Layered Mode Selection Logic Control for Border Security

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Abstract

Challenges in border security may be resolved through a team of autonomous mobile robots configured as a flexible sensor array. The robots will have a prearranged formation along a section of a border, and each robot will attempt to maintain a uniform distance with its nearest neighbors. The robots will carry sensor packages which can detect a signature that is representative of a human (for instance, a thermal signature). When a robot detects an intruder, it will move away such that it attempts to maintain a constant distance from the intruder and move away from the border (i.e. into its home territory). As the robot moves away from the border, its neighbors will move away from the border to maintain a uniform distance with the moving robot and with their fixed neighbors. The pattern of motion in the team of robots can be identified, either algorithmically by a computer or by a human monitor of a display. Unique patterns are indicative of animal movement, human movement, and mass human movement. To realize such a scheme, a new control architecture must be developed. This architecture must be fault tolerant to sensor and manipulator failures, scalable in number of agents, and adaptable to different robotic base platforms (for instance, a UGV may be appropriate at the southern border and a UAV may be appropriate at the northern border). The Central Arkansas Robotics Consortium has developed an architecture, called Layered Mode Selection Logic (LMSL), which addresses all of these concerns. The overall LMSL scheme as applied to a multi-agent flexible sensor array is described in this paper.

Keywords: Mode Selection Logic, Fuzzy Sensor Fusion Network, Border Security

1. INTRODUCTION

With the rising tide of illegal immigration overlaid with terrorism threats at home, the task of border security is becoming increasingly important. History has shown that fixed walls or fixed security monitors can be undermined, broken down, or evaded. Manned patrols are costly and impractical. Technological advances in the field of robotics may provide a flexible sensor array which can enhance monitoring of the borders.

A flexible sensor array refers to a team of mobile robots carrying a sensor package, such as a thermal imager, which can reliably detect a human signature. This array is spread across a border perimeter, and each robot attempts to maintain a fixed distance with its neighboring robots, such that a group of humans passing in the vicinity of the robots will be sensed by the sensor package.

As the signature moves towards the robots, the robots are designed to move away from the border and to maintain contact with the signature. Combined with the array's rule of maintaining a fixed distance with its neighbors, when one robot moves out of position, the section of the sensor array will deform towards the interior. This represents a detectable pattern, which either a human border agent with a heads up display can monitor or which algorithms can infer from robot positions and states. The differences between an animal crossing the border versus a mass of humans crossing the border can be distinguished.

Implementing a flexible sensor array with a team of mobile robots requires a controller architecture which is capable of handling an unstructured environment, cooperating among multiple agents, and interacting safely with humans. The Central Arkansas Robotics Consortium has been developing such an architecture, called Layered Mode Selection Logic (LMSL).

Unattended Ground, Sea, and Air Sensor Technologies and Applications IX
edited by Edward M. Carapezza, Proc. of SPIE Vol. 6562, 65620Q, (2007)
0277-786X/07/$18 · doi: 10.1117/12.718713

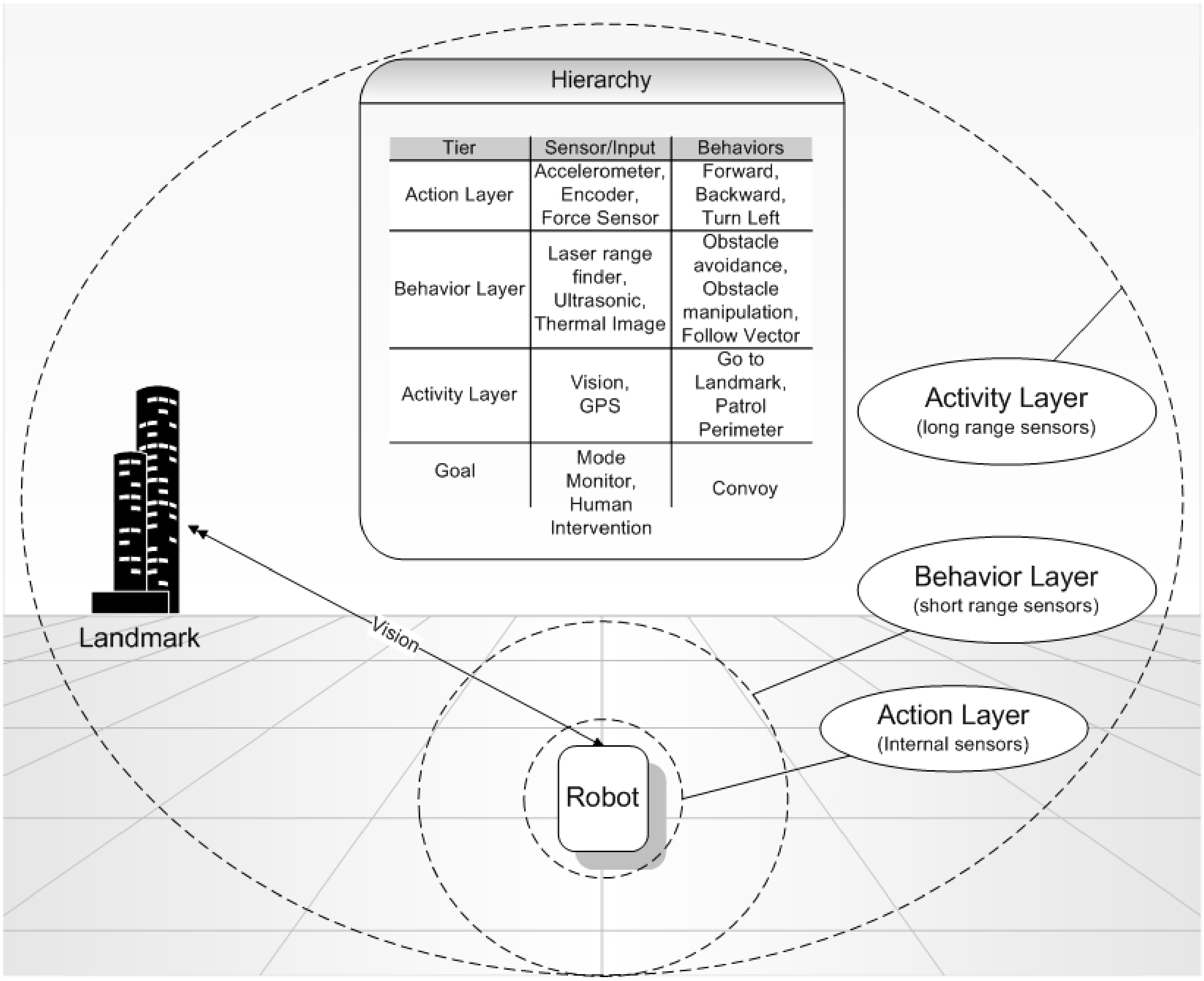

Figure 1 System Hierarchy

1.1 Layered Mode Selection Logic

Layered Mode Selection Logic (LMSL) is a hybrid control architecture which uses Mode Selection Logic (MSL) as a behavior coordination mechanism. The implementation details of the general MSL mechanism are presented in reference 1. MSL is similar to a Finite State Machine where a system has a finite number of states. For each state, the system's behavior is defined. Each state has a predefined set of conditions which, when satisfied, trigger the transition to another state. In MSL a system state is called a mode.

In Layered Mode Selection Logic (LMSL), modes are organized in a hierarchy. The lowest layer in the hierarchy, called the Action layer, is a reactive controller. Each mode in the Action layer encapsulates a basic robot function, such as "forward," "turn left," or "actuate manipulator." The Action layer provides hardware abstraction. The next layer, called the Behavior layer, is a behavior-based controller implemented using the MSL paradigm. The next two layers, the Activity layer and the Goal layer, can accomplish more complex tasks. Each layer's algorithm is defined by a Mode Selection Diagram (MSD).

The LMSL architecture addresses many of the functional requirements for a robot to perform in an unstructured enrionment[2]. LMSL is well suited for controlling multi-agent robot teams. LMSL is scalable to multi-agent systems due to the behavior based component of the architecture. LMSL allows for top down goal oriented group behavior design. Beyond the action layer, algorithm design is done through Mode Selection Diagrams. Design tools based on dropping and connecting predefined modes can be accomplished through a straight-forward Graphical User Interface (GUI). This architecture supports graphical monitoring tools to indicate what modes a particular robot is in and to monitor the transition patterns.

1.2 Fuzzy Sensor Fusion Network

A Fuzzy Sensor Fusion Network (FSFN) is a fuzzy inference system associated with a certain layer of the mode selection logic. A FSFN combines multiple inputs in a single fuzzy rules matrix. The sensors combined in an FSFN can be redundant, to support fault tolerance, or complimentary, to improve performance over a broader range of environmental conditions. In this architecture, fuzzy logic takes sensor values and maps them into discrete variables, called intermediate flags, rather than continuous outputs or command signals, which is traditionally done by fuzzy logic controllers. The intermediate flags, which are used by the LMSL for mode selection, signify the occurrence of an event. FSFNs have been shown to be fault tolerant to imprecise data and sensor failure[2].

Each level of LMSL uses a unique FSFN [see Figure 1]. On the lower layers, the types of events the FSFN detects are more explicit (for example collision detection) and the inputs to the FSFN are usually raw or processed sensor data. On higher layers, the FSFN requires more intelligent sensors to detect higher level events. For example, a vision system may be used to assess terrain and detect if the path in front of the robot is clear.

1.3 Mode monitor

Certain environmental conditions are difficult to detect using only sensor data. However, these conditions could be inferred from the emergent mode switching patterns. The mechanism that performs this function is called a Mode Monitor. It collects data, such as elapsed time in each mode or frequency of mode transitions. Mode monitors can be designed experimentally by inducing the environmental condition to be detected and logging the mode transition patterns. Emergent mode transition patterns can be identified later using data mining techniques on a data log of all mode transitions that a robot experienced.

The Mode Monitor can generate discrete outputs which can be used directly by the LMSL for mode transitions. The output of a Mode Monitor can be a continuous value that is fed into a FSFN and combined with other data.

2. METHODOLOGY

The implementation of border security using LMSL will require actions, behaviors, activities, and goals to be developed [see Table 1]. The library of Activity layer modes and Behavior layer modes for the general case are not yet fully developed. The behaviors will be described in terms of their desired outcomes.

Table 1 Modes for border security

Behavior	Activity	Goal
Pursue	More Flex	Border Security
Capture	Balance	
Patrol	Less Flex	

FSFN's that are capable of detecting boundaries, robots, and intruders are required. The Activity layer flags which will be needed to implement the proposed border security scheme are presented in Table 2.

Table 2 Intermediate Flags for border security

Flags	Layer	Source
Perimeter_Detected, Intruder_Detected, Intruder_Escaped	Activity	FSFN
Long_Pursuit, Short_Pursuit	Activity	Timer
Low_Density, Medium_Desnity, High_Density	Goal	Mode Monitor

The system will recognize two types of perimeters. The perimeter that the team is assigned to guard is called the Border Perimeter. A second perimeter, which serves as a limit to keep the robots from dispersing too far is called the

Constraining Perimeter. The intersection of the Border perimeter and the Constraining perimeter bounds a closed domain [see Figure 2].

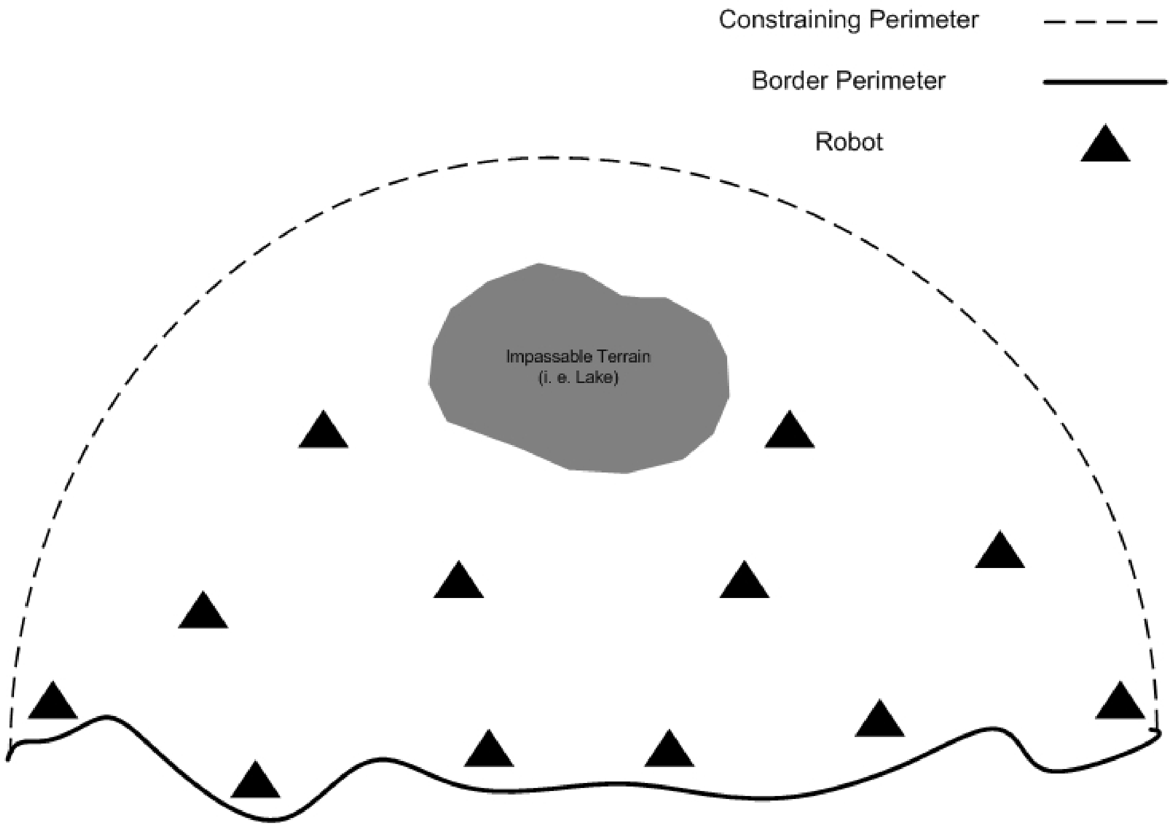

Figure 2 Border map

2.1 Behavior layer modes

In the Patrol behavior, robots are directed to maintain a centroid of distance between themselves and neighboring robots. The robots are attracted to the Border perimeter and may not cross the Constraining perimeter. The combination of these two rules results in the robots settling into a pattern along the Border perimeter with a more or less fixed spacing among themselves, depending on the terrain, number of robots, and length of the Border perimeter.

If a thermal or visual signature representative of a possible human is detected, the Capture behavior directs the robot to maintain a fixed distance from an intruder. While in Capture behavior, the presence of other robots is ignored and the Border perimeter attraction is ignored; however, the Constraining perimeter may not be crossed.

If a robot loses the signature from the intruder, it may enter the Pursue behavior. This behavior directs the robot to move in the direction of the last known heading of the intruder.   Other robots are ignored. The Border perimeter attraction is ignored, and the Constraining perimeter remains in effect.

2.2 Activity layer intermediate flags

The intermediate flags for the activity layer are Intruder_Detected, Intruder_Escaped, Perimeter_Detected, Shor_Pursuit, and Long Pursuit. Intruder_Detected indicates that a potential human has been encountered (see Table 2). The

Intruder_Detected flag will be generated by a FSFN using an array of complimentary sensors such as vision and thermal imager.

The Intruder_Escaped flag is triggered when the robot loses sight of the intruder. This flag is only triggered after an intruder has been detected. Perimeter_Detected indicates that the robot is nearing a Perimeter. The Constraining perimeter keeps the robot team from flexing too far from the Border perimeter. The Short_Pusuit and Long_Pursuit flags are set by timers, which start when the robot enters the Pursuit mode.

2.3 Activity layer modes

In the Less_Flex activity, the robot favors the Patrol behavior [see Figure 3]. The initial state of the robot is the Patrol behavior. If an intruder is detected, the robot enters the Capture behavior. The robot returns to Patrol behavior when either the intruder escapes or the robot encounters the Border perimeter or the Constraining perimeter. In Less_Flex, the robot makes no attempt to pursue an intruder, which minimizes the robot's displacement due to intruders.

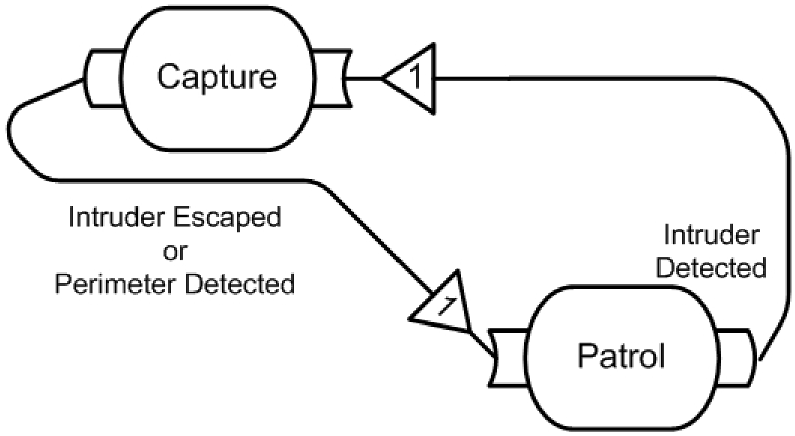

Figure 3 Less Flex Activity MSD

In the Balance activity [see Figure 4], the robot gives equal treatment to Pursuit and Patrol. The robot begins in Patrol behavior. When an intruder is detected, the robot enters the Capture behavior. If the Border perimeter or the Constraining perimeter is encountered while the robot has the intruder captured, the robot will not cross either perimeter, but will return to Patrol behavior. If the intruder escapes and no perimeter is detected, the robot will Pursue. While in Pursue behavior, if an intruder is detected, the robot will return to Capture. While in Pursue behavior, if a perimeter is encountered or the short pursuit timer expires, then the robot will return to Patrol.

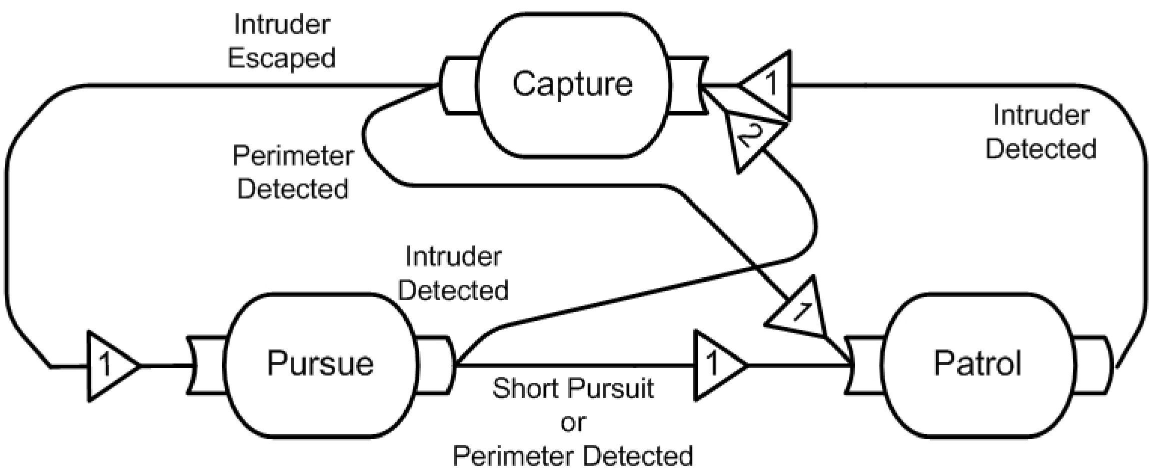

Figure 4 Balance Activity MSD

In the More Flex activity the robot prioritizes the Pursue behavior [see Figure 5]. The MSD for More Flex is similar to the Balance mode MSD. Instead of the short pursuit timer, a long pursuit timer is used. This gives the robot more time to reacquire its target before returning to Patrol.

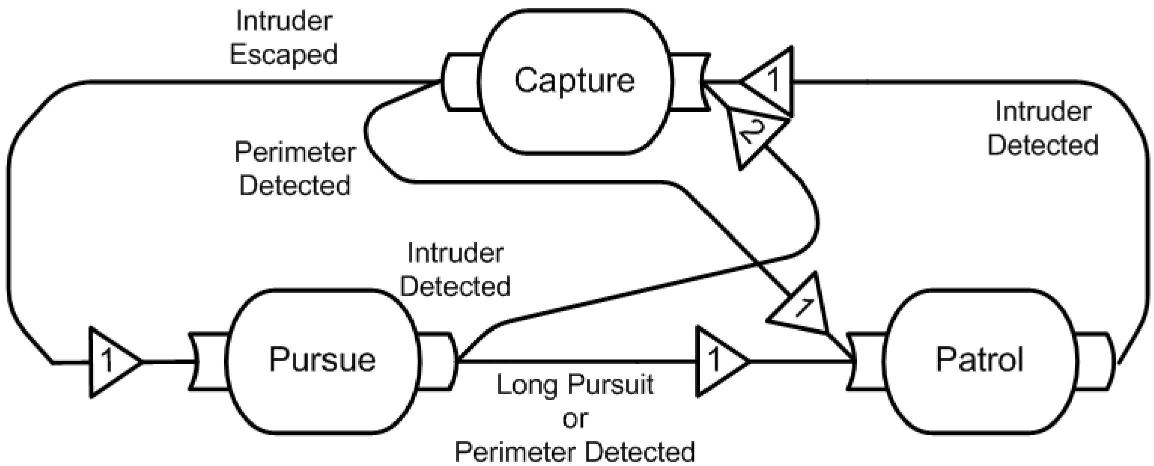

Figure 5 More Flex Activity MSD

2.3 Goal Layer

The Goal Layer, Border Security, is operating on each robot; however, the inputs to generate transition flags are initiated by a combination of intruder detection from the team of robots. The Border Security Goal [see Figure 6] transitions among the Activities, "Balance," "More Flex," and "Less Flex."

The purpose of the Border Security goal is to keep the robot formation dispersed without losing the integrity of the patrolled border. This dispersion allows a minimum number of robots to adequately monitor an area. It will vary with the intruder density. When more intruders are present, the robots guarding that section must be more concentrated to track them. When fewer intruders are present, the formation can be more disperse.

The Low_Density, Medium_Density, High_Density intermediate flags used in the Border Security goal are determined by a Mode Monitor. Each robot monitors the Behavior layer state of its near neighbors. The more near neighbors who are in the Capture or Pursue behaviors, the more intruders are present in the robot's vicinity. This value is a continuous variable that can be fed into a FSFN to set the "High_Density" and "Low_Density" intermediate flags. More robots in Patrol behavior would indicate that few intruders are being detected and therefore this section of border has a low intruder density. This value is fed into a FSFN to determine the "Low_Density" intermediate flag.

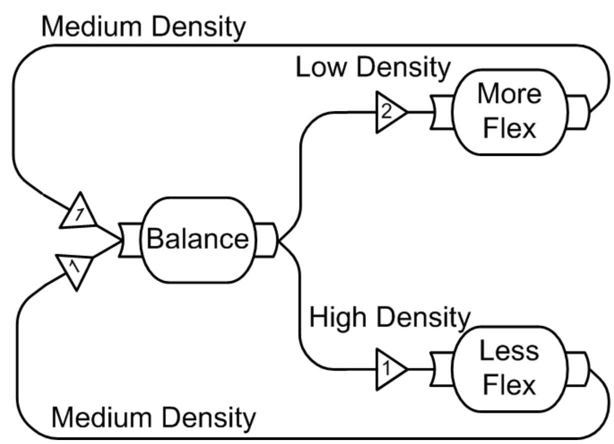

Figure 6 Border Security goal MSD

Initially all robots are in the Balance activity. When the "Low_Density" intermediate flag is set, the Activity is switched to "More Flex" which allows the robots to disperse over a wider territory. This activity should be the normal Activity in which the flexible sensor array remains when no intruders are present.

If the robots begin to detect intruders, the "Medium Density" flag will be set. If the number of intruders is large, both the "Medium Density" and "High Density" flags will be set. Once the "Medium Density" flag is set, the Activity on the robot switches to Balance, which decreases the amount of time in which the robot will remain in Pursue behavior upon losing contact with a signature. The likelihood that robots will remain in position increases, as each robot passes off an intruder to its near neighbors. The overall sensor array flexes in the direction of the intruders due to the Capture and Pursue behaviors of the robots actively engaged with intruders. The neighbors of these robots also adjust their positions, since the Patrol behavior requires them to maintain a centroidal distance with their near neighbors.

In the event of mass intrusion, the “High Density” flag will be set, which will transition robots into the “Less Flex” activity. In “Less Flex,” robots may Patrol or Capture, but may not Pursue. This tightens the sensor grid in the vicinity of a mass crossing.

As the intruder density decreases (either because the intruders return across the Border perimeter or because the have crossed the Constraining perimeter), the “Low Density” flag will be set, and robots return to the “More Flex” activity. The attraction of the Border perimeter will eventually return the flexible sensor array to its original configuration along the border.

Because the robots are sharing information about intruder contacts, at the point of many contacts, the robots will have the “High Density” flag set. Away from the contacts, robots who are not engaged with intruders will still have the “Medium Density” flag set.

The current prototype implementation of the Border Security goal is discretized into three Activities. If this proves to be too coarse a discretization, additional Activities (for instance “Even More Flex” and “Ludicrous Flex”) can be added to improve performance.

3. GRAPHICAL USER INTERFACE

The key advantage of the LMSL approach is that its abstractions can be presented to a human controller in a usable way. A graphical user interface (GUI) is being developed to present the robot state information to a human controller and allow the human controller to monitor and intervene with the robots.

One screen of the GUI presents a map showing the physical location of each robot. Each robot's color indicates its active behavior (i.e. whether the robot is patrolling, capturing, or pursuing). This map has a sidebar containing a bar graph. Each bar represents the number of robots executing a specific behavior. The bar colors correspond to the color scheme used to describe the behaviors the robots are executing. An MSD for the goal layer is displayed along the right-hand side of the map, and the color of each Activity in the MSD is modulated by the number of robots engaged in that Activity.

When the human controller selects a robot, an additional window will appear. This window contains the Activity MSD for that robot. Along the bottom of the interface, the current behavior in the MSD that the robot is executing is highlighted. The bottom of the window contains a line graph showing the history of behavior and Activity mode transitions. The width of each segment is modulated by the duration the robot spent in that mode.. The human controller may take control of the robot from this screen. The human controller can force the robot into a specific Behavior or Activity.

The GUI allows a human controller to easily determine that the flexible sensor array is being penetrated, because the bar graph with number of robots in Capture and Pursue behaviors will be abnormal. The rate at which these bars rise indicates the state of the intrusion. The pattern of robots moving out of position towards the Constraining perimeter indicates the location(s) of the intrusion. This information allows the human controller to dispatch human Border Patrol agents to intercept intrusions.

4. BEHAVIOR PROTOTYPE EXPERIMENT

A prototype border security behavior has been developed and tested. The general border security problem was simplified for the prototype system. This prototype behavior exhibited emergent behaviors which support its ability to maintain a secure perimeter.

The border region was simplified by reducing it to a single dimension. A one dimensional border allows for many of the random elements to be controlled. The orientation of the robots during interactions is more predictable. Having controlled interactions allows for a simple set of sensors to be used to detect the interactions. The types of interactions are reduced by combining robot and perimeter detections into a single type called a boundary detection. All other interactions are considered intruders.

The prototype behavior was tested on Lego Mindstorm robots [see Figure 7]. The robots use a pair of light sensor on either side to detect boundaries. The light sensors distinguish between colors. A boundary is designated by a white boundary identifier. Each robot has a boundary identifier on both sides such that when it interfaces with the other robots they detect each other as boundaries. Similar boundary identifiers are located at the limits of the perimeter.

The robots use a pair of touch sensors to detect intruders. The touch sensors are oriented such that when the robots interact, the light sensor will allow them to identify each other before the touch sensor is activated. An intruder is anything encountered but not identified as a boundary. In this experiment the intruder was a block of wood.

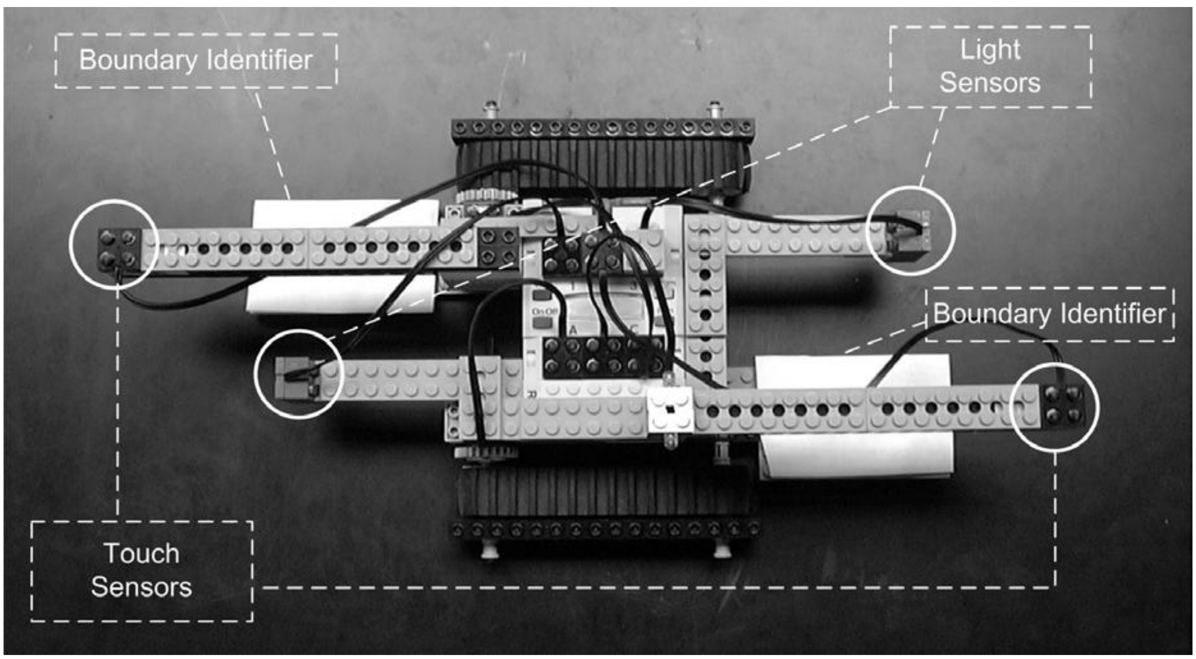

Figure 7 Lego border security robot

The prototype MSD is an implementation of the Balance activity [see Figure 8]. The general behaviors (Patrol, Pursue, and Capture) are made specific by adding left and right directions to them. The boundary detected intermediate flags are also made specific by the addition of a direction. (Left Boundary, Right Boundary). The Long Pursuit and Short Pursuit intermediate flags from the general case were omitted for simplification.

Each robot begins in a Patrol mode. While in Patrol, the robot travels in the specified direction (left or right) until one of two events occur:

1. A light sensor detects a boundary (another robot or a perimeter). This initiates a transition to the complimentary patrol mode, causing the robot to move away from the boundary. In the absence of intruders the robot will continuously cycle between Left Patrol and Right Patrol modes.

2. A touch sensor indicates the presence of an intruder. This initiates a transition into Capture mode. While in Capture mode the robot will maintain a fixed distance to the intruder. In this case the distance is limited by the range of the sensor. Since a touch sensor is used, the range is zero, meaning the robot will stay in contact with the intruder.

When the touch sensor is released the Intruder Escaped flag is set, causing the robot to transition into Pursue mode. It pursues in the same direction it had been patrolling when it performed the capture. The robot will remain in Pursue until the intruder is recaptured or a boundary is encountered

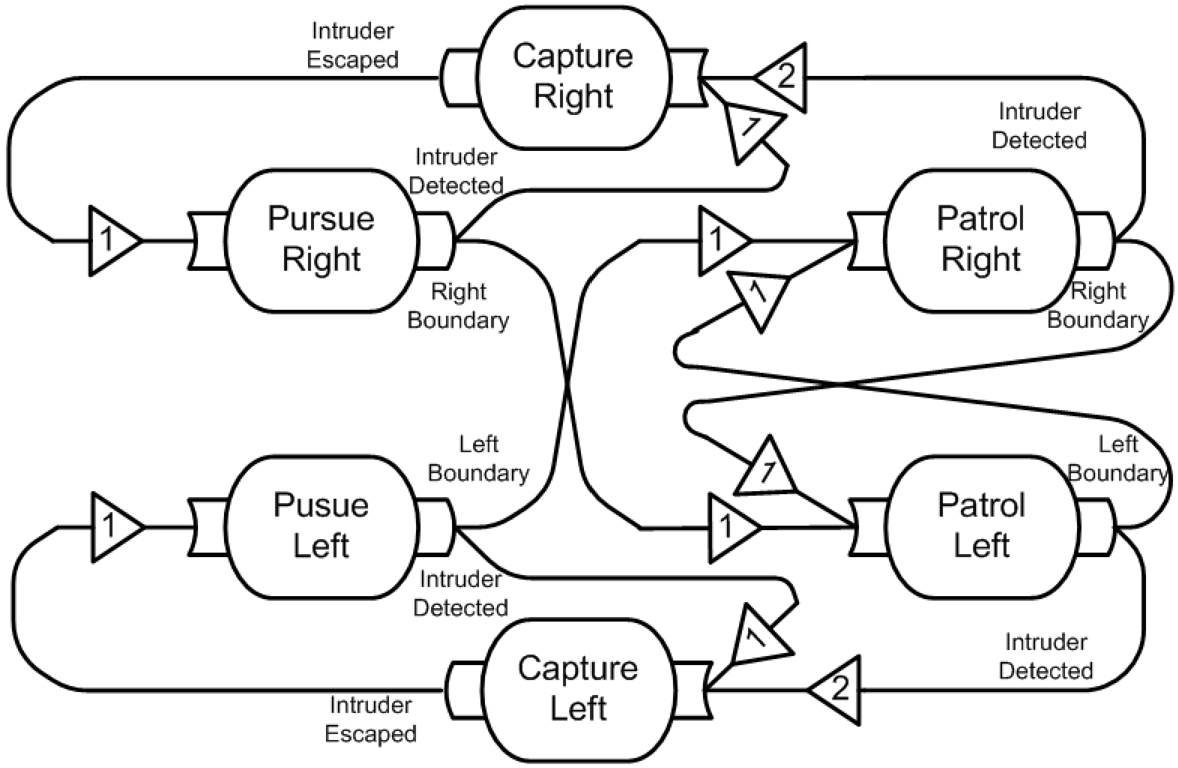

Figure 8 Prototype border security MSD

Two Lego Mindstorm robots running the prototype behavior were placed in a 2.75 meter track. A single stationary intruder was inserted at various positions on the track. Three distinct emergent behaviors were observed:

1. When no intruders were present, the robots patrolled the entire perimeter [see Figure 9]. The emergent behavior shows that the formation will uniformly distribute itself within the bounded region.

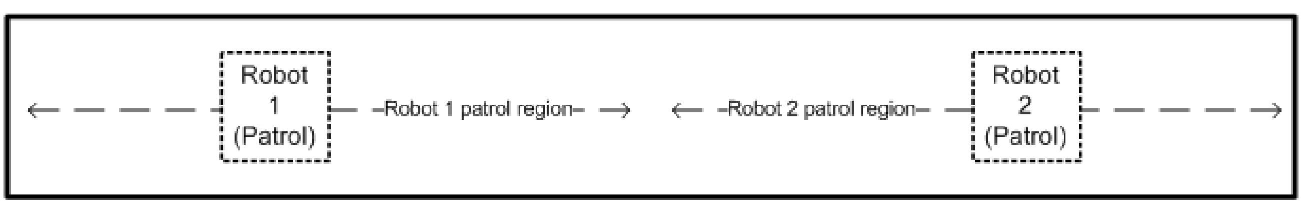

Figure 9 First emergent behavior

2. When an intruder was place between the robots, the robots captured the intruder from both sides [see Figure 10]. The emergent behavior shows that the robots will converge on an intruder. This emergent behavior leaves the border un-patrolled.

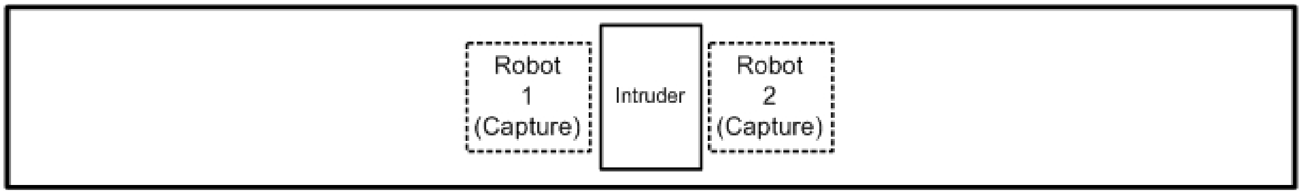

Figure 10 Second emergent behavior

3. When an intruder was placed on the outside of either robot, the robot nearest the intruder captured it while the neighboring robot patrolled the area that the capturing robot no longer visited [see Figure 10]. This emergent behavior shows that the formation will adapt to the presence of intruders.

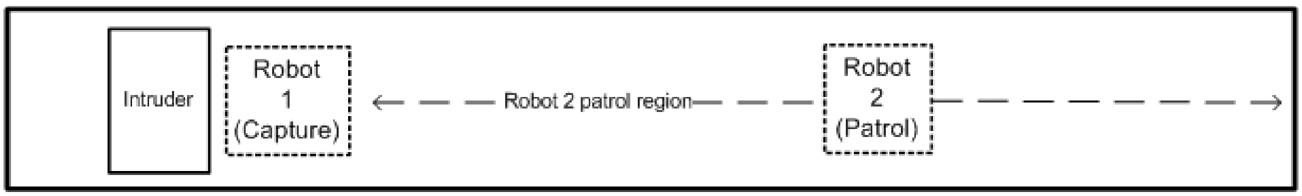

Figure 11 Third emergent behavior

Students in Hendrix College's Robotics course (Spring 2007) built, programmed, and tested over a dozen prototypes of these one-dimensional perimeter patrolling robots.

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