Intelligent Agents for the Autonomous Identification of Organized Formations

Sanjeeb Nanda
SDS International Inc., Advanced Technologies Division
3403 Technological Avenue, Suite 7
Orlando, FL 32817
407-282-4432
snanda@sdslink.com

Sandeep Nanda
KrupaJal Engineering College
Bhubaneswar, Orissa India
(91) 674-255-7266
sandeepnanda4u@rediffmail.com

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ABSTRACT: *The advent of sophisticated electronic sensors has enabled military planners to monitor the position and movement of forces on a battlefield with remarkable precision. However, dispersion strategies employed by an adversary can clutter the battlefield with a seemingly unrelated mass of heterogeneous entities numbering in the hundreds or more. Under these circumstances it is difficult to visually identify even the larger organized units constituting an enemy force. Such information is vital to opposing planners in forecasting the likely objectives of each enemy unit within the context of the adversary's overall battle plan and devising effective countermeasures. In this paper we present a set of statistical methods that may be applied to determine the relative proximity of behavior between entities and their peers within a candidate formation using a specific set of metrics. Using these methods, a model can be constructed to infer the constitution of formations by partitioning a given force, with each partition comprised of entities with correlated behaviors.*

1. Introduction

Acute battlefield visualization capabilities are critical to achieving superior situation awareness [5], [6]. Visualizing organized formations of an adversary on a battlefield is a critical element in that set [1]. Projecting the trajectories of such formations can aid the identification of the significant objectives of the adversary and the formulation of plans to counter it. However, in spite of considerable advancements in the state of electronic surveillance and information processing, the task of visualizing them remains a cognitive challenge that continues to be performed by skilled human operators. Furthermore, the limit of human acuity generally restricts the number of entities that can be concurrently tracked to make such determinations with any accuracy. Consequently, the need for automated methods to track adversarial entities and interpret the structure within them is compelling. Motivated by this need, this paper presents a statistical model for inferring the constitution of formations based on the correlation of the behaviors of entities within them.

Although research using Dempster-Shafer theory provides considerable promise for identifying clusters in force aggregations [2][7], models using simulated annealing may have equal value [3]. In this paper we discuss a model that iteratively converges to a solution for the problem by randomly assigning entities to candidate clusters and determining the optimality of their membership based on a finite set of user-defined criteria. Before describing the model we propose to use for associating entities to formations, we formally state the following definitions and develop the theory based on them.

2. The Model

Let $E = \{e_1, e_2, \ldots, e_N\}$ be a set of entities in a formation with the position of entity e_i on the x-z plane of the right-handed 3D coordinate system being $p(e_i) = \{x_i, z_i\}$. Then the center of gravity of the formation is given by the position $\{x_G, z_G\}$, where $x_G = (x_1 + x_2 + \ldots + x_N)/N$ and $z_G = (z_1 + z_2 + \ldots + z_N)/N$. Note that the center of gravity is simply a non-weighted average of the positions of the entities. Fig. 1 displays the center of gravity using a formation comprised of three entities at the locations (0, 0), (7, 14) and (14, 10) represented by triangles. The center of gravity of this formation is given by the square at the location (7, 8).

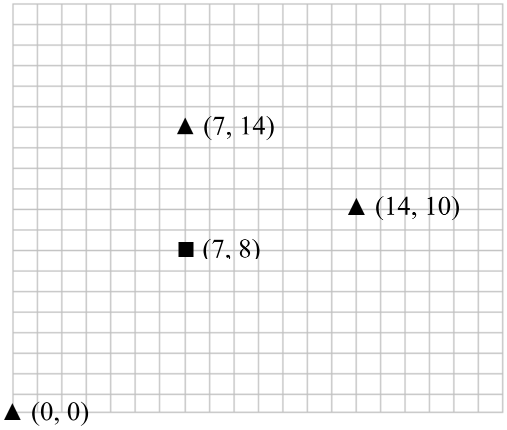

Fig. 1. A grid displaying three entities represented by solid triangles and their center of gravity represented by a solid square.

The center of gravity can be used as a representative of a formation to provide a sense of the position, speed, and heading of the formation by quantitatively averaging those parameters obtained for the various entities constituting it. Furthermore, we shall define the center of gravity of a formation relative to the point denoting the smallest x and z values for any entity in that formation. That point is denoted as the origin with coordinates (0, 0). This assumption is necessary to ensure that the center of gravity of a formation that is in motion does not change over time as long as the relative positions of its constituent entities remain invariant. Using this definition, we state the following set of criteria that may be used for determining the correlation of entities to formations.

(a) Proximity of an entity to the center of gravity of a formation.
(b) Proximity of the speed of an entity to the speed of the center of gravity of its group.
(c) Proximity of the direction of movement of an entity to the direction of movement of the center of gravity of its group.

The intuitive reasoning that motivates the choice of the aforementioned set of criteria is as follows. An entity is likely to be a member of a formation, if that entity's relative position with respect to (the center of gravity of) the formation is invariant for each tactical configuration of that formation, and/or its speed consistently matches the speed of (the center of gravity of) its formation, or its heading is fairly consistent with (the center of gravity of) its formation. Furthermore, we also want to show that if and when the position, speed or heading of the center of gravity of the formation changes there is a corresponding change in the position, speed and heading respectively of that entity. We start with the criterion that measures the distance of an entity to the center of gravity of a formation, and later show that this is substitutable by any of the other criteria. We now make the following set of intuitive observations.

> <u>Observation (i)</u> If a formation changes its configuration – and most likely its center of gravity – to execute a tactical goal, we can expect that, an entity within the formation has changed its position with respect to the center of gravity of the formation to execute a sub-task. An example of this scenario is where a platoon of tanks breaks up formation to flank an adversary and thereby changes its center of gravity. Then, a tank in one of the flanking units is likely to be at a distance from the center of gravity of its parent formation that is a function of the position of the center of gravity itself from the origin.

Fig. 2 illustrates the scenario mentioned in observation (i) in a limited setting using a formation comprised of two tanks T_1 and T_2. The hollow triangles Δ_1 and Δ_2 show the positions of the tanks T_1 and T_2 in a point in time in the past and the solid triangles $\blacktriangle_1$ and $\blacktriangle_2$ the current positions of those tanks respectively. The corresponding hollow and solid squares represent the center of gravities of the formation at the previous point and current point in time respectively. Note that the origin in the past is centered on the entity at (6, 16), and the origin at the current point in time is centered at the coordinates (4, 8), both designated by green-colored crosses. The arcs tipped with arrows display the paths followed by the tanks. Then, we observe that the center of gravity of the formation is initially at position (9, 16) that is at a distance of 3 from the origin while the entity on the right is at a distance of 3 from the center of gravity. Subsequently, the center of gravity of the formation at position (10, 9) is at distance of $\sqrt{37}$ from the origin while the entity on the right is at a distance of $\sqrt{37}$ from the center of gravity.

Unlike the previous example, an entity that is part of a formation may not necessarily change its distance from the center of gravity of the formation significantly whenever the center of gravity itself changes significantly or vice-versa. For instance, a set of tanks in an armored formation may be designated to mount a frontal assault while other tanks on the flanks of the unit execute a pincer movement. In that case, the change in distance between tanks in the center of the formation from the center of gravity of the formation is unlikely to be very significant. For example, Fig. 3 displays a formation of three entities at the locations (6, 14), (9, 18) and (12, 14), with their center of gravity shown by the hollow square. While the two entities on the flanks execute a pincer movement the tank in the center approached head on towards an adversary located on the southern end of the grid. Note from the final positions of the entities that, the change in distance of the entity in the center of the formation from the center of gravity is far lesser than that of its counterparts. However, such an entity is likely to retain its relative position within a formation and therefore, the distance of the entity from the center of gravity of its formation is always likely to be conservative. Conversely, entities on the flanks are likely to experience far greater changes in their distance from the center of gravity of their formations. From the preceding discussion we observe the following.

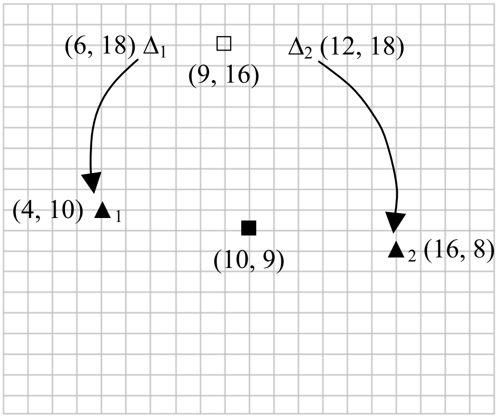

Fig. 2. A grid displaying the movement of two entities with their previous positions at Δ_1, and Δ_2, and their current positions at $\blacktriangle_1$ and $\blacktriangle_2$.

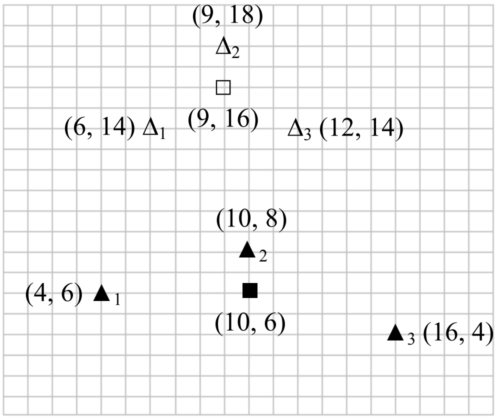

Fig. 3. A grid displaying the movement of three entities with their previous positions at Δ_1, Δ_2 and Δ_3, and their current positions at $\blacktriangle_1$, $\blacktriangle_2$ and $\blacktriangle_3$.

Observation (ii) If a formation does not change its configuration (and therefore its center of gravity) we can expect an entity within the formation to retain its position with respect to the center of gravity of the configuration. This is a fairly trivial observation.

Observation (iii) If an entity' mean distance from its formation's center of gravity is $f(d)$ when the formation's center of gravity is at distance d from its origin, then the expected value of the entity's distance from its formation's center of gravity when the formation's center of gravity is at distance d' from the origin, is $f(d')$ if d and d' are relatively close to each other. This is based on the assumption that, an entity within a formation can be expected to execute the same set of tactics assigned to it in a plan in future iterations of that plan, and thus maintain the same set of positions relative to the formation to execute its assigned set of tactics. Furthermore, by extension of this argument to all entities in a formation, we may expect the formation itself to have a configuration similar to that it used in the past, and therefore experience changes to its center of gravity similar to that in the past.

Note that, all the aforementioned observations state expectations of the events only and therefore those with a high probability of occurrence, but not with certainty. Using the aforementioned observations, we now define the mathematical framework necessary to quantitatively measure these criteria.

We may also expect the function $f(d)$ defining an entity's mean distance from its formation's center of gravity where d is the distance of the formation's center of gravity from the origin to be different for values of d lying in different intervals. This is based on the assumption that an entity's position with respect to its formation is likely to be unique to the specific tactic employed by its formation, which in turn is executed using a specific configuration with a unique center of gravity. For this reason, it would be intuitive to divide the sample space of all distances of the center of gravity of a formation from its origin into n intervals each of length d, d a positive integer, where each interval bounds the formation's center of gravity with specific configuration. Thus we have intervals of the form $[0, d)$, $[d, 2d)$, $[2d, 3d)$, … $[(n-1)d, nd)$. For each change in the center of gravity of the formation within the interval $[xd, (x+1)d)$, $0 \le x \le (n-1)$, we plot the frequency of the changes in distance of an entity from the center of gravity of its hypothesized formation.

Fig. 4 illustrates a case where the frequency of changes in distance of an entity from the center of gravity of its hypothesized formation is plotted as a function of distance ranging between say 0 to 10, 10 – 20, 20 – 30 meters and so on. Let us assume that this plot corresponds to changes in the center of gravity of the formation in the range of say 10 – 20 meters observed over 80 iterations. Let the mean value of this frequency distribution be υ, which in the case of the example equals 37.75 meters. Then, the standard deviation probability distribution is given by the value, $\sigma = \sqrt{(1/_N(\sum_{i=1}^{N}(x_i - \upsilon)^2)}$

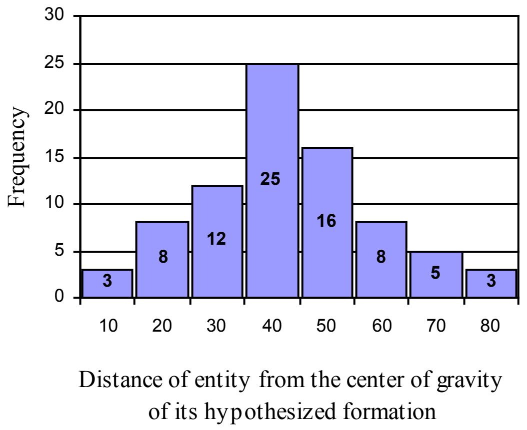

Fig. 4. A plot of the frequency of the observed distances of an entity from the center of gravity of its hypothesized formation.

In the case of the example $\sigma = 23.02$. We know that 68% fall within one standard deviation of the mean, 95% fall within two standard deviation of the mean, and 99.7% fall within three standard deviation from the mean. Thus, σ gives us a good indication of the frequency of events close to the mean. The lower the value of σ, the higher the number of events closer to the mean and vice-versa. Intuitively then, a lower value of σ indicates the likely existence of dependency between an entity and its hypothesized formation.

Observation (iv) Note that, each value of σ as defined in observation (iii) is evaluated for a corresponding distance of the center of that formation from its origin within an interval of the form $[xd, (x + 1)d)$, where $0 \leq x \leq (n - 1)$. Hence, based on observation (iii), it would be intuitive to reject an entity from inclusion into a hypothesized formation if the value of σ for that entity is significantly different from the average value of σ over all entities in that formation corresponding to a majority of intervals.

Observation (v) Once an entity has been rejected from its hypothesized formation, we select an alternate formation into which it may qualify, or create a new formation comprised of that entity alone. The formation into which the entity qualifies for membership is decided using a function comprised of the weighted sum of factors that include proximity to the candidate formation's center of gravity, velocity and directional heading. This is similar to the technique applied in Genetic algorithms for maximizing or minimizing the objective function.

Observation (vi) Up to this time we have used the criterion of "distance" to highlight all observations, but we can easily substitute criteria such as speed and directional heading to achieve similar results. For instance, we may measure the correspondence between values of pairs of metrics such as the speed of an entity and the corresponding speed of the center of gravity of its hypothesized formation. Similarly, we may measure the correspondence between values of the directional heading of an entity and the corresponding directional heading of the center of gravity of its hypothesized formation.

Using observations (i) through (vi), we can state the algorithm for identifying the inclusion of an entity into a hypothesized formation as given in Fig. 5. Let $c_i(e)$ define the value for entity e and $c_i(F)$ the value of the center of gravity of the hypothesized formation F containing e, in iteration i using criterion c. Let $c(F)$ denote the entire sample space of potential values for the formation F using criterion c.

```
while (simulation continues) do at time intervals of $\Delta t$
{
  Partition the likely values of $c(F)$ into $n$ partitions.

  for each entity $e$ in $F$ do
  {
    for partition $i \leftarrow 1$ to $n$ do
    {
      // Compute the new mean for $c(e)$
      $\upsilon \leftarrow (\upsilon \times (i - 1) + c_i(e))/i$;

      // Compute the new standard deviation for $c(e)$
      $\sigma \leftarrow \sqrt{(1/_i(\sum_{k=1}^{i}(c_i(e) - \upsilon)^2)}$

      // Computes the average of the standard
      // deviation for entity $e$
      $sigma[e] \leftarrow ((i - 1) \times sigma[e] + \sigma)/i$;
    }
  }

  // Compute the average of the standard deviation
  // for all entities and store it in $sigmaF$
  for each entity $e$ in $F$ do
  {
    if $sigmaF \leftarrow sigmaF + sigma[e]$;
    $mismatch[e] \leftarrow 0$;
  }
  $sigmaF \leftarrow sigmaF/|F|$;
```

```
  // Determine entities whose standard deviations exceed
  // the average for their formation by a threshold value
  // $T$. Count the number of such cases for $e$ using the
  // variable $mismatch[e]$
  for each entity $e$ in $F$ do
  {
    if $|sigma[e] - sigmaF[e]| > T$ then
      $mismatch[e] \leftarrow mismatch[e] + 1$;
  }

  // If number of mismatches exceeds the number of
  // criteria then we should reject the possibility of $e$
  // being a member of the formation $F$.
  if mismatch[$e$] > $|c|$ then
    reject $e$ from $F$;
}
```

Fig. 5. The algorithm to identifying the inclusion of an entity into a hypothesized formation.

3. Conclusions

The viability of the model presented in this paper is supported by the success of similar approaches in solving a variety of optimization problems. However, a drawback they all possess is the prolonged amount of time such models consume to converge to a steady state and yield a feasible solution. Nevertheless, their value is indisputable.

4. References

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5. Author Biographies

Mr. Sanjeeb Nanda is a research and development engineer with the Advanced Technologies Division of SDS International. His experience spans the areas of simulation, biometrics, parallel computing, and fault-tolerance in computing. He is currently pursuing a doctorate in Computer Science.

Mr. Sandeep Nanda is a lecturer at Krupajal Engineering College in India. His experience spans the areas of mathematical modeling, simulation and supercomputing.