Intruder Preference and Route Selection: A GIS Data Approach

Griffin Mathews

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INTRUDER PREFERENCE AND ROUTE SELECTION: A GIS DATA APPROACH

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Executive Summary

The Department of Homeland Security (DHS) requested an Engineering Research and Development Center study incorporating modeling and simulation to determine the selection, amount, and optimal location of sensor suites along the U.S. Border. The study objective is to maximize the probability of detection and apprehension of illegal elements attempting to enter. A study on intruders and their preferences were conducted to create an intruder preference value map to determine the preferred intruder routes taken after crossing the border. The results of this research were integrated into another study on the selection and simulation of sensor suites.

Intruder context and preferences were researched to determine the relevant terrain characteristics to avoid detection after crossing the border. An initial scenario was created to include the remote Chinati Peak region (along the Texas-Mexico border) for dismounted intruders with no information on current sensors. Geospatial data representing terrain characteristics and metadata of the region were combined on a common value scale based on decision analysis techniques using the ArcGIS Python library (ArcPy) to create an intruder preference map. The weights were adjusted to represent different types of intruders or intrusion scenarios.

The intruder preference map was then used to create routes for intruders in the Chinati peak region. Starting locations for intruders were created based on the U.S.-Mexico border and ending locations were created an arbitrary distance away, e.g., 30 miles. The ArcGIS Distance Accumulation function was used to create a least-cost route from each starting point to each ending point based on the intruder preference map. The mesh of probable routes was then output to the sensor selection and simulation model for hot spot analysis. A sensitivity analysis was then conducted by changing the weights of the inputs into the intruder preference map to examine the flexibility of capturing intruder preferences.

Prioritized future work will include new areas of analysis other than the Chinati Peak region, new scenarios, and improvements on the ArcPy model. An automated method for the creation of starting and ending points should be created. A new scenario incorporating the use of vehicles while crossing should be implemented. Obstacles should be incorporated directly into routing rather than using weights. Continued research on quantifying intruder behavior, motivation, and preferences should also be conducted. Corridor analysis and other stochastic approaches should be considered to add uncertainty to the preferred intruder routes.
1. Introduction

Border security has become an increased concern in the United States in recent years. The 7,000 miles of land borders with Canada and Mexico [1] are an important economic gateway for the travel and trade of trillions of dollars each year. Safe and lawful entry into the country is enforced by the government to prevent access to those who attempt to illegally enter. The border security departments are continually improving their methods of detection and apprehension of illegal entities. This study focuses on a method of predicting intruder behavior and routes as they attempt to cross the border.

2. Problem Definition

This section begins with a description of the overall project’s context. Background research on intruder behavior is then described, followed by a review of system requirements. Finally, the methodology for incorporating GIS data and value modeling is described.

2.1. Project Context

The United States Customs and Border Patrol (CBP) of the Department of Homeland Security (DHS) works to protect and secure the borders of the U.S. from the “illegal movement of weapons, drugs, contraband, and people while promoting lawful trade and travel” [1]. Currently, CBP deploys various technologies to enforce hundreds of U.S. laws and regulations along the border. Although the U.S. has increased its priority on border security, Transnational Criminal Organizations (TCO) continue to adapt their drug productions, smuggling methods, and routes. The CBP leads the interagency efforts preventing these types of illegal activities requiring increased efforts to develop new technologies, methodologies, training, infrastructure, and facility investments [2]. Using System Engineering techniques, a study incorporating modeling and simulation has been conducted to determine the type, quantity, and optimal placement of sensor suites along the U.S. border to maximize the probability of detection and apprehension of illegal elements attempting to enter. This research develops methods for predicting the routes of intruders in remote sections after crossing the border.

2.2. Background Research on Intruders and Border Security

Unsurprisingly, little published research was found related to intruder routes and sensor selection for border security as this problem is a national security concern. However, some
publications provide information on the intruders that were apprehended. The socio-economic and political context of intruders typically fall into at least one of three categories [3]:

<table>
<thead>
<tr>
<th>Category:</th>
<th>Description:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic Opportunity</td>
<td>Crossings of those who desire to relocate to the U.S. to find work. This is typically 2/3 of the attempted crossings. [4]</td>
</tr>
<tr>
<td>Smuggling</td>
<td>Crossings of those who are attempting to move illegal goods across the border.</td>
</tr>
<tr>
<td>Terrorist Activity</td>
<td>Crossings of those with the intent of attacking the nation.</td>
</tr>
</tbody>
</table>

The socio-economic context of an intruder can influence the method and routes taken for each attempt at crossing. For example, many attempting to cross for economic opportunity will attempt to cross again after being deterred [5]. Most migrants crossing (~90%) will employ smugglers to assist in crossing, typically in small groups of 3-4 at a time [5]. Smugglers will be more experienced by crossing the border multiple times and know how to avoid detection more than a migrant. Due to this variability, it is difficult to know where and how an intruder will cross the U.S. border (~3,500 miles in total [6]).

Another problem exists when attempting to determine the routes, preferences, and characteristics of those crossing the border. The only source of data on border crossings is from those who are detected and/or apprehended. Entities are crossing the border who are never detected and/or apprehended. Therefore, the total number of attempted crossings are unknown and result in entities with unknown preferences, methods, objectives, and characteristics not captured in this research.

2.3. Stakeholder and Requirements Analysis

A prediction of the potential route’s taken by intruders after crossing the border is critical to determining the optimal placement of sensors. However, intruders have different motivations, objectives, and preferences for crossing the border. This can result in significantly different decisions for route selection.
Intruders may have some level of knowledge of sensors, obstacles, and other detection/apprehension mechanisms used by border patrol agents, influencing the route taken. The method of traversal (walking vs. vehicle use), weather, and terrain characteristics will also influence the route selected. To determine the preferred routes for an intruder it is assumed they attempt to minimize the probability of detection and maximize safety, ultimately resulting in the probability of a successful intrusion.

The influence diagram in Figure 1 displays the relationships between elements affecting an intruder’s decision (blue boxes) while crossing the border. Calculated uncertainties (green circles) such as weather, terrain characteristics, and the method of transportation are known by the intruder and influence the time of day and routes taken. For this analysis, no knowledge of sensors is included in modeling intruder preferences. The selection of a route and time of day will influence the duration of travel, probability of detection, and safety along the route. The duration of the route will influence the probability of detection and safety of the route, signified as an objective by the orange hexagon. The probability of detection and safety along the route will influence the main objective: the probability of a successful intrusion.

This research identifies potential preferred intruder routes based on terrain characteristics captured in GIS data and metadata for a specified area of analysis. Possible starting points and ending points for the intruder must be created. These points should be derived from geographical
context based on background research on the area of interest. Once the route(s) are calculated they must be output into a module for sensor suite simulation and selection.

2.4. GIS Methodologies

Using the ArcGIS software suite as the modeling platform, we created a quantitative model using geospatial data and metadata. ArcGIS Pro contains a model builder feature allowing for the automation of several sequential geospatial analysis tools. It also supports exporting these models into Python scripts using ArcPy, an ArcGIS Python Library. These functions have significant flexibility and can compute very complex processes with very large amounts of data. Also, ArcGIS Pro provides outputs to visualize the intruder preference map and intruder routes. Decision analysis techniques such as an additive value model [7], modified for ArcGIS, are used to capture the complexities of intruder’s decision preferences over the terrain.

2.5. Intruder Preference Value Modeling

As an intruder moves from the starting point to the ending point, they choose (consciously or subconsciously) the next locations they will move through based on their preferences and objective(s). The area an intruder moves through to reach their destination can be divided into discrete pixels at a relevant scale (5m, 10m, 30m, 50m, etc.). Each pixel can be assigned a value based on the intruder’s preference for a specific terrain characteristic at the unique pixel cell. For example, the speed of movement can be assigned a value between 1 (fastest) and 10 (slowest) in every cell to represent the ability for an intruder to move through the location.

Once relevant terrain characteristics for the scenario are selected and given a value representing the intruder’s preferences, they can be normalized and combined with weights (measuring the importance of each characteristic) to create a combined preference raster using the additive value model. The combined preference raster will be used to run a least-cost optimization model to determine the optimal route for an intruder based on the intruder preference map.

---

i 5 meters per pixel were used for this analysis.

ii A scale of 1 being the most preferred and 10 being the least preferred is selected so a least-cost tool can be used for creating routes. The least-cost route then relates to the most preferred route an intruder could take.

iii A raster in Geographical Information Systems (GIS) is like a digital photograph (where each pixel is given a color value). Instead of a color, each cell in a raster is given at least one alphanumerical value (from a single number to a written description). Each cell can have multiple values for different characteristics.
The accumulative least-cost map is created by converting the center of each cell into a node and connecting each node to its 8 adjacent neighbors. The distance for moving from one adjacent node to the next (Figure 2), accumulatively from one node to the next (Figure 3), and diagonally from one node to the next (Figure 4) is calculated with the geographical distance and cell cost in Figures 2-4.

Accumulative costs to move between the source nodes are calculated iteratively. The nodes neighboring the source node are calculated first based on the Cost Raster (Figure 5) and the least-cost node is selected (Left picture Figure 6). The neighbors for the least-cost node are calculated and the process is repeated for every node in the raster. Once every node is calculated, the accumulative least-cost raster (Right picture Figure 6) has been calculated and the optimal accumulative least-cost route can be created.\(^\text{iv}\)

\(^{\text{iv}}\) The cost-distance functions have been updated by ESRI. Explanations are based off the legacy distance toolkit. Distance Accumulation and Optimal Path as Line are calculated slightly differently, but ESRI has not released documentation of the updated formulations and calculations. The tool’s functionality remains quite similar. [13]
The source raster shows one starting point (the cell with number 2) and three possible ending points (the cell with number 1). The cost raster contains a cost between 1 and 10 to move through each cell, representing an intruder’s preferences. [8]

Figure 5 – The source raster shows one starting point (the cell with number 2) and three possible ending points (the cell with number 1). The cost raster contains a cost between 1 and 10 to move through each cell, representing an intruder’s preferences. [8]

The least-cost cell is selected for each iteration. Once every cell is calculated the least-accumulative cost raster has been calculated and the optimal accumulative least-cost route can be created. [8]

Figure 6 - Costs to move from the source cells are calculated iteratively. The least-cost cell is selected for each iteration. Once every cell is calculated the least-accumulative cost raster has been calculated and the optimal accumulative least-cost route can be created. [8]

The route created using the Optimal Path as Line tool will represent the preferred route for an intruder from the starting location to the ending location. It is the optimal route assuming a completely logical decision process was used. Any erratic behavior by an intruder could cause the route to become obsolete. To avoid this disadvantage, multiple routes from different starting and ending points should be created as a mesh network of routes\(^\text{v}\). It should be repeated for multiple starting and ending locations to develop a mesh of possible routes.

3. Solution Design

This section describes the overall model development process and elements for an intruder preference map, routing, and output into subsequent models.

3.1. Intruder Preference Map for Predicting Illegal Element Routes

There are four main inputs into the model (described in detail in Section 3.3): terrain characteristics, scenario selection, intruder preference measures, and relative weights for the measures. The inputs are used in ArcPy to create a preference map, subsequently used to create preferred intruder routes. The model will output a preference map and routes for the sensor selection and simulation models. A flow diagram of the model is in Figure 7.

\(^v\) The mesh network of routes will be used for Hot-Spot analysis as part of the Sensor Selection and Simulation model.
Figure 7 – Flow Diagram of the model. GIS data and intruder scenarios are input into ArcPy. ArcPy normalizes the measures, creates a risk map, and calculates the least-risk route for the intruder. The risk map and routes are then fed into the sensor optimization and selection model.

Input into the model will be based on a predetermined scenario of analysis including:

- Terrain Characteristics in the form of GIS Data
- A selected scenario including an area of analysis, method of transportation, time of day, temperature, and starting/ending locations
- GIS data and metadata measures for intruder preferences
- Relative measure weights for intruder preferences.

Depending on the scenario the location of interest, GIS data, and terrain characteristics will change. New GIS data might be required depending on the terrain and intruder preferences in the new location of interest.

Once the input data is collected from SAGE\(^vi\), it will be fed into the ArcPy implementation of ArcGIS where measurements of intruder preferences are normalized and combined to create an intruder preference map. The intruder preference map is then used to create routes for an intrusion based on the starting and ending locations, creating a mesh of possible routes in the specified analysis area. The routes and the preference map are subsequently analyzed in the sensor selection model.

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\(^vi\) See 4.2
4. Scenario Implementation

This section first selects a basic intruder scenario including the area of analysis and intruder characteristics. The creation of the intruder preference map and preferred intruder routes are then explained. Finally, the results of a sensitivity analysis are reviewed and an explanation of feeding the model’s output into subsequent models is given.

4.1. Selected Intruder Scenarios

Seven categories of intrusion characteristics were created to represent the most probable factors affecting an intruder\textsuperscript{vii}. Each category has several possible selections resulting in a high number of unique scenarios that can be analyzed. A basic scenario was selected from each option to simplify the complexities of analyzing multiple scenarios when building the model. Each blue box in Figure 8 represents one of the seven categories for scenario development. Underneath the blue boxes are the options for each category. One option for each category must be selected to create a complete scenario.

![Figure 8 - Possible intruder scenarios and options](image)

The routing category represents an intruder’s objective while crossing, ultimately affecting the measurement weights. Speed or safety can be prioritized by increasing the weights for the measurement.

\textsuperscript{vii} Background research did not provide a clear methodology for selecting or measuring intrusion factors so these are hypothesized factors. They should be updated with more background research.
The Chinati Peak region, shown in Figure 9, was selected as the initial area of analysis as the region because it is considered remote, with little to no border security infrastructure. The time of intrusion was set to day to avoid complexities with night travel. Walking, one of the main methods of traveling and the least complex to model was selected as the intrusion method. Adverse weather conditions were not included to reduce the complexity of modeling. Intruders were assumed to have no level of information on the sensors. Four terrain characteristics: obstacles, landcover, slope percent, and speed were selected and equally weighted (25%)\textsuperscript{viii}.

4.2. Explanations of GIS data and Meta Data

GIS data for the Chinati Peak region is acquired from SAGE, an effort by the Army Geospatial Center to provide geospatial data for analysis [9]. All data sources used in this research are in Table 1 with descriptions and sources for each file.

Table 1 – GIS Data with descriptions and sources.

<table>
<thead>
<tr>
<th>Data Name</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCM_DISMOUNT_50_6kph</td>
<td>Raster dataset with the speed an entity can move across the area while dismounted (no vehicles). Unit: kilometers per hour</td>
<td>SAGE</td>
</tr>
</tbody>
</table>

\textsuperscript{viii} Background research has no data on measuring terrain characteristics and intruder preferences. No relation between characteristics and preferences are known.
### LandCover_VISNAV
Raster dataset with the various types of land an intruder might cross.

### Obstacles
Raster dataset with the types of obstacles an intruder would typically avoid while traveling across the area.

### SLP_Percent
Raster dataset with the slope of the cell. Unit: % (rise/run)

### SLP_Degree
Raster dataset with the slope of the cell. Unit: ° (degree)

### HillShade
Raster dataset with the coverage provided by raised ground (hills, mountains, ravines, cliffs, etc.)

### Mexico_and_US_Border
Feature class dataset with a line representing the border between the United States and Mexico.

#### 4.3. Intruder Preference Map Creation

Once the GIS data has been collected in raster format it must be combined to a raster representing all intruder preferences. Each raster cell has a specific value attributed to it, which is used to measure the preferences of the intruder for the area. Combining multiple rasters requires the values to be normalized\(^x\) to the same scale. Each input raster was assigned a specific value from 0-10, where 0 is the most preferred for an intruder, and 10 is least preferred for an intruder. To assign values, the ArcGIS Reclassify tool \(^{[10]}\) is used on the “VALUE” field for each raster, with missing data (cells with no value) set to “NODATA” and given either a value of 0 or 10 depending on the intruder’s preference. Four of the GIS Data sets were converted into a value scale.

Every continuous reclassification range is automatically calculated in the ArcGIS software to create equally spaced intervals\(^x\). As background research continues it might be required to change the intervals to be unequally spaced based on the distributions of preferences. For data sets where the data a discrete, no intervals are required. Value scales, including NODATA values, are provided in Tables 2-5. The reclass value in each table represents

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\(x\) HIFLD: [https://hifld-geoplatform.opendata.arcgis.com/datasets/mexico-and-us-border](https://hifld-geoplatform.opendata.arcgis.com/datasets/mexico-and-us-border)

\(x\) Normalization converts values to a common scale without changing the relative relationships between values.

\(xi\) For example, if the values are reclassified into 10 equal intervals, each interval will contain 10% of the data.
the level it is preferred by an intruder. The original or lower/upper-value columns represent the
original data value in the raster data set.

*Table 2 – Reclassification Values for CCM_DISMOUNT_50_6kph. The original values represent how fast an intruder
can move in kilometers per hour.*

<table>
<thead>
<tr>
<th>Lower Value</th>
<th>Upper Value</th>
<th>Reclass Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.503674</td>
<td>10</td>
</tr>
<tr>
<td>0.503674</td>
<td>1.007348</td>
<td>9</td>
</tr>
<tr>
<td>1.007348</td>
<td>1.511023</td>
<td>8</td>
</tr>
<tr>
<td>1.511023</td>
<td>2.014697</td>
<td>7</td>
</tr>
<tr>
<td>2.014697</td>
<td>2.518371</td>
<td>6</td>
</tr>
<tr>
<td>2.518371</td>
<td>3.022045</td>
<td>5</td>
</tr>
<tr>
<td>3.022045</td>
<td>3.525720</td>
<td>4</td>
</tr>
<tr>
<td>3.525720</td>
<td>4.029394</td>
<td>3</td>
</tr>
<tr>
<td>4.029394</td>
<td>4.533068</td>
<td>2</td>
</tr>
<tr>
<td>4.533068</td>
<td>5.036742</td>
<td>1</td>
</tr>
<tr>
<td>NODATA</td>
<td></td>
<td>10<strong>xi</strong></td>
</tr>
</tbody>
</table>

*Table 3 – Reclassification values for Obstacles. The reclassed values are arbitrary. Built-Up Areas (cities) would
increase the chance of detection. Steep Terrain and Swamps are difficult to travel across.*

<table>
<thead>
<tr>
<th>Original Value</th>
<th>Description</th>
<th>Reclass Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>310</td>
<td>Water</td>
<td>1</td>
</tr>
<tr>
<td>320</td>
<td>Forest</td>
<td>2</td>
</tr>
<tr>
<td>390</td>
<td>Swamp</td>
<td>8</td>
</tr>
<tr>
<td>330</td>
<td>Steep Terrain</td>
<td>9</td>
</tr>
<tr>
<td>350</td>
<td>Built Up Area</td>
<td>10</td>
</tr>
<tr>
<td>NODATA</td>
<td></td>
<td>0<strong>xiii</strong></td>
</tr>
</tbody>
</table>

*Table 4 – Reclassification values for Slope Percent. Slope percent is the percent rise over run in the cell.*

**xi** No speed value means it is slow/impossible for an intruder to cross, which is not preferred.
**xiii** The absence of obstacles is preferred for an intruder.
<table>
<thead>
<tr>
<th>Lower Value</th>
<th>Upper Value</th>
<th>Reclass Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>30</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>50</td>
<td>60</td>
<td>6</td>
</tr>
<tr>
<td>60</td>
<td>70</td>
<td>7</td>
</tr>
<tr>
<td>70</td>
<td>80</td>
<td>8</td>
</tr>
<tr>
<td>80</td>
<td>90</td>
<td>9</td>
</tr>
<tr>
<td>90</td>
<td>1170</td>
<td>10</td>
</tr>
<tr>
<td>NODATA</td>
<td></td>
<td>0\textsuperscript{xiv}</td>
</tr>
</tbody>
</table>

\textit{Table 5 – Reclassification values for LandCover_VISNAV. Each value represents the type of land in each cell.}

<table>
<thead>
<tr>
<th>Original Value</th>
<th>Description</th>
<th>Reclass Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deciduous Forest</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Evergreen Forest</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Grassland</td>
<td>3</td>
</tr>
<tr>
<td>30</td>
<td>Orchards</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>Water</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>Agriculture, Other</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Scrub/Shrub</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>Barren/Sparsely Vegetated</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>Wetland, Permanent Herbaceous</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>Urban/Built Up</td>
<td>10</td>
</tr>
<tr>
<td>NODATA</td>
<td></td>
<td>10\textsuperscript{xv}</td>
</tr>
</tbody>
</table>

\textsuperscript{xiv} No slope is preferred for an intruder.
\textsuperscript{xv} Unknown land cover types are not preferred
Figure 10 shows an overlay of the intruder preference map over satellite imagery of the Chinati Peak region. Each cell has a value associated with it, representing the combined normalized values of the input rasters. Preferred cells are given a lower value and non-preferred cells are given a higher value.

**Figure 10 - A comparison of satellite imagery and the normalized, combined values of the intruder preference map.**

### 4.4. Preferred Intruder Routes Creation

#### 4.4.1. Starting and Ending Points

After the intruder preference map is created, it is used to create desirable intruder routes. Starting and ending points for the Chinati Peak region were arbitrarily created based on the Mexico-U.S. border. 50 starting points were created by the ArcGIS Feature to Point tool\textsuperscript{xvi} by inputting a feature layer\textsuperscript{xvii} consisting of the border in the area of analysis. The border layer was then copied with the Copy Feature tool\textsuperscript{xviii}. The copied layer was moved ~30 miles northeast to the edge of the Chinati Peak region to represent the ending location. The copied layer was then converted to points using the Feature to Point tool\textsuperscript{xx} to create 10\textsuperscript{x} ending locations. Figure 11

\textsuperscript{xvi} The “Percent” option is used and set to 2%.
\textsuperscript{xvii} Documentation of Feature Layers can be found at: https://pro.arcgis.com/en/pro-app/help/mapping/layer-properties/feature-layers.htm
\textsuperscript{xviii} The layer cannot be simply copied and pasted in the contents panel and subsequently edited. Each layer in the contents panel in ArcGIS retains its connection to the original data source. If you copy and paste a layer and then edit the copied layer, it will also edit the original layer. Using the Copy Feature geoprocessing tool will allow the copy and editing of a unique layer with no connection to the original data source.
\textsuperscript{xx} The “Percent” option was used, set to 10%.
\textsuperscript{xx} The selection of 10 ending locations was arbitrary, based on filling the area of analysis from the map.
shows the sequence of converting the U.S.-Mexico border lines into starting and ending locations.

![Sequence of converting U.S.-Mexico border lines](image)

*Figure 11 – Sequence of taking a feature class with the U.S.-Mexico border, copying and transposing it ~30 miles away from the border, and converting to points.*

### 4.4.2. Spatial Analyst Toolkit

The intruder preference map and intruder starting points were input into the distance accumulation tool\[xii\]. The distance accumulation tool outputs the distance accumulation raster and distance backlink raster based on the starting point. These rasters are input into the Optimal Path as Line tool along with the ending points to create the optimal route for an intruder. The Optimal Path as Line tool is set to iterate over each ending point in the ending points feature class using “OBJECT ID” as the destination field and “EACH_CELL” as the path type. The outputted optimal path is then appended into a feature class.

All the tools are run in a loop for each starting point to ensure a unique distance accumulation and distance backlink are created for routing. This results in an optimal route to every ending point from every starting point, creating a mesh network of routes for the area of analysis as shown in Figure 12.

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\[xii\] The Distance Accumulation tool was originally run in ArcGIS model builder to populate the default values for horizontal factor, vertical factor, and distance method. Any parameter not used was input as: “"."
4.5. Integration with Sensor Selection

Once the routes are created, they are then output to the Sensor Selection and Simulation model. The feature class file containing the routes and the intruder preference map raster must be transferred from the project folder to the model. The feature class can be exported inside ArcGIS by selecting Data -> Export Features. The feature class will be used in ArcGIS, so no modifications are required.

4.6. Sensitivity Analysis

A sensitivity analysis was conducted to examine the ability of the model to capture different intruder preferences. The weights (originally set to equal weightings of 25%) were changed to prioritize the speed of movement across the border. This represents intruders who are more interested in minimizing the duration of travel than the safety of the routes. Figure 13 shows a significantly different intruder preference map and routes resulting from the change in weights.
5. Future Work

This section describes a prioritized list of future work required to improve the model. Suggested improvements to the model’s methodology are also explained.

5.1. Future Work

5.1.1. Areas Other Than Chinati Peak

The end goal of the research is the ability to select sensors at any point of the border, requiring the ability to create intruder preference maps and routes in multiple areas of analysis. New areas of analysis should be selected and analyzed with the tools to test the model’s flexibility.

5.1.2. Automating Starting and Ending Points

The current methodology requires the manual creation of intruder starting and ending points. To allow for dynamic input and flexibility to run in multiple areas these points should be automatically created. It should be possible to take the border feature class, convert to a specified number of points, create a copy for the endpoints, and move the endpoints a specified distance away from the border. The direction the endpoints will be moved should be on the
American side of the border. The distance will also vary based on the scenario and area of analysis.

5.1.3. New Intruder Scenarios

Multiple new scenarios should be examined to test the model’s flexibility in capturing different types of intruder’s preferences. The characteristics from Figure 8 and the area of analysis should be modified for different intruders and intrusion scenarios. This may uncover assumption errors in measuring intruder preferences/terrain characteristics as well as errors in the modeling process. The process for creating the intruder preference map and preferred intruder routes should ultimately be able to be created for any region on the U.S. Border.

5.1.4. Incorporation of Obstacles in Routing

As intruders cross the border area there are regions of terrain inaccessible to traversal, especially with the inclusion of vehicles (For example, a car would not drive through water). In the creation of routes in the current model, obstacles are penalized in the intruder preference map with a high value (not preferred). This does not completely prevent intruders from traversing over inaccessible terrain, possibly resulting in inaccurate routes. The inaccurate routes can be rectified by using the in_barrier_data parameter in the Distance Accumulation ArcGIS tool. The parameter allows for a raster or feature layer containing inaccessible terrain barriers to be input into the tool.

5.1.5. New Terrain Characteristics and Measurements

In the process of creating a basic model, only four terrain characteristics were used to measure intruder preferences. As well, research was unable to provide quantitative methods of measuring the impact terrain characteristics have on intruder behavior. Continued research on relevant terrain characteristics and methods of measuring the characteristics should be done to better predict intruder routes.

5.1.6. Road Preference

Some intruders, especially those driving vehicles to cross the border, will prefer to move across roads or other pre-made trails. Some intruders will desire to avoid roads as roads could

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xxi Documentation of the Distance Accumulation Tool can be found at: https://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/distance-accumulation.htm
increase the probability of detection. The model does not currently incorporate any level of preference of roads into the creation of the intruder preference map. The preference map could be improved by adding a raster layer of roads, converted to a relevant value scale, and weighted for the analysis scenario.

5.2. Suggested Modeling Improvements

5.2.1. Machine Learning for Intruder Preferences and Terrain Characteristics

One of the main difficulties in data collection is the determination of relevant intruder preferences and terrain characteristics. Little research or data on the relation between these factors has been found. One hypothetical approach would be using Machine Learning to determine the terrain characteristics and intruder preferences by analyzing historical data on intruder routes. Relevant features can be recognized by taking known intruder routes, inputting several types of terrain data into the model, and training the model to recognize characteristics intruders prefer. Machine learning could also be used to predict intruder routes given bins of intruders based on their socio-economic and political context of crossing.

5.2.2. Stochastic Approaches

The current modeling process creates an intruder preference map and preferred intruder routes deterministically. However, human behavior is often erratic, illogical, and/or unknown. Therefore, uncertainty exists in the routes and map created. A stochastic approach to creating a preference map and routes could incorporate some of this unpredictable behavior. Simulating the most probable routes based on intruder preferences would capture some of the uncertainty in human behavior for the model.

5.2.3. Least-Cost Corridor

One major drawback of a single-line route predicting intruder behavior is the inability to capture uncertainty in the route. A mesh network of intruder routes is used to reduce and capture the variability in intruder behavior but is not perfect. An alternative method to route creation would be the use of a Least-Cost Corridor [11] as shown in Figure 14.

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xxiii A raster layer of roads and trails could be created by taking a road/trail network feature layer and using the feature to raster tool: https://pro.arcgis.com/en/pro-app/tool-reference/conversion/feature-to-raster.htm
A corridor would capture the range of routes an intruder could take from the starting point to the ending point based on a specified threshold. The threshold could be modified to allow for sensitivity analysis, increasing or decreasing the size of the corridor.

![Diagram of corridor and single preferred route comparison]

*Figure 14 A single preferred route compared to a preferred corridor. [11]*

6. Summary

We observed through the results of this study the use of terrain characteristics as a possible method for predicting intruder behavior using geospatial data. Preferred routes for intruders based on weighted measurements were inferred using ArcGIS Pro software and are used to determine the optimal placement of sensors through future modeling efforts. Intruder behavior is difficult to predict but through improved methods of measuring intruder preferences and modeling improved sensor placement can be used to better detect and apprehend intruders.

7. References


8. Appendix

8.1. Overall Task Swimlane Diagram

The figure below shows the overall framework for the integrated study on sensors. Each row represents different responsibility groups for the different functions of the overall project. For this paper’s research focuses on the row title “SAGE (ArcGIS)”. Each box represents a function, and the arrows represent data connections between the functions. For this research, input data is taken from SAGE, the data is passed to a function creating the intruder preference map, and then passed into a function creating the intruder routes. After this, the data from the “Build Routes” function is passed into the “Optimally Place Sensors Function”.

![Overall Task Swimlane Diagram](image-url)
8.2. ArcPy Intruder Preference Map and Routing Code

The ArcPy code for creating the intruder preference map and routes can also be found in the ERDC git hub.

```python
import arcpy

# Set Extent
arcpy.extent = "C:\Intruder Preference\ArcGIS Files\MF_Chinati_Peak_5m\FOUNDATION.gdb\MF_Chinati_Peak_5m"
from arcpy import env
from arcpy.sa import *

def Setup():  # Intruder Attractiveness Map and Routing Model
    # To allow overwriting outputs change overwriteOutput option to True.
    arcpy.env.overwriteOutput = True
    # Check out any necessary licenses.
    arcpy.CheckOutExtension("spatial")
    arcpy.CheckOutExtension("ImageAnalyst")

    # Set path of input rasters
    Intruder_Preference_Map = "C:\Intruder Preference\SensorMap.gdb\Intruder_Preference_Map"
    Intruder_Preference_Map_Clipped = "C:\Intruder Preference\SensorMap.gdb\Intruder_Preference_Map_Clipped"

    # Raw Data location reference
    CCM_Dismount_50_6kph = "C:\Intruder Preference\ArcGIS Files\MF_Chinati_Peak_5m\Mobility.gdb\CCM_Dismount_50_6kph"
    Obstacle_2 = "C:\Intruder Preference\ArcGIS Files\MF_Chinati_Peak_5m\FOUNDATION.gdb\obstacles"
    Slope_Percent_2 = "C:\Intruder Preference\ArcGIS Files\MF_Chinati_Peak_5m\FOUNDATION.gdb\SLP_percent"
    LandCover_VISNAV_2 = "C:\Intruder Preference\ArcGIS Files\MF_Chinati_Peak_5m\FOUNDATION.gdb\LandCover_VISNAV"

    # Create copy of previous Intruder Routes for backup
    Intruder_Preference_Map_Unique = arcpy.Copy_management(Intruder_Preference_Map, arcpy.CreateUniqueName(Intruder_Preference_Map))

    # Process: Reclassify_1 (Reclassify)
    weight1 = 0.7
    weight2 = 0.2
    weight3 = 0.05
```
weight4 = 0.05
print("Combining Rasters")
Intruder_Preference_Map_Unique = outreclass1*weight1 + outreclass2*weight2 + outreclass3*weight3 + outreclass4*weight4
print("Rasters Combined")
# Clip raster to region
# Every time I try to clip I raise error 999999: Unspecified error. Skipping.
# print("Clipping raster to extent")
# arcpy.Clip_management(in_raster, rectangle, out_raster, {in_template_dataset}, {nodata_value}, {clipping_geometry}, {maintain_clipping_extent})
# arcpy.Clip_management(in_raster=Intruder_Preference_Map_Unique, rectangle="512175.9321 3263651.8228 596767.2498 3360649.6227", out_raster=Intruder_Preference_Map_Clipped, in_template_dataset=Selected_Region, nodata_value="3.4e+38", clipping_geometry="ClippingGeometry", maintain_clipping_extent="MAINTAIN_EXTENT")
# print("Raster clipping completed")
# Intruder_Preference_Map_Clipped.save("C:\Intruder_Preference_Map")
print("Saving Intruder Preference Map")
Intruder_Preference_Map_Unique.save("C:\Intruder_Preference_Map")

# In[176]: WeightedOverlay(WOTable(
#       
#        ["speed", 70, 'VALUE', outreclass1],
#        ["obstacles", 20, '', outreclass2],
#        ["slope", 5, '', outreclass3],
#        ["landcover", 5, 'VALUE', outreclass4],
#     ],[0,0,0,0]))
# outsuit.save("C:/sapyexamples/output/outsuit.img")
print("Setup Completed! Intruder Preference Map can be found at: " + str(Intruder_Preference_Map_Unique))
Setup()

def Routing(): # Intruder Routing v3
    # For debugging
    import time
    # To allow overwriting outputs change overwriteOutput option to True.
    arcpy.env.overwriteOutput = True
    # Check out any necessary licenses.
    arcpy.CheckOutExtension("spatial")
    IntruderStartingBorderPoints = "C:\Intruder Preference\SensorMap\SensorMap.gdb\Condensed_Intruder_Start_Points"
    IntruderEndingPoints = "C:\Intruder Preference\SensorMap\SensorMap.gdb\Condensed_Intruder_End_Points"
    Intruder_Preference_Map = "C:\Intruder Preference\SensorMap\SensorMap.gdb\Intruder_Preference_Map"
    Intruder_Routes = "C:\Intruder Preference\SensorMap\SensorMap.gdb\Intruder_Routes"
    Selected_Region = "C:\Intruder Preference\ArcGIS Files\MF_Chinati_Peak_5m\FOUNDATION.gdb\MF_Chinati_Peak_5m"
    # Clip to extent (NOT IMPLEMENTED)
    # This should remove the raster outside of the Chinati Peak region when displayed on ArcGIS Pro
    # print("Clipping intruder preference map")
    # arcpy.Clip_management(in_raster=Intruder_Preference_Map, rectangle="512175.9321 3263651.8228 596767.2498 3360649.6227", out_raster=Intruder_Preference_Map_Clipped, in_template_dataset=Selected_Region, nodata_value="3.4e+38", clipping_geometry="ClippingGeometry", maintain_clipping_extent="MAINTAIN_EXTENT")
    # print("Intruder preference map clipped")
    # Create copy of previous Intruder Routes for backup
    # print("Creating copy")
    Intruder_Routes_Unique = arcpy.Copy_management(Intruder_Routes, arcpy.CreateUniqueName(Intruder_Routes))
    # Delete previous Intruder Routes
    print("Removing previous routes")
    arcpy.DeleteFeatures_management(Intruder_Routes_Unique)
    # Loop through every starting point

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numRows = arcpy.GetCount_management(IntruderStartingBorderPoints)
with arcpy.da.SearchCursor(IntruderStartingBorderPoints, ['SHAPE@', 'OBJECTID']) as cursor:
    for row in cursor:
        # NOTE: The print statement will be incorrect if OBJECTID does not start at 1
        print('Point: {0} of {1}'.format(row[1], numRows), end = ' 
')
        # Process: Distance Accumulation (Distance Accumulation)
        Distance_Accumulation_Raster = "C:\\Intruder Preference SensorMap.gdb\Distance_Accumulation_Raster"
        Accumulation_Backlink = "C:\\Intruder Preference SensorMap.gdb\Accumulation_Backlink"
        Out_source_direction_raster = "C:\\Intruder Preference SensorMap.gdb\Out_source_direction_raster"
        Out_source_location_raster = "C:\\Intruder Preference SensorMap.gdb\Out_source_location_raster"
        print("Current Process: Distance Accumulation", end = ' 
')
        #DistanceAccumulation(in_source_data, {in_barrier_data}, {in_surface_raster}, {in_cost_raster}, {in_vertical_raster},
        {vertical_factor}, {in_horizontal_raster}, {horizontal_factor}, {out_back_direction_raster}, {out_source_direction_raster},
        {out_source_location_raster}, {source_initial_accumulation}, {source_maximum_accumulation}, {source_cost_multiplier},
        {source_direction}, {distance_method})
        arcpy.gp.DistanceAccumulation_sa(row[0], Distance_Accumulation_Raster, Intruder_Preference_Map, "", "", "", "",
        "BINARY 1 -30 30", "", "BINARY 1 45", Accumulation_Backlink, Out_source_direction_raster, Out_source_location_raster, "", "", "",
        "", "", "PLANAR")
        print("Current Process: Optimal Path as Line", end = ' 
')
        # Process: Optimal Path As Line (Optimal Path As Line)
        Optimal_Intruder_Route = "C:\\Intruder Preference SensorMap.gdb\\Optimal_Intruder_Route"
        # OptimalPathAsLine(in_destination_data, in_distance_accumulation_raster, in_back_direction_raster, out polyline_features, destination_field, path_type)
        arcpy.gp.OptimalPathAsLine_sa(IntruderEndingPoints, Distance_Accumulation_Raster, Accumulation_Backlink, Optimal_Intruder_Route, "OBJECTID", "EACH_CELL")
        print("Current Process: Intruder Routes Appended", end = ' 
')
        # Process: Append (Append)
        Intruder_Routes_Unique = arcpy.Append_management([Optimal_Intruder_Route], Intruder_Routes_Unique, "", "", "",
        "")[0]
        print("Appended: " + Optimal_Intruder_Route + " 
")
        print("Done! Intruder routes can be found in: " + Intruder_Routes_Unique + " 
")
Routing()