A Procedural Approach to Route Planning for Dismounted Simulated Agents under Fire

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ABSTRACT

Modeling dynamic behavior of agents on a simulated battlefield allows analysts to accurately understand the effects of various technologies and tactics on the battlefield. Efforts by the Department of Defense have been successful in exploring the dynamic behavior of mounted entities like tanks and helicopters on simulated battlefields due to the large volume of physics based equations that dictate the behaviors of mechanical systems. These same simulations, however, fail to accurately represent the largest portion of combat operations in the real world—dismounted military operations. Over long distances and time frames, military movements can be sufficiently described by current models. Capability gaps exist when modeling Soldier movement over short, tactical distances when under fire. This paper proposes and documents the development of a tactical route agent to fill this gap by creating a series of costing mechanisms dealing with agent metabolic cost, exposure to the enemy, and risk of fratricide to determine realistic routes for agents engaged in combat.

Author Keywords

Combat Modeling and Simulation; Dismounted Combatants; Route Planning; Pandolf's Metabolic Equation; Line of Sight; Fratricide; EASE-DMF; LTF; COFFEE;

ACM Classification Keywords

C.2.4 DISTRIBUTED SYSTEMS; D.1.1 FUNCTIONAL PROGRAMMING; I.2.8 PROBLEM SOLVING, CONTROL METHODS, AND SEARCH; I.6.1 SIMULATION AND MODELING

INTRODUCTION

An infantry platoon conducts a combat patrol by foot along the side of a ridge when it comes under fire from an enemy position on the top of the ridge 200 meters away. After gaining fire superiority with an initial base of fire, 2nd squad is ordered to move up the hill to envelop the position and ensure the destruction of the enemy element. 2nd squad moves to the far left of the platoon's position and begins to bound up to its final assault position in the immediate vicinity of the enemy position. While moving, the squad bounds in its teams, taking care to minimize exposure to the enemy and avoid the possibility of fratricide from friendly weapons currently trained in their direction.

Contemporary simulation systems such as One Semi Automated Forces (OneSAF), Infantry Warrior Simulation (IWARS), and others used by various agencies within the Department of Defense (DoD) model vehicle movement quite well, but neglect the realities of dismounted combat [1]. This neglect prevents simulation systems from being able to describe operations like that described above and illustrated in the OV-1 in figure 1.

While all simulation "models (are) by nature…simplified and therefore fictional or idealized representation[s]" of the real item that they wish to describe, there must be a reasonable level of realism for the model to have any utility [2]. As modeling and simulation (M&S) activities become a greater part of the acquisition and operations research (OR) domains, our models must better approximate the effects of real world factors on soldier and equipment behavior. Future simulation platforms must be able to adapt to model all aspects of the systems they are depicting to have any merit.

In this document, we discuss the design of a new simulation model for dismounted infantry behavior referred to as the tactical route agent or TaRA. TaRA compares factors of metabolic expenditure, exposure to the enemy, and fratricide risk to procedurally generate short distance routes for simulated entities under fire. When completed TaRA will be able to combatant movement behaviors on the battlefield whenever called upon by a host simulation system. TaRA is currently being developed within the Component Object Framework for Fast Execution and Evaluation (COFFEE) as part of the Executable Architectures for Systems Engineering—Distributed Modeling Framework (EASE-DMF) project being led by the Department of Systems Engineering (DSE) at the United States Military Academy (USMA) and the Army's Simulation, Training and Technology Center in Orlando (STTC Orlando) as a standalone model to be accessed by other simulation platforms attached to the project[3].

To explain TaRA's development, this paper focuses primarily on the metabolic aspects of the model and is organized in the following manner. The second section of this document summarizes the research and theories supporting TaRA's development and proposes a usable metabolic model. The third section describes TaRA's architecture and the implementation of underlying theories. The final section of the paper outlines future steps associated with the project.

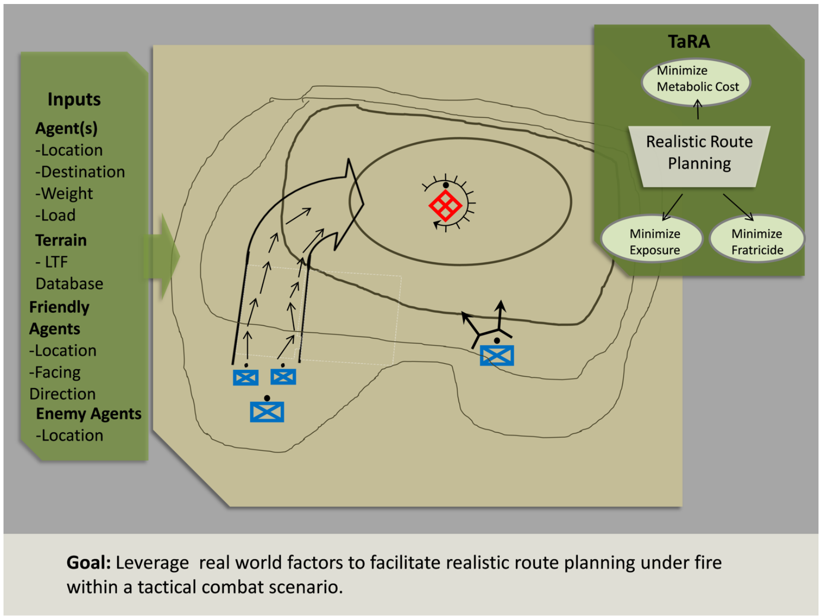


Figure 1. TaRA's OV-1 depicting a sample operation scenario for the agent's use.

SUMMARY OF RESEARCH

This section discusses aspects of the base of knowledge that underwrites TaRA, summarizing the literature review that was one of the initial deliverables for this project.

Doctrinal Issues

Dismounted infantry operations represent the majority of combat operations conducted by the U.S. Army. As such, dismounted movement and combat have always been centerpieces of Army doctrine.

Field Manual (FM) 21-18 is the main Army publication dealing with dismounted movement. Published in 1990, the document discusses lessons of military foot movement learned from conflicts up until that point. The FM recommends that "commanders must reduce the [Soldier's] carried load to the minimum mission essential and survival equipment" by allocating additional transportation assets in the form of trucks or armor to carry part of a Soldier's load [4]. For a conditioned Soldier, his/her maximum fighting load "should not exceed 48 pounds and the approach load should not exceed 72 pounds" including all worn and carried clothing and equipment [4]. In addition to suggesting load limits for dismounted movement, FM 21-18 describes a model that describes the rate of metabolic expenditure in relation to the amount of time that a conditioned individual is able to maintain a certain rate of exertion. This model is shown here as figure 2. Any usable model for dismounted simulation will likely have to be able to confirm this model's results.

An addendum to FM 21-18 exists in FM 3-97.6 which discusses military operations in the mountains. The fourth chapter of the document expands the model pushed forward by FM 21-18 to include the effects of elevation change on route movement. The FM states that planned movement time should be increased by an hour for every 300 meters of incline and 600 meters of decline [5]. The information posed by this FM is most useful for model validation, but offers little on how to actual develop such a model.

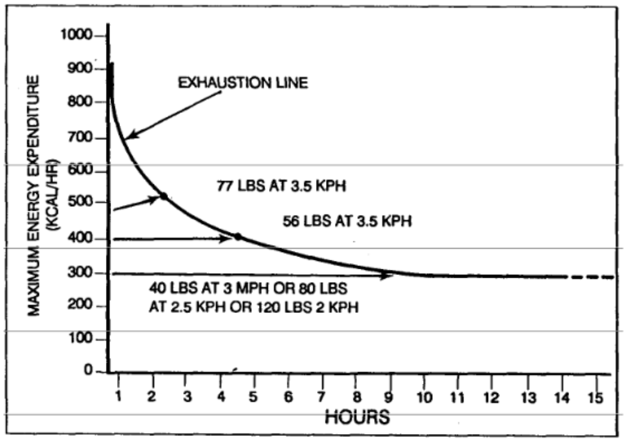


Figure 2. Plot of energy expenditure versus time for dismounted movement under load.

Unfortunately, these doctrinal references run into trouble when applied to the modern world. The doctrine only works when conditions are as explained by the FMs. *The Modern Warrior's Combat Load* published by the U.S. Army Center for Army Lessons Learned (CALL) regarding a study conducted with cooperation from Soldiers of Task Force Devil during Operation Enduring Freedom III (OEF III) offers a new perspective on the amount of weight that Soldiers carry daily. According to the report, Soldiers routinely carry at least 12 more pounds than would be allowed under the limitations of FM 21-18 for their fighting load. CALL's report questions the validity of standing doctrine and begs for the development of new technology and doctrine to help Soldiers do their jobs [6]. Any useful simulation model must be able to explain and represent the sorts of loads described in *The Modern Warrior's Load*.

Movement Analysis

Despite doctrinal gaps in the explanation of dismounted movement, a plethora of studies exist to analyze and explain the realities of carrying loads as a dismounted soldier. Some of these studies dealt with the possible degradation of mental faculty under load in respect to navigation and radio operations [7]. Another set of studies, commissioned by the Army laboratories at Natick, MA discussed the effect of loaded movement on rifle marksmanship. One such study, conducted by Ito, Sharp, Johnson, Merullo, and Mello concluded that extended aerobic exertion greatly impaired rifle accuracy; however, this accuracy was regained fully after between 1.5 to 3.0 minutes of rest [8]. All of these studies provide useful calibration information for the development and implementation of new simulation models.

Though not focused on the effects of load on dismounted movement, Long and Srinivasan's study entitled "Walking, Running, and Resting under Time, Distance, and Average Speed Constraints" illustrated some important concepts for use in TaRA. The study analyzed the behaviors of individuals given a destination and a required arrival time [9]. Researchers then recorded the behavior of these individuals. According to the completed study, individuals automatically regulate themselves as they travel, alternating between running, walking, and resting depending on the perceived intensity of the course [9]. Long and Srinivasan then concluded that the total energy used would resemble equation 1 where the proportion of time spent running, walking, and resting multiplied by their associated velocities equaled the average velocity for the course [9].

$$E_{tot} = [(1 - \lambda_r)V_w(E_w) + \lambda_r V_r(E_r)]\, T_{allowed} \qquad (1)$$

E_{tot} (watts) is the total energy expenditure of a movement

λ_r is the proportion of time spent running

V_w (m/s) is the velocity of walking

E_w (watts) is the energy expenditure rate of walking

V_r (m/s) is the velocity of running

E_r (watts) is the energy expenditure rate of running

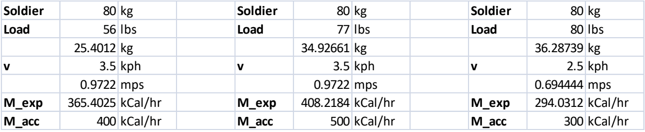
$T_{allowed}$ (s) is the time allowed for the movement

This equation is significant because it indicates the possibility that humans, consciously or unconsciously, predict the amount of effort that they have to put in to a task to perform that task within given constraints. When moving short distances over short periods of time, participants in the study tended to sprint the duration in order to meet their time hack, while longer distances had much more of a mix of movement strategies [9]. This suggests that humans automatically set a level of expenditure to accomplish a movement task that accounts for their perception of the actual task and any surprises that they may encounter.

Existing Models

Combing the research documented above, a variety of models are born to describe dismounted combat. The IWARS simulation package itself carries three different movement models within it. By analyzing what already exists on the shelf, this study was able to determine the "best-of-breed" model that would become the base of TaRA. Out of all the models reviewed, three stood out for possible implementation.

An Australian study entitled *Load Carriage of the Dismounted Combatant* provided many interesting insights into the realities of dismounted movement. The study is very in depth and covers a variety of aspects associated with dismounted movement on the battlefield. The study's tabular movement model is based on Pandolf's equation for movement which considers Soldier weight and load as well as terrain type and grade on the rate of energy expenditure incurred by a moving agent [10]. Pandolf's base equation is modeled below in equation 2. When measured against the values provided in figure 2, assuming a standard sized individual and cross country terrain, we arrive at the values captured within figure 3. These experimental values (M_exp) do not explicitly match the accepted values from figure 2, but are close enough that we may consider the model validated.



Soldier	80	kg		**Soldier**	80	kg		**Soldier**	80	kg
Load	56	lbs		**Load**	77	lbs		**Load**	80	lbs
	25.4012	kg			34.92661	kg			36.28739	kg
v	3.5	kph		**v**	3.5	kph		**v**	2.5	kph
	0.9722	mps			0.9722	mps			0.694444	mps
M_exp	365.4025	kCal/hr		**M_exp**	408.2184	kCal/hr		**M_exp**	294.0312	kCal/hr
M_acc	400	kCal/hr		**M_acc**	500	kCal/hr		**M_acc**	300	kCal/hr

Figure 3. Validation trials for Pandolf's equation.

$$M = 1.5W + 2.0(W + L)\left(\frac{L}{W}\right)^2 + \eta(W + L)[1.5V^2 + 0.35VG] \qquad (2)$$

V (m/s) is the agent's calculated velocity
G (%) is the grade of the slope along the path in question
W (kg) is the agent's weight
L (kg) is the agent's load
M (kCal/hr) is the agent's metabolic rate
η is the scalar value representing terrain type

Another model found in the research was developed by Waldo Tobler at the University of California at Santa Barbara in 1993. While discussing the modeling of geographic information, Tobler presents a mathematical approximation of a hiking function that compares walking velocity to gradient slope [11]. Tobler's formula is contained below in equation 3. The strength of Tobler's model is that it seems to match the rules of thumb for route movement contained in FM 21-18 and, therefore, matches the body of empirical data currently available to this study [4]. The model, however, fails to account for other factors that would influence soldier mobility, such as load or agent self-weight.

$$W = 6e^{-3.5*|S+0.05|} \qquad (3)$$

W (kph) is the walking velocity of the agent.

S (%) is the slope of the terrain being traversed

The most interesting model and that which earns the title of "best in breed" is that associated with the speed regulation model (SRM) included as part of IWARS. Like the Australian model, SRM is based on Pandolf's equation

(Eq. 3). Unlike the Australian model, however, SRM includes a second equation which determines a maximum metabolic rate possible for a simulated entity and then uses that, in combination with a version of equation 3 resolved for V, to calculate the speed and metabolic expenditures of an agent during movement [12]. Both of these equations are described below as equations 4 and 5 respectively.

$$M_{max} = M_{\infty} + (M_0 - M_{\infty}) * e^{\{-\left(\frac{t}{b}\right)^m * \left(\frac{t_{\infty}}{(t_{\infty}-t)^{\frac{1}{\alpha}}}\right)\}} \qquad (4)$$

M_{max} (kCal/hr) is the maximum metabolic rate for time t
M_{∞} (kCal/hr) is the metabolic rate that can be maintained infinitely, 300kCal/hr
M_0 (kCal/hr) is the metabolic rate of instantaneous exhaustion, 2135kCal/hr
t (hr) is the estimated time of agent movement
t_{∞} (hr) is the longest time able to be marched, 10 hrs
b is a scalar value, 0.31211
m is a scalar value, 0.33397
α is a scalar value, 4

$$V = -0.35G + \frac{\sqrt{(0.35G)^2 - \frac{9W + 12(W+L)(\frac{L}{W})^2 - 6.97332 * M_{max}}{\eta(W+L)}}}{3} \qquad (5)$$

V (m/s) is the agent's calculated velocity
G (%) is the grade of the slope along the path in question
W (kg) is the agent's weight
L (kg) is the agent's load
M_{max} (kCal/hr) is the agent's maximum allowed metabolic rate
η is the scalar value representing terrain type

The SRM is important because it partially supports the Long and Srinivasan's theory of self-regulation by using the agent's perception of the rate of expenditure needed to accomplish the task at hand. Equation 3 dictates a metabolic rate that allows for some average rate of movement to cover the distance required in the amount of time allowed. This is an important feature that is not present in any of the other models reviewed as part of this study. Because of this, the SRM model serves as the base for TaRA's development and implementation.

IWARS' SRM, however, is only valid for a small range of slopes and velocities. Pandolf's model really only works for "level" ground with a grade less than +/- 5%. Beyond these values, the model ceases to approximate the velocity data contained within FM 21-18 with the accuracy this study desires [4].

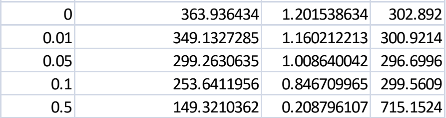
Proposed Metabolic Model

To better represent the behavioral effects caused by the increased effort and slower speeds encountered on steep slopes, this study proposes the creation of an interim metabolic model. This model is to be used by TaRA until such a time as a more ideal model can be conceived. Our interim model replaces equation 5 of the SRM with equation 6 below. Equation 6 uses a scalar modifier derived from Tobler's Hiking Function (equation 3) to determine agent speeds that better fit the rules of thumb put forth in FM 21-18. [4, 11]

$$V = \frac{6e^{-3.5*|S+0.05|}}{5.036742} * \frac{\sqrt{\frac{9W + 12(W+L)(\frac{L}{W})^2 - 6.97332 * M_{max}}{\eta(W+L)}}}{3} \qquad (6)$$

V (m/s) is the agent's calculated velocity
G (%) is the grade of the slope along the path in question
W (kg) is the agent's weight
L (kg) is the agent's load
M_{max} (kCal/hr) is the agent's maximum allowed metabolic rate
η is the scalar value representing terrain type

An effective costing metric for this metabolic model is made difficult by changing velocity and slope. As shown in figure 4, when the slope increases, both velocity and metabolic cost decrease according to our model. In order to make it more expensive to traverse slopes than level ground, the metric of metabolic rate divided by velocity has been adopted for TaRA, as in equation 7.



Grade (%)	Metabolic Rate (kCal/hr)	velocity (m/s)	met/v
0	363.936434	1.201538634	302.892
0.01	349.1327285	1.160212213	300.9214
0.05	299.2630635	1.008640042	296.6996
0.1	253.6411956	0.846709965	299.5609
0.5	149.3210362	0.208796107	715.1524

Figure 4. Metabolic rate, agent velocity, and metabolic costing data across increasing gradients.

$$c = \frac{M_r}{V} \qquad (7)$$

c (kCal*s/hr*m) is the adjusted cost of a route interval

M_r (kCal/hr) is the metabolic rate

V (mps) is the agent's velocity

ARCHITECTURE

Concept of Design

TaRA is designed to be an environment independent route planning tool for the simulation of dismounted combat. This project sought to leverage stable intermediate forms of the various costing metrics and algorithms to ensure a fully functional project. Internal complexity between individual objects within the program was also used as a design heuristic to further accommodate the goal of a "stateless" tool. TaRA relies on the environments it supports to hold most of the relevant information, possessing a small memory footprint and allowing the program to be able to service multiple simulations as part of EASE-DMF. To do this, however, TaRA requires environmental data be stored in the Layered Terrain Format (LTF) developed by Applied Research Associates (ARA) [13].

TaRA works by dividing the terrain database into multiple polygons of a homogeneous terrain type and determining a cost of any point within these polygons using the models described below. Cost metrics are weighted and fed into an A* search algorithm adapted from the LTF services already used as a part of COFFEE. The A* search finds the lowest cost path across the weighted measures such that it represents a soldier's movement behavior under fire.

Moving Parts

TaRA's architecture relies on the functioning of four different costing models and a memory cache in order to determine agent routes. These parts are described below.

Metabolic Costing Model A

The initial metabolic costing model (Met A) for TaRA is a subclass of our proposed model. It is designed to calculate continuous routes over distances of between 50 and 200 meters or more based on metabolic considerations alone.

The model first uses equation 4 to calculate the expected metabolic rate of the simulated entity over the course of the movement. For a movement within 50 and 500 meters, the expected time conforms to equation 8. The important part of this equation is the inclusion of metabolic reserve that accounts for a combatant's ability to react to unexpected conditions on the battlefield as suggested by Long and Srinivasan [9].

$$t = \frac{(m) * d}{v} + R \qquad (8)$$

t (s) is the estimated time of movement

m is a scalar modifier for distance to approximate route curvature. (Standard implementation is 1.5)

d (m) is the linear distance between start location and destination

v (m/s) is an arbitrary velocity for the traveling unit (Standard implementation is 2.0 m/s)

R (s) is the modifier for the agent's energy reserve. (Standard implementation is 600s)

Met A then uses M_{max} to determine the costs associated with movement through various polygons of the terrain database using equations 6, 2, and 7.

Metabolic Costing Model B

Metabolic Costing Model B (Met B) solves for the routes dealing with the 3-5 second bounds that Soldiers are trained to make while in combat. The model's implementation makes it another subclass of this study's proposed base model. using equation 4 to determine the agent's rate of metabolic expenditure for the bound. As with Met A, the model assumes a metabolic reserve for every movement; in this case, a value of 7 seconds is used for every bound. The cost of movement to any point in any polygon is then calculated using equation 4 as before.

After every bound calculated by Met B, the agent's usable metabolic rate is adjusted to model the degradation of its repeated sprint ability (RSA) over time. TaRA's RSA model is adapted from a study dealing with the effects of a carbohydrate rinse on the ability of athletes to perform multiple sprints in a row [14]. Our model here uses a linear approximation of the data contained in figure 4 to model the decrease in RSA for an agent bounding in combat.

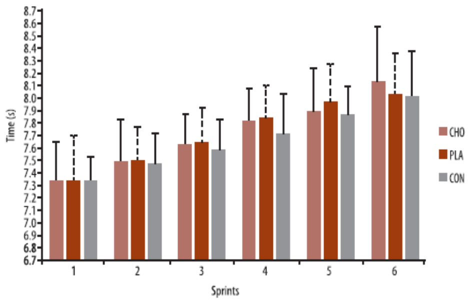


Figure 5. Graphical Depiction of RSA ability from Carbohydrate Mouth Rinse study.

As the original study only accounted for rest cycles of 15 seconds between sprints, Met B conducts a linear transformation of the data to account for real life rest cycles experience during bounding maneuvers. For the basic cases discussed by this study, the rest time for bounding agents is considered to be 63 seconds as established by early work-rest ratios in primitive models for TaRA. Due to the model's linear nature, this study assumes that an agent's RSA will only be degraded 24 times to replicate 25 combat rushes. This number is adjusted from an Australian study of standard dismounted assaults that measured the bound metrics for Australian soldiers conducting operations over distances between 100m and 150m [15]. For our purposes, these distances are to be considered standard operating distances for the bounds that are likely to be modeled by TaRA.

Enemy Exposure Model

The Enemy Exposure Model (EEM) relies on the existing Line of Sight (LoS) check function that already exists as a part of the LaSER/LTF library. The metric output by the model is directly related to the overall percentage of exposure over a section of path. This value is influenced by the relative amount of time exposed to the enemy over the length of a path step.

Fratricide Risk Module

Fratricide prevention is a crucial part of tactical operations. TaRA uses a fairly simple and robust model (FRM) to help approximate the risk of friendly fire during tactical movement toward a specified objective. TaRA contains a data file describing a series of templates for surface danger zones (SDZs) for various weapons able to be modeled with the agents in a simulation [16]. A template is applied to the database and the possible locations for the currently moving entity. A prohibitively high cost is applied to any location within the rendered SDZ. This calculation is accomplished by a simple point search function compared to the simulated area of the SDZ.

For the purposes of TaRA's initial delivery, only one SDZ model is provided. This SDZ model is suitably simplified to be only a 60 degree sector that extends for 550 meters from its origin to represent the behavior of a 5.56 millimeter round chambered in the Army's M4 Carbine. Operationally, the SDZ is centered on the unit guide of any simulated unit to reduce the number of calculations required by TaRA during the route planning process. This means that during movement calculations, an SDZ is centered on any enemies present and the facing direction of any support-by-fire (SBF) unit.

Implementation

TaRA is implemented in two basic steps. The first step calculates a general route for a simulated unit and the second calculates individual bounds between the start and end positions of an unit. The sequence diagram in figure 6 depicts TaRA's function graphically as a sequence diagram.

Initial Route Planning

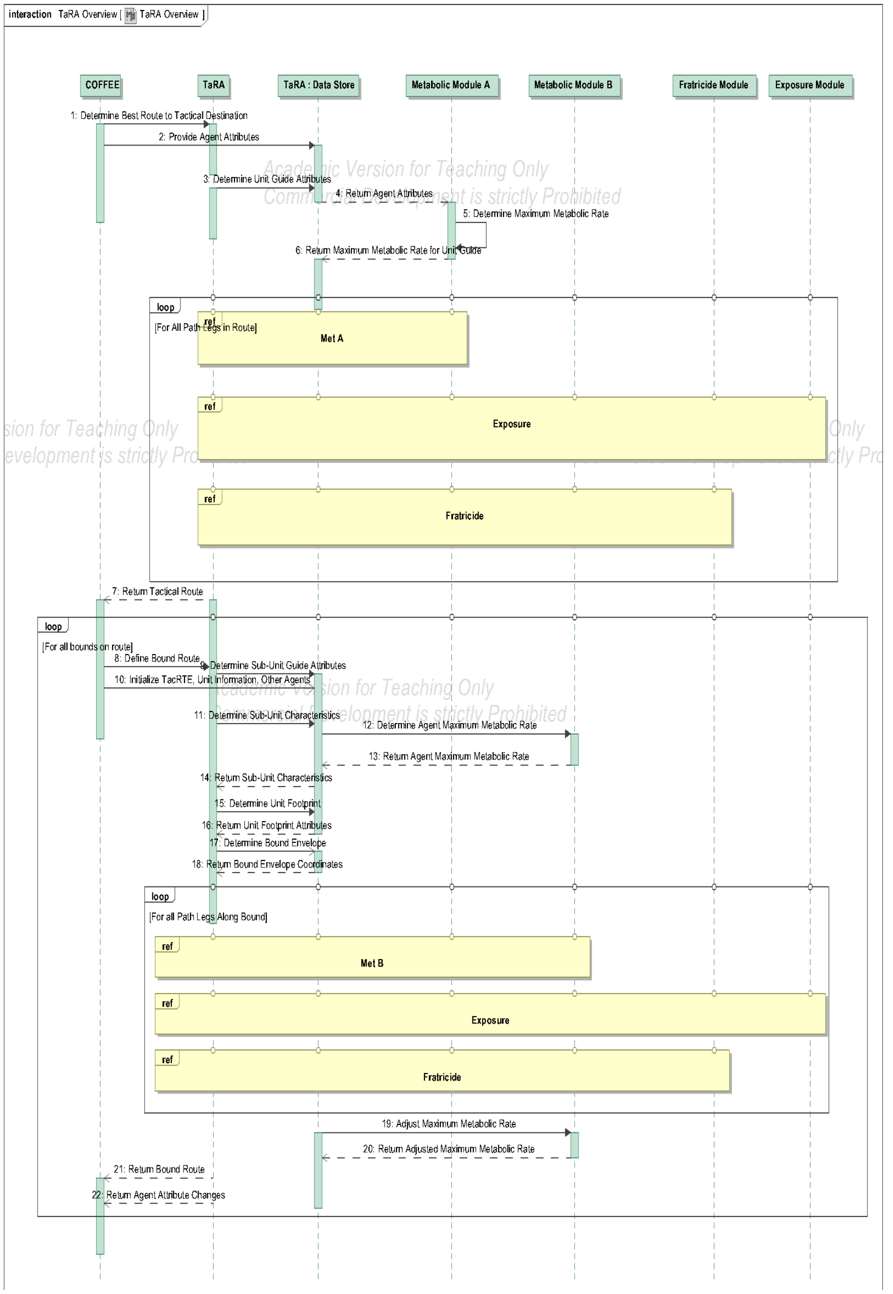


Figure 6. Sequence diagram depicting TaRA's internal and external functions.

When TaRA is initially called by a simulation platform, it receives the general information regarding the units moving and all other entities in the units' vicinity. The simulation agent provides unit location, destination, characteristics and other key attributes to TaRA. TaRA temporarily stores this information in a memory cache and uses the identified unit guide's information to calculate a continuous route to the destination. This route, called a "hand rail" is calculated using Met A, EEM, and FRM and then passed back to the simulation agent for execution. This route can be recalculated at any time by another call from the simulation agent.

Bound Planning

After a hand rail has been established, the simulation agent can request the calculation of a bound or multiple bounds by subordinate units to the simulated unit in question by issuing another call to TaRA. This call is accompanied by the initial hand rail and all of the relevant simulated entity attributes and information. TaRA uses this information to design a horizontal footprint centered on the hand rail that will act as the left and right boundaries for the bounding movements to be calculated. A destination envelop is then generated within these boundaries to mark the distance likely able to be covered by the simulated entity in between 3 and 5 seconds of rushing. A point within this envelop is calculated by use of TaRA's costing models and then a bound route is planned to that specific point using Met B, EEM, and FRM. This bound route is then passed back to the simulation agent and TaRA stands by for another call to calculate the next bound. This process is shown in the lower loop of the sequence diagram in figure 6 and graphically in figure 7.

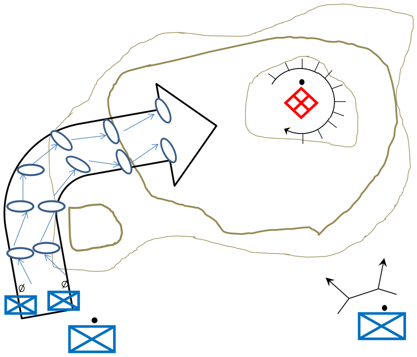


Figure 7. Graphical representation of the bounding process used by TaRA.

FUTURE WORK

Realization of Concept

TaRA is undergoing actual development under contract with ARA. This document's author is serving as project manager to ensure the program's timely development within COFFEE. Once it has been completed, time will be spent validating the simulation's utility and tweaking the programs value scale to achieve a realistic mix of metabolic, enemy exposure, and fratricide concern based on subject matter expert feedback.

Further Adaptation

This program represents a proof of concept that simulations can procedurally develop realistic routes for simulated entities under fire. After its initial development, it is expected that additional refinements can be made to expand the model's realism and utility for analysis. The refinement process will resemble the spiral method favored by software engineers [17].

Possible refinements include the development of a more sophisticated enemy exposure model that weights points on the terrain database based on the passage of simulated bullet between enemies and the moving entity. This would allow the model to distinguish between points of cover and points of concealment. Another possible refinement is to adapt the SDZ protocol to better represent more weapons in the arsenal of both the U.S. Army and that of other powers in the world to more realistically model the types of weapons employed on the battlefield and their effects to combat movement.

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