overall lek size seems to be highly influenced by female availability [4].

Both "hotshot" behavior and the hot spot hypothesis are potential indicators of lek formation, and while they are competing theories, they overlap minimally and are both useful in different ways in our robotic behavioral implementation. The hot spot theory proves useful for determining the robot lek location related to available target resources, while the hot shot theory provides a model for robot lek formation itself, independent of available resources.

B. Hotshot Behavior

An important aspect of lek behavior is the idea of the "hotshot" male. These males are highly successful and other males gather around them in order to encounter mates that they would not otherwise have attracted [2]. In normal lek behavior the "hotshot" male would be chosen based on the result of the attractiveness to potential females, but in our robot lek behavior it will be assigned a priori to a specific robot; the basis for the selection will be either the sensors available to the robot or an arbitrary assignment made before deployment. Normal bird leks have multiple "hotshots" that cluster in the middle of the lek, with secondary males clustered around them holding smaller territories. In our simulations, since the leks will be small, each will only contain one "hotshot". We will use multiple "hotshots", however, to create multiple leks. This is important for our behavioral implementation because these "hotshots" will be

integral in both communication and leadership roles for the leks.

C. "Hot spot" Hypothesis

The "hot spot" hypothesis is hotly contested among ornithologists. It generally states that the distance between leks should be equal to a female home range plus the distance from which a lek can be detected, and that leks should be located in an area that maximizes the overlap of female home ranges [6]. Evidence that supports this hypothesis includes the observations that bird leks are preferentially located in open areas that have a high volume of female traffic, and that females visit leks near their nests [4]. For the purposes of this research, the "hot spots" for the robots to settle into will be configured based on the distribution of resources and potential traffic patterns.

III. IMPLEMENTING THE LEK BEHAVIOR

A. MissionLab Mission Specification System

*MissionLab*² was developed by the Mobile Robot Laboratory at Georgia Tech and allows code to be executed both in simulation and on real robot platforms [7,8]. Supported platforms include the iRobot ATRV-Jr and Pioneer AmigoBot among many others. The *MissionLab* environment was built generally to run military-style missions. For the purposes of this project, *MissionLab*'s simulation environment is used, while the robotic implementation has been developed separately using Microsoft Robotics Developer Studio 2008 for the iRobot Create robotic platform.

When implementing the basic lek behavior, a buffer zone is used that lek participants settle into when drawn towards other participants. This area is represented by the yellow circle in Fig. 2. A single robot lekmate is shown by the blue circle. This behavior repels a lekking robot from any should it enter into the inner red circle, while it is attracted to (moves towards) if it enters within the green circle.

The lek behavior was implemented within *MissionLab*, and can be freely combined with other pre-existing behaviors such as obstacle avoidance, moving to a goal

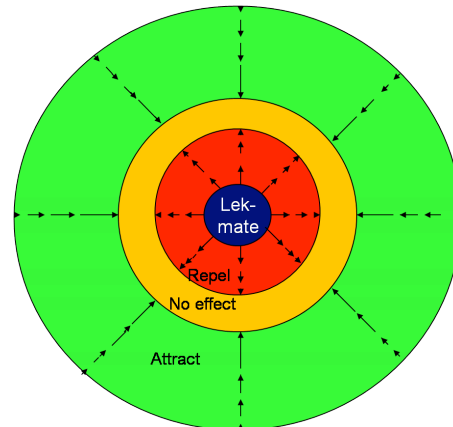


Figure 2. Lek Vector Field Model.

² *MissionLab* is freely available for research and educational purposes at: <http://www.cc.gatech.edu/ai/robot-lab/research/MissionLab/>

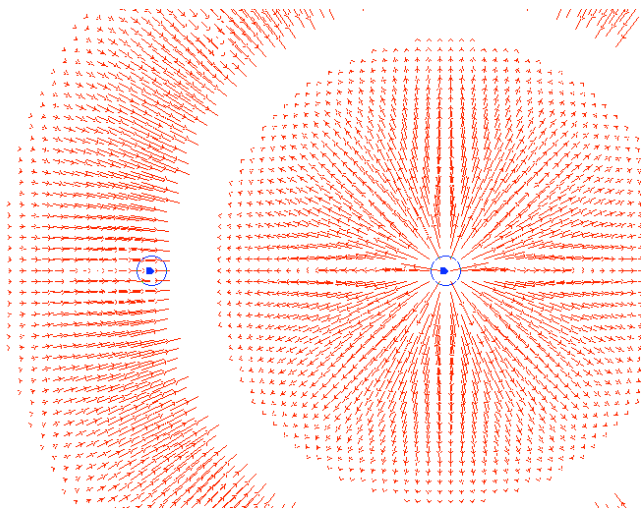


Figure 3. *MissionLab* lek vector field in simulation, the leftmost robot is the one that the field is created for based on the effect of the lekmate robot on the right (i.e., the force is exerted on the robot on the left). The arrows indicate the direction and magnitude that the robot would move if it were at that location. The different areas are also the same as those represented in Figure 2.

location, or noise (a random walk). This allows for the generation of complete assemblages of behaviors that can be connected via a finite state acceptor to build up entire arbitrarily complex missions [9,10]. A screenshot of an actual vector field produced by a single robot in a two-robot lek is shown in Figure 3. In this case the robot to the left in the field would directly approach the attractor robot until it is within the buffer zone.

Implementation in *MissionLab* takes place in C++ code, using the built-in vector and simulation specific functions. To create the vector field illustrated in Figure 3, the positions of all robots within a certain radius are found. These positions are then used to create an additive vector either toward or away from the other robots. At run-time, however, only a single vector need be created for each relationship between robots, keeping computation tractable.

An implementation decision was to use vectors with controlled (linearly decreasing) magnitude, rather than ballistic (constant magnitude) vectors. This provides a more controlled approach to the buffer zone area, which is important when considering the potential for multiple relationships between lekmates. This way, a more stable formation can evolve quickly and with the use of a smaller buffer region, minimizing the potential for overshoot. This controlled magnitude vector is computed based on the distance of the current robot from the edge of the attraction or repulsion zones.

The obstacle avoidance behavior was the next addition to the lek assemblage. The obstacles create repellant vectors that change the courses of the individual robots and their resultant formations. Each individual robot exhibits an obstacle avoidance behavior, and when combined with the lek behavior, permits the lek to move through obstacle fields in formation, as shown in Figure 4.

Implementing the biologist's hot spot hypothesis was the next logical step. In this case, the robots should aggregate

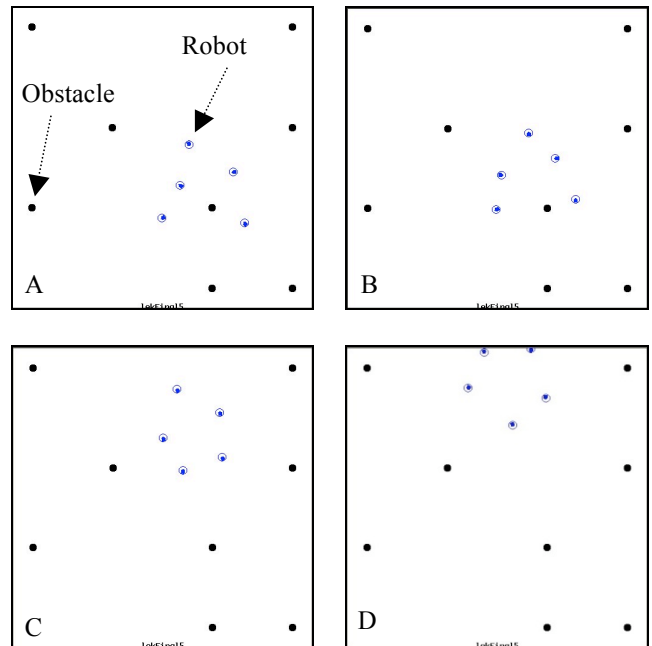


Figure 4. Robot progression from beginning (A) to aggregation (B) to formation moving through the obstacle field (C) to stable formation (D). Robots are represented by box inside a circle and obstacles are represented by dark black circles.

away from obstacles, and near individual hot spots. The locations where the lek forms are influenced by the attraction of lek members to the nearest hot spot. This is realized as an attraction vector, proportional to the distance between the robot and a hotshot.

Finally, the simulation was implemented in a manner such that the strength of the lek behavior could be varied depending on if the stimulus for the behavior was a regular lek member or a hotshot. This allows for more variations in the lek behavior (e.g. allowing a hotshot to be more influential in the formation of a lek). This strategy can allow the hotshots to control the overall movement of the lek and eliminates direct communication required between individual robots [11].

B. Microsoft Robotics Developer Studio and iRobot Create

The physical robot platforms used for experiments (Fig. 5) are: (1) iRobot Creates with the Element BAM (Bluetooth Adapter Module), the drive-on dock, three Virtual Walls, (2) WowWee Rovio Wi-fi robots and (3) a Windows XP machine running Microsoft Robotics Developer Studio.

Microsoft Robotics Developer Studio was chosen because it already had code to run on the iRobot Create platform, and would allow our experiments to be more easily recreated.

This implementation is being finalized and actual results will be available in the final version of the paper.

IV. SIMULATION RESULTS

In simulation, we examined the manner in which the lek behavior allowed groups of robots to structure themselves in formation, both at a hot spot and on the way to a hot spot.



Figure 5: Example photo of potential robot lek.

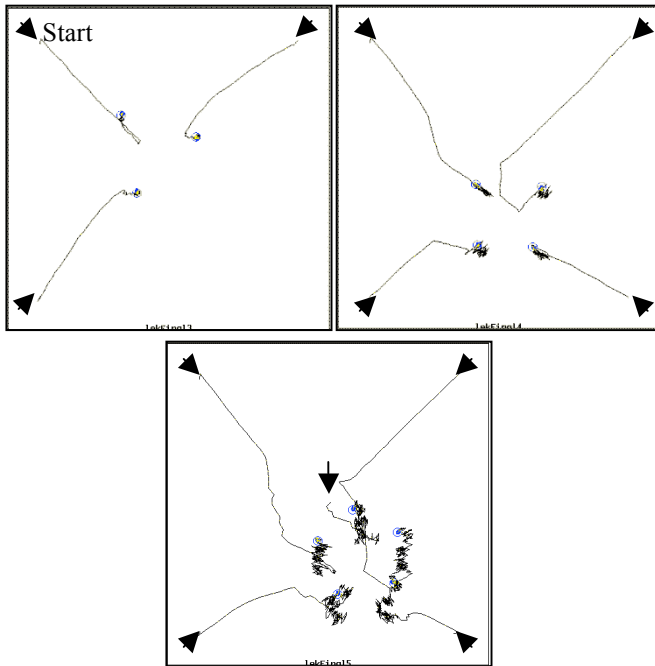


Figure 6. Robot lek formation examples including robot trails. Start points are indicated by the arrows, end points by the dark spots where the robots have been shifting.

The results are not unlike our previous research in formation control [12], which was not biologically inspired, but now with the addition of the two lek theories regarding hotshots and hot spots, and annular buffer zone, instead of a circular region. Examples of the formations created by a lek are shown in Figure 6. A lek with three participants formed a rough triangle, a lek with four participants formed a square, and a lek with five participants formed a pentagon. These structures are robust even in the presence of obstacles (Figure 4) due to the integration of the lek behavior with an obstacle avoidance behavior [10]. In the simulation, the robots form up, but continue to move in place due to the wander behavior (noise schema) [10] present in the behavioral assemblage used in the simulation. The details of the implementation are presented in the Appendix.

The underlay shown in Figure 7 is from the location used by [5], and was also used in previous studies by various authors mentioned in [5]. It is an area in Long Valley, California that contains forested, clear, and snow-covered areas. The obstacles added to the simulation are small and located between the robots' spawn points and the hot spots to further demonstrate that obstacle avoidance is feasible and can be accomplished by the group on its way to establish a lek. The navigation to the hot spots is accomplished individually by each member of the lek. The hot spots are, as for the obstacles, placed by the user. Hot spots are shown on the underlay as red circles.

The typical behavior of a group of six robots, including one hotshot, in the presence of a single hot spot is shown in Figure 8. Typically, nearby robots form loose formations as they travel to the hot spot. Once at the hot spot, the robots aggregate into a regular shaped lek (similar to Figure 6) centered upon the hotshot.



Figure 7. Underlay used for the simulations of Long Valley, California. This area was used in multiple biological studies as mentioned in [13].

The use of multiple hotshots in the presence of multiple hot spots creates multiple leks. One typical simulation run depicted in Figure 9 shows multiple lek formations located at the center of each the hot spot. The leks formed are the result of a combination of factors including the initial locations of both the hotshot and regular lek members, the path traveled by the lek members across the environment, and the location of the hot spots themselves. While we currently differentiate between different hotshots within the environment, the model presented is general enough to incorporate such factors by varying the gain of the lek behavior associated with each hotshot in proportion to the relative attractiveness of each hotshot. An examination of such factors on the formation of multiple leks in the presence of multiple hotshots and hot spots serves as an interesting avenue for future work.

V. SUMMARY AND CONCLUSIONS

The lek behavior in itself has already proven to be adept at producing formations of arbitrary numbers of robotic agents in the presence of unevenly distributed resources. It is heavily inspired by ethological models of male bird mating behavior observed in the wild. The addition of the “hot spot” hypothesis and the use of hotshot participants, drawn from biological theories, make this behavior more useful in a broader range of potential scenarios, such as search-and-rescue or reconnaissance operations. The ability to have a team of robots form up into multiple formations, each with a central leader (hotshots), adds to the versatility of the original purely distributed control approach, although it does add vulnerability should the leader fail or be destroyed. Also, the addition of a mechanism to allow grouping in a specific area based on its resources (hot spots) allows a greater probability of detection or discovery for a wide variety of mission profiles.

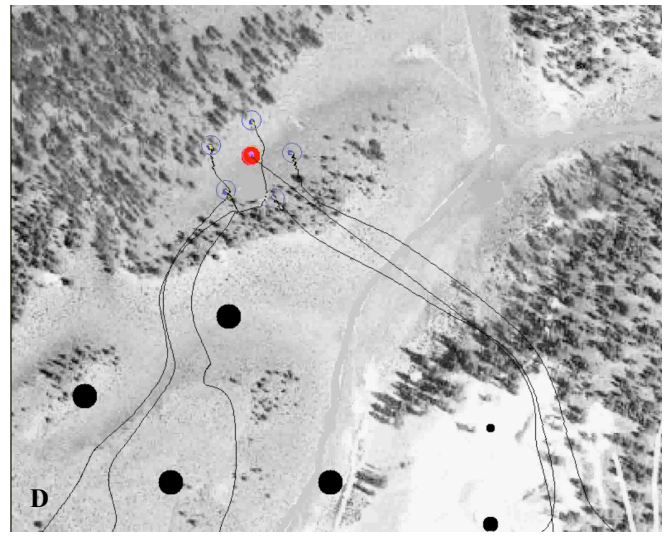
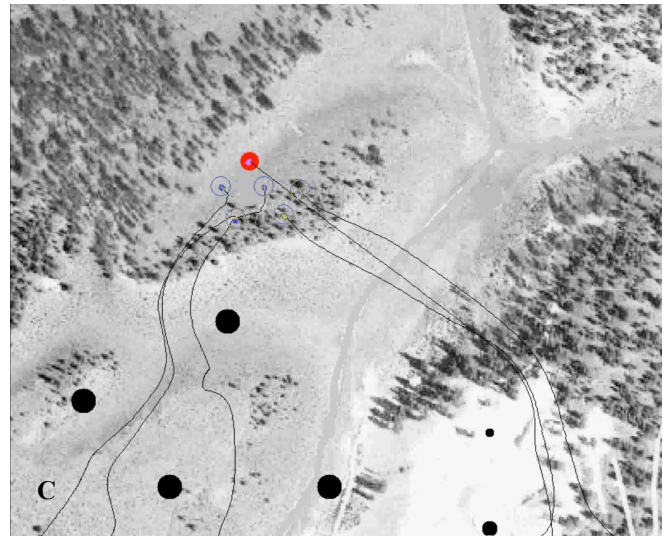
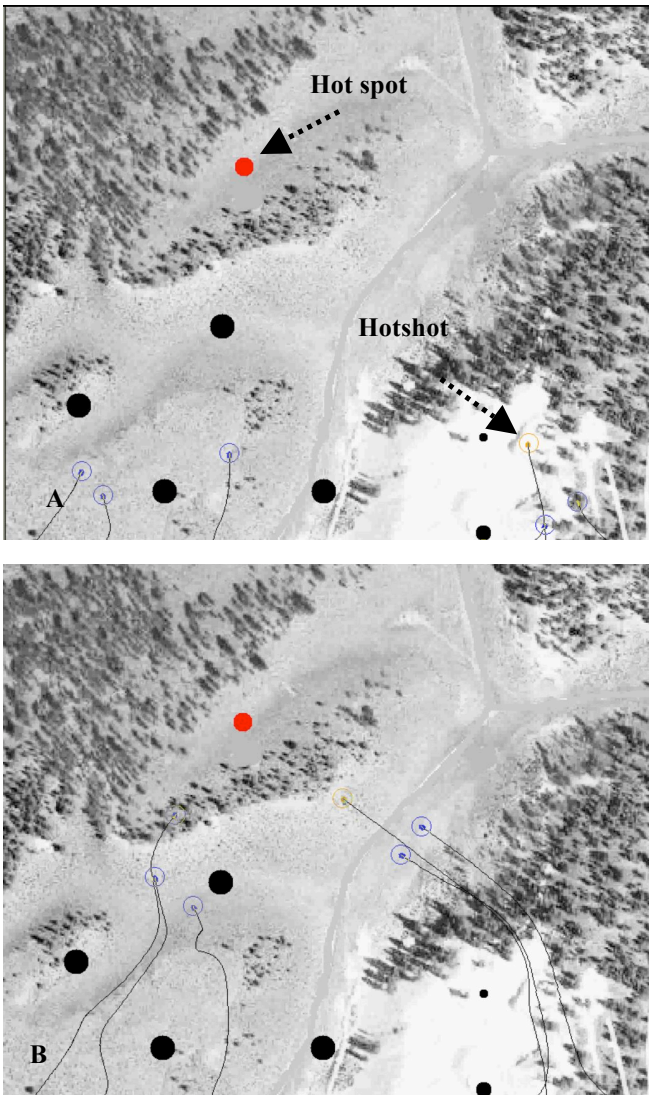


Figure 8. The generation of a lek from a group of five robots, one hotshot, and one hot spot. (a). Five regular robots and one hotshot begin moving towards the hot spot. (b). Nearby robots form loose formations as they travel to the hot spot. (c). The hotshot moves to the center of the hot spot other robots begin to form lek around the hotshot. (d). Robots finalize lek formation around the hotshot.

APPENDIX

This appendix contains the behavioral formulas and associated parameters used in each lekmate.

a) Lek behavior: Variable attraction/ repulsion behavior for group formation based on distance from other robot.

$$V_{mag} \begin{cases} \frac{R-d}{R}, & R \leq d \\ 0, & A_{min} < d < R \\ \frac{A_{max}-d}{A_{max}-A_{min}}, & A_{max} \leq d \leq A_{min} \end{cases}$$

$V_{direction}$ = Direction from the center of the robot to the center of the other robot

where:

- d = Distance of robot to another robot
- R = Radius of the repulsion sphere
- A_{min} = Inner radius of the attraction sphere
- A_{max} = Outer radius of the attraction sphere

b) Hot spot attraction: Variable attraction to location behavior. Used for attraction to a specific spot or spots.

$$V_{mag} = \frac{H - d}{H}$$

$V_{direction}$ = Direction from the center of the robot to the center of the hot spot

where:

- d = Distance of robot to a hot spot
- H = Maximum hot spot detection distance

c) Avoid-obstacle: Repel from object with variable gain and sphere of influence. Used for collision avoidance.

$$V_{mag} \begin{cases} \infty, & d \leq r \\ \frac{\max - d}{\max - r}, & r < d \leq \max \\ 0, & d > \max \end{cases}$$

$V_{direction}$ = Direction from the center of the robot to the center of the obstacle, moving away from obstacle

where:

- max = Maximum obstacle detection sphere
- d = Distance of robot to obstacle
- r = Radius of obstacle

d) Noise: Random wander with variable gain and persistence. Used to overcome local maxima, minima, cycles, and for exploration.

- $V_{magnitude}$ = Adjustable gain value
- $V_{direction}$ = Random direction that persists for specified number of steps

Parameter	Value	Units
Lek behavior assemblage		
Lek gain	.2	
Noise gain	.01	
Noise p	10	
Repel sphere	40	m
Attract sphere	50	m
Maximum detection sphere	150	m
Avoid obstacle gain	1	
Avoid obstacle sphere	70	m
Avoid obstacle safety margin	2	m
Hot spot gain	.7	
Hotshot gain	.7	
Lek behavior near hotspot (within 30 m)		
Lek gain	.5	
Noise gain	.05	
Noise p	10	
Repel sphere	40	m
Attract sphere	50	m
Maximum detection sphere	150	m
Avoid obstacle gain	.85	
Avoid obstacle sphere	30	m
Avoid obstacle safety margin	.5	m
Hot spot gain	.5	
Hotshot gain	1	
Hotshot lek behavior assemblage		
Lek gain	.2	
Noise gain	.01	
Noise p	10	
Repel sphere	40	m
Attract sphere	50	m
Maximum detection sphere	150	m
Avoid obstacle gain	.65	
Avoid obstacle sphere	50	m
Avoid obstacle safety margin	2	m
Hot spot gain	.8	
Hotshot gain	0	
Hotshot lek behavior near hotspot (5 m)		
Lek gain	0	
Noise gain	.01	
Noise p	10	
Repel sphere	35	m
Attract sphere	40	m
Maximum detection sphere	300	m
Avoid obstacle gain	.5	
Avoid obstacle sphere	1.4	m
Avoid obstacle safety margin	.5	m
Hot spot gain	0	
Hotshot gain	0	

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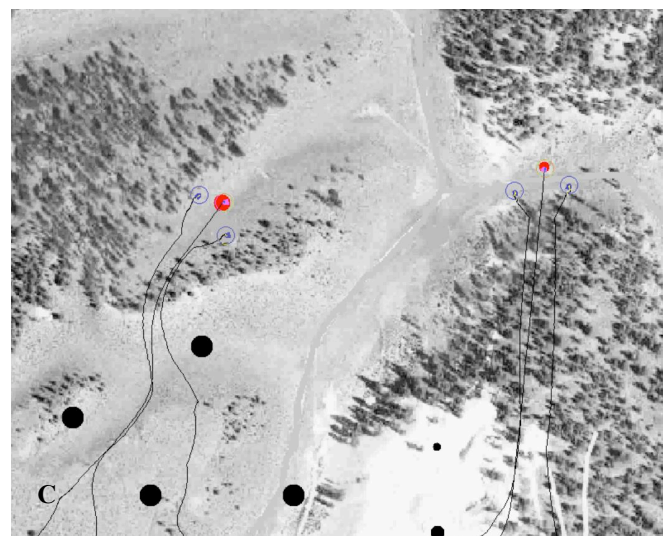
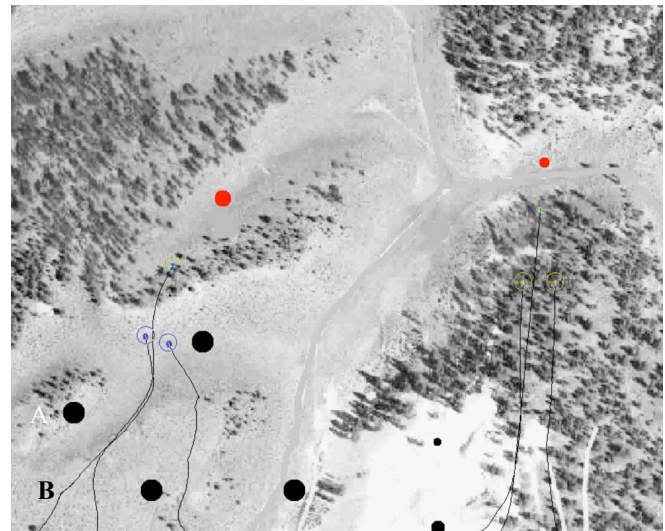
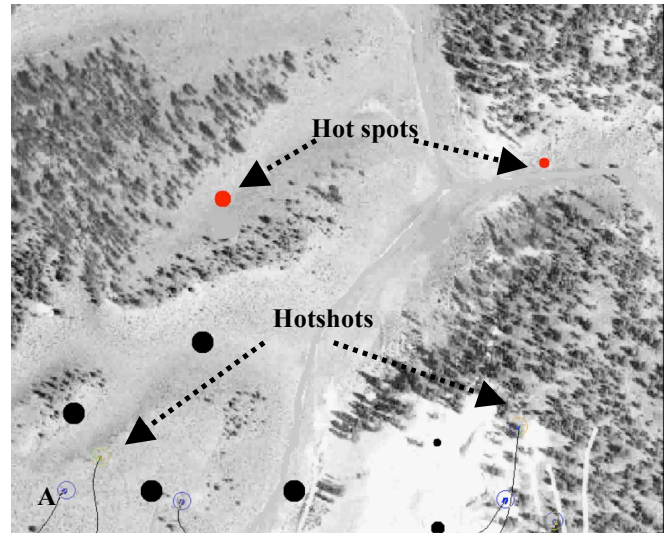


Figure 9. The generation of two leks from a group of four regular robots, two hotshots, and two hot spots. (a). The four regular robots and two hotshots begin moving towards the hot spots. (b). Each hotshot leads a loose formation of two regular robots to the hot spot nearest to them. (c). Once at the hot spots, the regular lek members form a lek around the hotshots.