Cooperative Blue-Force Tracking (BFT) and Shared Situation Awareness (SA) in Complex Terrains

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ABSTRACT

According to studies of network enabled capabilities, improved cooperative blue-force tracking (BFT) combined with timely shared situation awareness (SA) in complex terrains would increase mission effectiveness especially when and where participant coordination and synchronization are most critical. At the same time, such timely, pervasive and persistent SA offers the opportunity to decrease undesired collateral damage and fratricide by supporting the more desired and lasting effects, and by providing mass media more opportunities to focus on positive outcomes of allied operations. This paper reports on adaptive networks for mobile (mounted or dismounted participants) and stationary (fixed) units, that include networked sensors. These networks are extended to cooperatively build up a map of the relative location of all communicating and sensing units. Then, two possibilities of computing the estimated geolocation of each unit will be explored where radio pseudoranges, Global Positioning System (GPS) and inertial measures are combined in order to obtain and maintain accurate geolocation in adverse conditions such as during GPS denial. The first option computes the relative positions and passes the results to the navigation component of each unit. The second option consists of sending the estimated distances between the units to a navigation component and then develops a geolocation map of all units. The remainder of the paper addresses the users' exploitation of the improved network to share information that contributes to better SA and maintain its currency, i.e., using dead reckoning (DR) position prediction to reduce the rate of position report updates while maintaining the desired accuracy and currency of shared information.

1.0 INTRODUCTION

Improved shared awareness depends on a variety of factors spread over different domains, from cognitive to information technology. The later, the focus of this paper, includes improvements in networks, networked sensors, geolocation, data fusion, information management and information sharing. The novel aspect of this paper reveals the potential synergy gained by integrating such improvements. It consists of integrating together the followings: advanced mobile ad hoc networks (MANETs), wireless self-healing autonomous sensing networks (SASNet), radio location measurements, Global Positioning System (GPS), inertial navigation system (INS) based on higher-precision low-cost miniature inertial measurement units (IMUs), geographic information system (GIS), and capable handheld devices for command and control (C2) and information management (IM) with interfaces to users such as touch-screen displays usable in cold, hot, dusty, wet, low-light and in full sun environments.

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Such integration in handheld devices can be applied to domestic, commercial and military applications. It allows for the provision of unprecedented levels of self- and shared-situation awareness (SA) and decision making capabilities for disperse civilian and military operations, providing continuous shared blue-force tracking (BFT) of assets and people in all conditions, including indoor, as well as more persistent sensed data about non-participating elements or opposing forces in an operational theatre. The novel solutions for cooperatively generating and sharing localization information in an integrated sensor-based GPS-INS-GIS-Radio system presented in this paper support some of Canada's high priority concepts and capability developments such as Joint Fires Support, Network Centric Operations and Integrated Soldier System.

One important justification for the proposed integration is based on the fact that at the Earth's surface, GPS signals are very weak, making them susceptible to jamming and attenuation. Conversely, the small distances between nodes make MANET cooperative radio networking, network localization and tracking relatively resistant to jamming. Advanced MANET radio signals allow for much improved measurements of time of arrival (TOA), time difference of arrival (TDOA), and sometimes angle of arrival (AOA), for locating a source of signal position in two or three dimensions.

On the other hand, an IMU is insensitive to radio jamming, making it the ideal complement for a resilient geolocation system in the complex terrains and adverse operating conditions often encountered in military operations. However, an INS, dead reckoning (DR) from an initial reference, has a tendency to drift over time unless updated with new reference positions. The complementary nature of low-noise but drifting INS errors and noisy but unbiased GPS errors makes the combination an excellent candidate for the application of Kalman filter concepts. For the proposed integration, LOng RAnge Navigation (LORAN), radio-network positioning from advanced MANETs and sensor networks, digital compasses, baro-altimeters or other sensors may supply additional aiding measurements required for limiting INS error growth in the momentarily absence of GPS, radio-connectivity or radio-ranging measures. In addition, DR position predictions may be exploited to extend the validity of shared geolocation information based on the physical characteristics of the tracked objects. Such prediction with bounded geolocational errors can be used to speedup network topology adaptation and increase end-user confidence in the geolocational data provided.

Here is an application example during a clearing operation where all participants are equipped as described: When members of a task force or platoon move into a building, positioning information can be generated and shared using multiple network communication technologies to refine the level of precision and accuracy beyond what is possible to achieve by relying only on individual location information. The idea is to plant a few anchor nodes with known precision geolocations (e.g., GPS based) outside the building and, as some of the members move into the building they can lay motes (small sensor devices) leaving a trail of breadcrumbs behind. In doing so, the soldiers inside the building can ensure that no one else gets into the building while they are performing their searching or sweeping operation. Additionally, the mobile radio network maintains communications among the parties involved in the operation, and provides position and presence information sharing for enhanced SA that can significantly improve operational effectiveness. The sensor nodes, the motes, form a network that extends geolocation indoor by using the anchor points as references. The MANET cooperative radio networking and the sensor network also serve as sources of measurements to the integrated navigation system.

The material will be presented in the following order. Section two describes MANET and SASNet functionalities and potential measurements for sharing geocoded data. Section three presents two-radio geolocation Kalman filter measurement models. Section four addresses the issues of information management and DR before presenting some conclusion material in Section five.

2.0 MOBILE RADIO NETWORKS

In mission-critical operations, a mobile radio network maintains communications among the parties involved in the operations and provides information sharing for enhanced SA that can significantly improve teams' operational effectiveness. Recent advances in MANET enable the automatic network formation among ad-hoc radio nodes in the absence of any fixed networking infrastructure. The network topology knowledge gathered in MANET imparts relative location information in terms of neighbourhood, node presence and reachability conditions among the network participants. The networking capability and the mechanism to maintain topology information offer messaging facilities to share the location information among different groups of the deployed forces. The radio cooperative localization algorithm generates location maps for different subnets of the network, or for the entire network. Multiple network communication technologies can be used simultaneously to improve such local and shared position information. The location estimates obtained through radio ranging and cooperative localization schemes become one set of inputs to a Kalman filter to produce improved INS outputs at each mobile node and can take advantage of sensor networks consisting of a variety of specialized nodes: motes, fusion and management nodes and geo-referenced anchor nodes.

The Mobile Ad hoc and Sensor Network Systems group of CRC conducts research and development activities in the domain of MANETs and wireless sensor networks that will be described in the following sub-sections.

2.1 Mobile Ad-hoc Networks

As reported in [1], MANETs [2] have been a topic of great interest to various nomadic communities, location-based services (LBS), predictive computing [3], government agencies and military organizations. One of the main characteristics of a MANET is that mobile nodes can join or leave the ad-hoc network in a dynamic fashion. In addition, mobile nodes can modify their relative position, with respect to other mobile nodes, within a geographical area. Compared to fixed network architecture, ad-hoc networks promise great advantages, such as the ability to instantly deploy mobile nodes, and the mobile nodes' ability of reconfiguring and of preserving connectivity during topology changes. Highly desirable for establishing communications among "on the move" operational personnel, such intelligent self-forming [4] radio networks offer information that can be exploited for enhanced SA. While GPS and INS devices provide self-location and tracking measurements, the mobile radio networking devices establish a global view of the dynamic relationship among all the nodes, fixed or mobile.

A hierarchical military MANET architecture based on a cross-layering design that imposes information exchanges between the routing layer and the application layer can provide presence tracking and position tracking to each user with minimal overhead through different network hierarchies. Using a scalable Hierarchical Optimized Link State Routing (HOLSR) [5], nodes presence information (in terms of Uniform Resource Locator (URL), which is obtained form Session Initiation Protocol (SIP) application) and location information (obtained from hardware device or through localization calculation) can be piggybacked onto the HOLSR routing message and disseminated into proper parts of network.

Based on the hierarchical features of the HOLSR routing, nodes in a military network can track other nodes depending on their access privileges. Each node within a cluster can have a detailed map of other nodes in its cluster while the cluster heads have a view of the nodes in their cluster as well as other cluster heads that are at the same higher topology level. This is compliant with a plausible access control structure in military networks. A node that is higher in the network hierarchy (such as a task force commander) would track all the other nodes in the network, while a node located in the lower hierarchy (such as a dismounted soldier) would only track other soldiers within his/her own platoon. For example, in Fig. 1, personnel in the platoon net would know the presence/location of their peers within their own platoon. The platoon commander not only has the presence/location information about his/her platoon members, but also gets the presence/location information of other platoon and troop commanders at level 2 within the same cluster. The platoon commander can also obtain the presence/location information of the nodes in the troop cluster if required. The task force commander, however, has a complete view of the nodes under his/her task force, and also the nodes under other combat team commanders. That can be translated in the user application domain to unclutter the displays of users high in this hierarchy, i.e., the information of individuals in lower clusters can be summarized by sharing and showing a single symbol and delimitating its geolocation area for uniquely identifying each cluster while the default for own cluster will provide the full details of its participants.

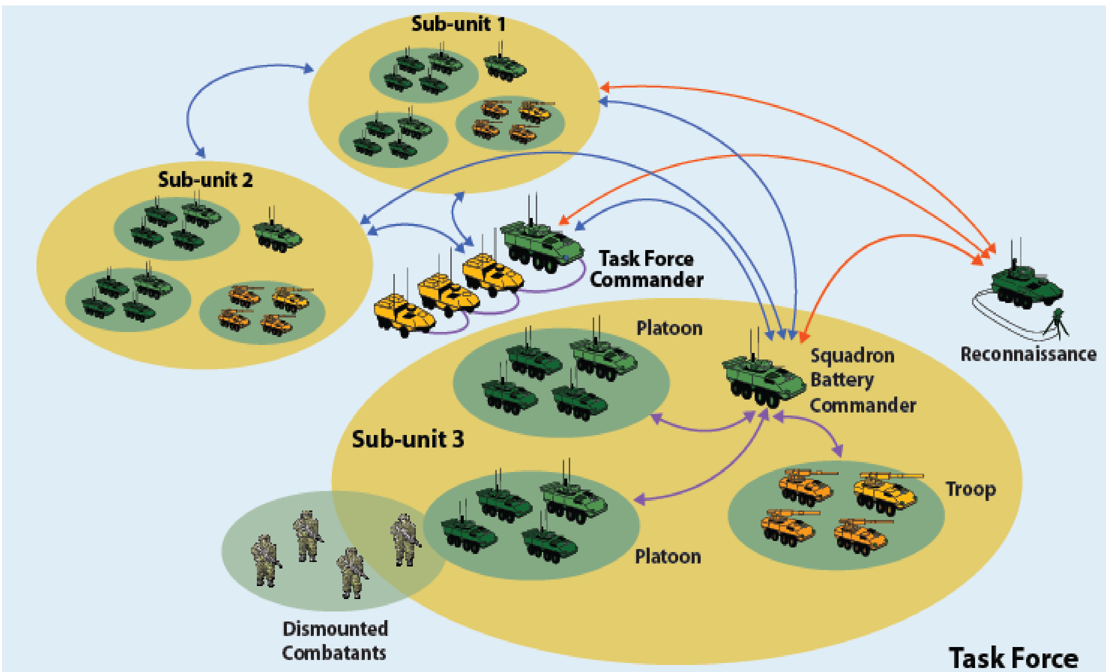


Figure 1: Example of a Hierarchical MANET Architecture

With the node presence/location information collected in the HOLSR topology database, a cross-layering design can be introduced between the application and the routing layers. Then, a map application could be implemented in each node, which interacts with the HOLSR to dynamically track the presence and position of network entities, and display them on the graphical user interface.

2.2 Wireless Sensor Networks

CRC and DRDC Valcartier's SASNet system consists of resource-rich specialized nodes in conjunction with small sensor devices or motes that detect various phenomena and transmit the information to a management node.

SASNet is a tiered embedded wireless sensor network (WSN) that exhibits a hierarchical networking architecture as illustrated by Figure 2. Containing both small-form-factor low cost sensors (motes at Level 1) for extended monitoring coverage and resource-rich specialized nodes (nodes at Level 2 of this hierarchy) for enhanced communication and application specific processing, SASNet aims to facilitate rapid network deployment with enhanced system efficiency, reliability and usability, and therefore enhance the effectiveness of personnel and provide relevant and accurate SA information attune to the contemporary military operational environment.

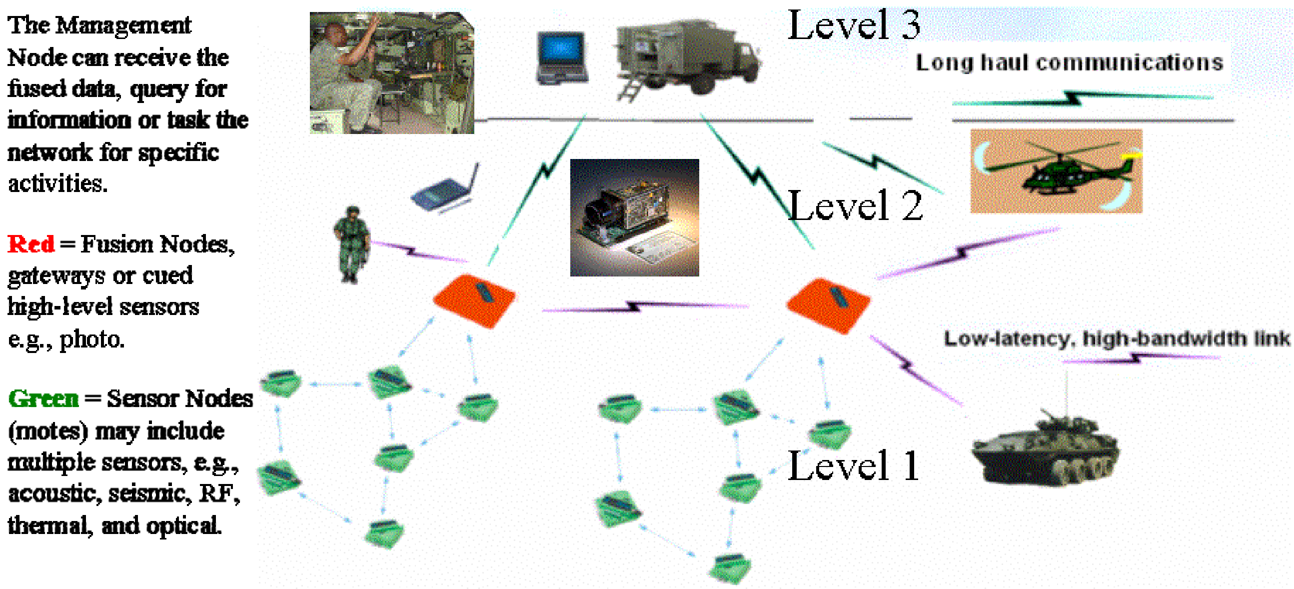
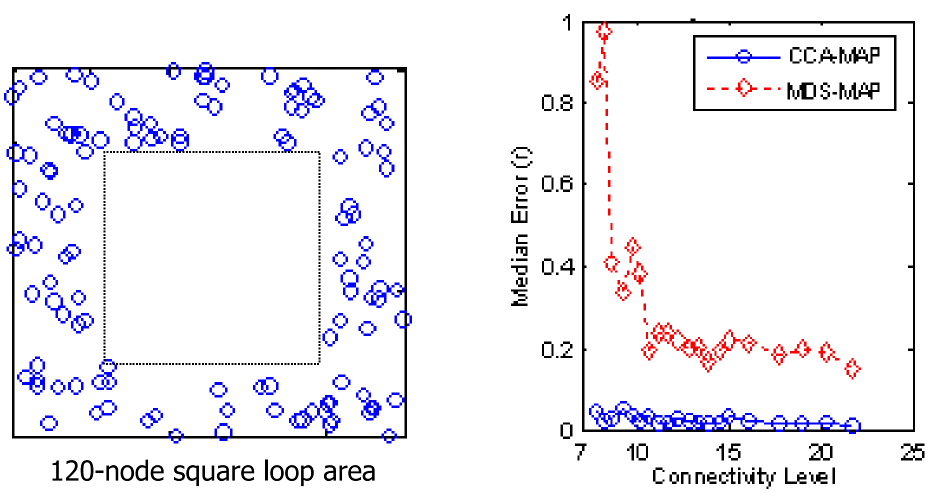


Figure 2: SASNet Layered Architecture

The Sensor Nodes (SNs) or motes of Figure 2 detect the events of interest and facilitate event classification and confirmation. The resource-rich nodes provide services such as: (i) data storage and fusion which are referred to as Fusion Nodes (FNs) (ii) long-range data communications, and (iii) actuation. A FN keeps track of command/response queries, aggregates information, stores history of events that have occurred within its area coverage. A FN may be equipped with an interface that provides long-range communication to remote users or may be connected to a device that provides the long-range communication facility. Actuation is the ability of the FNs to control components such as camera activation and aiming. Examples of actuators would be cameras that can take pictures when activated and directed to the target area by a FN. At Level 3 of the hierarchy of Figure 2, the Management Node (MN) provides the global view of the system with respect to application, operational control and system management, including tasking sensors. In SASNet, authorized users can flexibly access the system from the FNs at Level 2 or from the MN at Level 3. The SASNet supervisor uses the MN to obtain the global view and full management control of the SASNet system from Level 3 down to Level 1. Using a handheld device, a laptop or a PC station, a user with proper authorization can query and subscribe for events, receive the alerts, view histories of the system activities, perform system operation and maintenance tasks, etc. The SNs and FNs form into neighbourhood clusters that interconnect through capable fusion nodes to construct a SASNet system. Various types of mote sensors can be deployed in a cluster for detection of different phenomena. SASNet thus has great agility and expandability, operating from possibly a small-scaled single cluster to a much larger coverage of interconnected systems.

In order to provide an improved shared SA, accurate location information is indispensable in SASNet. Such location data were previously computed using an efficient non-linear mapping technique based on the Curvilinear Component Analysis (CCA) proposed by Pierre Demartines and Jeanny Hérault [6]. It produced satisfactorily accurate results for stationary nodes with a minimum of anchor nodes (anchor nodes know their exact positions either from systems such as GPS or INS, or by having been deployed at planned positions or specific geolocations). In [7], we propose a distributed cooperative node localization scheme called CCA-MAP to facilitate the localization task in SASNet. The CCA-MAP scheme [8] builds local maps at each node in the network and then patches them together to form a global map. Each node computes its local map using only the local information. If accurate ranging capability is available in the network, local distance between each pair of neighbouring node is measured and known. Otherwise, only connectivity information is applied. After computing the local map, a randomly selected starting node uses its local map as the starting current map. Each time, a neighbour node whose local map has the largest number of overlapping nodes with the current map, it is selected to be merged into the current map. To merge a new local map into the current map, a linear transformation (translation, reflection, orthogonal rotation and scaling) is determined to ensure that the coordinates of the common nodes in the new local map best conform those in the current map. The procedure of map merging described here is similar to the approach discussed in [9] and [10]. When at least three anchor nodes are found in the patched current map, an absolute map of the current map can be computed using the coordinates of the anchor nodes to obtain the absolute coordinate values of all the nodes in the current map.

Here are three candidate approaches that apply the CCA-MAP localization algorithm to compute cluster/global maps in a SASNet architecture. In the first approach, each SN and FN computes its local map independently. Then a randomly selected node (can be either a FN or a SN) starts the map patching procedure and then the current local map is transmitted within the Level 1 network for future merging until it becomes a global map. In the second approach, each SN builds its local map from the local neighbour distance information and sends their local map to the associated FN or navigation component so that the FN merges the local maps into a global map. In the third approach, each SN sends its local distance information to their respective FN. The FN builds the local maps on behalf of the SN and then patches the local maps into a global one. In SASNet, to relieve the resource-constrained SNs from the heavy computing and communication demands from the localization algorithm, the computation of the local maps should be carried by the more powerful FNs.



a) Randomly placing 120 nodes in the area between an inner and outer square in a manner that attempts to fulfil this property

b) Positional error as function of node connectivity

Figure 3: Comparison between MDS-MAP and CCA-MAP performance

Our extensive simulations results show that compared to another leading cooperative node localization algorithm, the MDS-MAP [10] that employs multi-dimensional scaling, the proposed CCA-MAP approach significantly improves position estimate accuracy. Figure 3 a) shows an example of a 120-node network with nodes randomly placed to form a loop over the occluded square area where the comparison of CCA-MAP and MDS-MAP is carried out. Figure 3 b) compares CCA and MDS performance in terms of positional error as function of node connectivity where r is the radio range radius required for achieving the node connectivity using the 120-node network described. Furthermore, these simulation results also show that CCA-MAP most of the time limit the error median below 5 % of r using a minimum number of anchor nodes while these results show that MDS-MAP delivers a median at least twice as large, much above 10 % of r. Consequently, exploring approaches like CCA-MAP offers promising avenues for location tracking in large scale WSNs.

With such a localization scheme, each node in SASNet becomes self-aware of its estimated position information, which turns out to be a sufficiently accurate geolocation for network topology and sensed geocoded information. Using that feature, SASNet could also become a reliable information source for BFT. Once the SASNet system has been deployed and the absolute location of each node in the network is computed, the mobile units that are close to SASNet, whether they are dismounted soldiers, platoon or task forces which does not have GPS signal because of the terrain, would receive the absolute coordinates and measurement information such as TOA, TDOA and AOA from at least 3 SASNet nodes (SNs or FNs) using SASNet control messages. With such information, the location of the mobile units could be computed using trilateration scheme [11]. Such location reading, together with the estimated error could be taken as one of the inputs to the Kalman Filter for further processing as will be described in section 3.3.

2.2.1 Measurements

One of the techniques for estimating TOAs and TDOAs assumes a distributed clock architecture where each radio node clock synchronised to a universal reference, e.g., from GPS. If GPS is not available, each node reduces its clock differences with other nodes by exploiting the carrier frequencies and Doppler estimates from all participating radio transmissions received directly. Each receiver downconverts the radio-frequency signal to baseband, then digitizes it, extracts time codes (can be incorporated to users' packets and MANET's control packets such as the HELLOs) and TOA measurements. That can be used on any data links. Then the TOAs can be used directly or transformed into TDOAs as inputs to a position estimator algorithm. The estimated new positions are then used for subsequent calculations.

Alternate techniques exploit a synchronization channel to achieve synchronization as exemplified in [12] for satellite measures of DTOA and differential frequency of arrival (DFOA). The synchronization procedure is accomplished during uplink and downlink transmission bursts where the satellite measures for time and frequency errors relative to an assigned channel are exchanged in a continuous process and repeated until the satellite determines that the time and frequency errors are within the service tolerance. It appears that such procedure would not be practical for MANETs and more research in this area is required in order to achieve the desired measurement precision at low computing costs and minimal channel overhead. Nevertheless, given the broadband front ends and digital signal processing (DSP) capacity of current and future radios, high accuracy TDOA estimates allow providing operational location services, e.g., the Enhanced Position Location Reporting System (EPLRS)[1] advertised a position accuracy with a Circular Error Probability (CEP) of 15 metres, using a synchronization scheme in an ultra-wideband radio system a 25 cm ranging estimation error was achieved [13], and in a cargo environment with multipath and blockage, precision in the order of 5 feet was obtained [14]. However the integration of MANET, WSN such as SASNet, INS, GIS, IM and C2 has

[1] http://www.raytheon.com/products/stellent/groups/public/documents/content/cms01_052749.pdf

more to offer than EPLRS like solutions since such integration 1- can provide higher accuracy when all sources are available, 2- can deliver positioning information during radio silence by exploiting INS and DR, 3- can extend radio connectivity by using SASNet, 4- can be built to better integrate with other Canadian systems, and 5- can use GIS information and DR to extend the length of time without GPS and radio connectivity.

2.2.2 Collaborative electronic support measurements

SASNet-like technologies can be exploited to enhance classic electronic support measurement (ESM) systems by providing geographically distributed aids in the form of multiple sensors in an area of an operational theatre. Collaborative ESMs offer not only a geometry advantage but the opportunities of a large number of sensors having a proximity or range advantage over large form-factor systems that need to be on platforms that are unfortunately easily detected and identified by opposing forces. Small form-factor devices can be easily carried and hidden along paths on the move for improved mobility and fast deployment in preparation of critical operations.

The concept of collaborative electronic support measurements relies on the fact that specialized ESM nodes can provide specifications of signals to be searched for and detected by moles. Dedicated moles' DSPs use the signal prototypes to be detected, measure the TOAs of such signals and then the moles send the TOAs with appropriate signal characterizations for the specialized ESM nodes to exploit such information. Estimated ranges of detected signals for known geolocations are then used as supplementary measures to line-of-bearing (LOB) measurements intrinsic to ESM systems [15]. Emitter geolocation based only on LOBs (with precision limited by achievable space-diversity and cost constraints) provides less accuracy than when adding ranging measures such as TOAs and TDOAs from a larger number of sensors distributed in the theatre with better geometry and proximity to the emitters.

Given that a large number of moles increases the likelihood of one being close to an emitter, alternative measurements can exploit the signal strength as a first order estimate of the emitter-mole distance. This is especially true as the emitters to be localized operate at higher frequency and low power. This is similar to the near-far interference paradigm where the fundamental laws of propagation play a dominant role [16]. Figure 3 presents positional error results from simulations using a free-space propagation model for the radio range.

3.0 RADIO GEOLOCATION KALMAN FILTER MEASUREMENT MODELS

3.1 Inertial Navigation Background

The presence of an INS has been a central, critical feature of high-value military platforms for decades. An INS uses orthogonal triads of gyroscopes (gyros) and accelerometers to sense rotations and accelerations in three dimensions relative to inertial space. The gyros and accelerometers measure changes in orientation or velocity, making an INS a sophisticated DR device. Knowledge of initial conditions (position, velocity and attitude) is required if the sensor measurements are to be used for navigation. Navigation is most often mechanised in a (topocentric) local level coordinate frame (we will use a north, east, down local level frame). Initial position, always supplied by an outside source, must provide the origin of the local level frame in an Earth-centred, Earth-fixed frame. Initial estimates of velocity and attitude are most often obtained by ensuring the INS is stationary relative to the Earth's surface. Then, initial velocity (in the local level frame) can simply be assumed to be zero. Initialisation of attitude requires the determination of the orientation of the sensor frame relative to the navigation frame. In any local level frame, the horizontal (e.g. north-east) plane is defined to be perpendicular to the local gravity vector. For a stationary INS, gravity is the only signal measured by the accelerometers. Therefore, the outputs of the accelerometers define the gravity vector and thus the direction of the vertical and orientation of the horizontal plane. In a similar process, east and north can be determined using the gyro outputs: the Earth's rotation is the only signal measured by stationary gyros. The projection of the Earth' rotation vector onto the horizontal plane is entirely in the north direction: the outputs of the gyros can be used to define north (and east). The orientation of the sensor frame relative to the local level frame has now been completely defined.

After alignment (attitude initialisation), the INS can begin to navigate. The accelerometer and gyro outputs, in the sensor frame, are integrated in a complex "strapdown navigator" to provide navigation outputs in the local level navigation frame. While navigating, the gravity and Earth's rate signals that provided the exclusive information used for alignment must be removed from the sensor outputs before integration. A simple latitude and height dependent gravity model and a latitude dependent Earth's rate correction are typically used to correct the sensor measurements.

Error-free navigation is only possible in an idealised INS that has perfect sensors, i.e., with no alignment errors and perfect gravity and Earth's rate corrections. In the real world, each of these factors contributes to errors that are integrated along with the desired signals. The most significant error sources are generally system specific. However, any INS is unstable in the height channel because of positive feedback between gravity and height errors (a height error leads to a gravity model error which causes a vertical acceleration error that leads to an additive height error). Some kind of height control is needed to maintain INS height stability.

Of the remaining error sources, accelerometer and gyro errors are of most interest to the present discussion: Earth's rate errors are strictly latitude dependent, and if proper procedures are followed, alignment errors can be assumed to be largely attributable to sensor errors. As a general rule, DR error growth is a function of INS sensor error magnitudes.

A traditional INS is a highly-precise, well-calibrated and expensive device that was expected to DR for hours while maintaining good navigation accuracy. Very often, a continuous velocity sensor is used to limit the size of velocity errors and thus the rate of growth of position errors. An aircraft might use air speed data, a ship would use a water speed sensor, and a land vehicle could use a wheel speed sensor. Kalman filtering has been used for decades to optimally use data from external sensors to estimate INS sensor and navigation errors.

3.2 INS / GPS Integration

Prior to the deployment of GPS, there were no positioning systems that had global coverage and adequate accuracy for justifying and necessitating the use of expensive high-quality INSs. With the advent of GPS and similar global position, velocity and timing (PVT) systems, "continuous", "global" position and velocity data are available at "all times" in "all places". For many applications, stand-alone GPS provides suitable service for many non-critical applications. In many other applications, the high data rates and attitude data available from an INS make an INS/GPS integration the preferred solution. With GPS data available on the order of once per second or less (instead of once per hour or worse), an INS only has to DR for a very short length of time so that less accurate inertial sensors can be used. Today, gyros and accelerometers based on Micro-Electro-Mechanical Systems (MEMS) technology are being used to create INSs that are orders of magnitude smaller, more energy efficient and cheaper than traditional systems. These benefits come at the expense of sensors errors that are orders of magnitude larger than traditional inertial sensors. Much of the technology developed for traditional inertial navigation can be applied to MEMS systems: strapdown navigators, Kalman filtering, etc. However, current MEMS gyros are not sensitive enough to sense the Earth's rotation, requiring the use of an independent source for azimuth alignment.

GPS has become ubiquitous in allied armed forces, and these forces have become very dependent on the PVT information from their GPS receivers. Military users share the signal blockage, attenuation, interference and multipath problems experienced by their civilian counterparts. In addition, a soldier on the battlefield can expect his/her adversary to further restrict GPS access through active jamming. Here is another potentially valuable application for inertial-based integrated navigation. In fact many high-value assets are already equipped with a traditional INS. For lesser valued assets and the dismounted soldier, cost, weight and power consumption make a traditional INS impractical. However, great value could be gained through the use of a MEMS-based integrated system.

Here is the dilemma: a MEMS integrated system would be useful to bridge GPS outages, but without GPS aiding, the system errors would quickly grow to unacceptably large values. The integrated system will perform significantly better than a standalone INS because of the calibration (inertial sensor error estimation) inherent in the Kalman filter implementation, but bridging is still typically limited to times on the order of 10 to 100 seconds. The answer to the dilemma lies in the power of the Kalman filter: aiding is not limited to GPS. Any source of position, velocity or attitude information can theoretically be used in the filter to limit INS error growth. There are numerous possibilities, but for the present purposes, we will restrict the discussions as follows: the "platform" will be limited to the dismounted soldier, and the aiding information will be limited to what can be collected from a radio that is part of a MANET. In addition, the discussion will concentrate on the development of measurement models that can be used in an integrated Kalman filter.

3.3 MANET Radio Kalman Filter Measurement Models

Considering the MANET radio system as a generic positioning system, there are a number of measurement types available that can be used to calculate the position of an individual radio. These include TOA, TDOA, and AOA. Each positioning model relies on the positions reported by neighbouring radio nodes. These interactions complicate the network positioning algorithms. For example, if Node A is using the information from Node B to estimate its position, Node B should not be relying on information from Node A to estimate its position. Ignoring these restrictions introduces dependencies between nodes that would be very difficult to adequately model. However, in the following discussions, network dependencies will not be considered. The positions of each "control" node (supplying measurement information from a known position) will be considered to be independent of the positions of all other nodes.

Two levels of measurement modelling will be considered. The first is simply a position. At this level, it is assumed the node's position has been computed elsewhere and is supplied to the integrating Kalman filter. The Kalman filter position measurement model is simple and straightforward: the filter requires the node's position estimate, a position accuracy estimate, and nothing more. At the second level of modelling, the node's position is not known a priori. Measurement information (to allow calculation of TOA, TDOA or AOA) from surrounding control nodes is collected and used to update the Kalman filter. Along with the measurement information, accuracies of the measurement information as well as the positions and position accuracies of each control node are required.

The advantage of the position measurement approach is simplicity and low network overhead. However, filter measurements are only available when an adequate number of control nodes are available. The second approach uses more complex models and higher network overhead. It has the advantage of being able to update the filter when as few as one control node is available.

3.3.1 Kalman Filter Measurements

The details of a Kalman filter implementation of an integrated navigation system will not be presented here. There are many excellent references on the subject, e.g., [3, 17]. Suffice it to say that the Kalman filter is a two-step process. Both steps estimate a vector of unknown errors (called states in the state space formulation). The unknowns describe position, velocity, attitude and accelerometer and gyro errors for the INS. Errors for aiding sensors are often included in the state vector. When external measurements from the aiding sensors are not available, INS states are propagated forward in time using a complex error model. Any aiding sensor states are propagated with simple models. When data is available from any aiding sensor, a Kalman filter measurement is formed and the filter is updated: the filter's a priori estimate and the measurement information are weighted and combined in an optimal fashion to reduce the size of the state errors.

The effect of any particular measurement on a particular state varies, e.g., an X-position measurement has a direct effect on the INS X-position error but has a much smaller effect on the Y-position. Of particular interest there are the secondary effects of X-position measurements that can also improve the X-velocity filter estimates as well as decreasing the attitude and INS sensor errors. Smaller INS sensor errors lead to attitude and velocity errors that grow at lower rates; smaller attitude errors lead to lower velocity growth rates, and smaller velocity errors lead to lower position error growth rates. This is the "calibration" process that leads to longer acceptable bridge times when measurements are degraded or unavailable.

A velocity measurement cannot reduce position errors but will reduce velocity, attitude and sensor errors. Similarly, attitude measurements tend to reduce attitude and sensor errors. Both produce the resultant calibration effects.

Given that optimum position accuracy is the primary goal of the current application, this produces a hierarchy of sorts with position measurements at the top, followed by velocity and attitude measurements. Position measurements reduce expected INS position errors that in turn affect geolocation accuracy; other measurements reduce the rate of growth of the position errors.

Note that TOA, TDOA, AOA and similar measurements would fall into the category of position measurements, with the ability to reduce position errors. In Kalman filtering terminology, the INS position states are *observable* using these measurements. GPS receivers measure the Doppler frequency of the carrier signal from tracked satellites to produce line-of-sight velocity values (analogous to pseudoranges with range bias). Used as Kalman filter measurements, the GPS line-of-sight velocities would reduce INS velocity errors. In theory, a similar process could be used in a radio network, though it is currently not practical.

Using the notation of reference [17], a generic Kalman filter measurement equation can be written as

$$z_k = h_k \vec{x}_k + v_k \ .$$

The scalar measurement, z_k, is defined as a linear combination of the filter states, $\vec{x}_k$, plus measurement noise, v_k. The row vector h_k describes the linear relationship between the states and the measurements.

In the discussions to follow, z_k and h_k for specific measurements will be derived. The state vector is assumed to be comprised of INS position, velocity, attitude, accelerometer, and gyro states in three dimensions along with aiding sensor states appropriate for the specific measurements.

3.3.2 Position Model

Position models will vary depending on the coordinates supplied. Here a generic Cartesian frame model will be derived. It can be adapted to almost all possible scenarios. The model can be applied directly to a geo-referenced Cartesian frame, e.g. Universal Transverse Mercator (UTM) and Military Grid Reference System (MGRS), or to a local frame that is not georeferenced. If position is supplied as latitude, longitude and height, the measurements can be easily formed in a local level Cartesian frame. This will be explained below.

The Kalman filter position measurement in any local level frame can be written as

$$\bar{z}_p^{\ell} = \begin{bmatrix} x_{AID}^{\ell} - x_{INS}^{\ell} \\ y_{AID}^{\ell} - y_{INS}^{\ell} \\ z_{AID}^{\ell} - z_{INS}^{\ell} \end{bmatrix}.$$

If the coordinates are given in terms of latitude (ϕ), longitude (λ) and height (h), the following equivalent measurement can be used.

$$\bar{z}_p^{g} = \begin{bmatrix} \dfrac{\phi_{AID} - \phi_{INS}}{\overline{R}_E} \\ \dfrac{\lambda_{AID} - \lambda_{INS}}{\overline{R}_E \cos\phi} \\ h_{INS} - h_{AID} \end{bmatrix}$$

While the first equation was written in a generic local level frame (indicated by the ℓ superscripts), this model is written specifically in the local geographic (north, east, down) frame. Since height is positive up and the local geographic frame is positive down, the sign of the height equation has changed, i.e., $h_{AID} - h_{INS}$. A simple rotation in azimuth (and possibly a reflection) will transform this equation into any other local level frame. $\overline{R}_E$ is the radius of a spherical Earth model (usually 6,371,000 metres for the WGS84 ellipsoid).

To derive the corresponding H-matrix (with 3 rows and n columns, where n is the number of states), the measurement equation has to be written in terms of the states.

$$\bar{z}_p^{\ell} = \begin{bmatrix} \left(x^{\ell} - \delta x_{AID}^{\ell}\right) - \left(x^{\ell} - \delta x_{INS}^{\ell}\right) \\ \left(y^{\ell} - \delta y_{AID}^{\ell}\right) - \left(y^{\ell} - \delta y_{INS}^{\ell}\right) \\ \left(z^{\ell} - \delta z_{AID}^{\ell}\right) - \left(z^{\ell} - \delta z_{INS}^{\ell}\right) \end{bmatrix} = \begin{bmatrix} \delta x_{INS}^{\ell} - \delta x_{AID}^{\ell} \\ \delta y_{INS}^{\ell} - \delta y_{AID}^{\ell} \\ \delta z_{INS}^{\ell} - \delta z_{AID}^{\ell} \end{bmatrix}$$

Then, the measurement matrix can be derived as

$$H_p^\ell = \frac{\partial \vec{z}_p^{\,\ell}}{\partial \vec{x}} = \begin{bmatrix} 1 & 0 & 0 & \cdots & -1 & 0 & 0 & \cdots \\ 0 & 1 & 0 & \cdots & 0 & -1 & 0 & \cdots \\ 0 & 0 & 1 & \cdots & 0 & 0 & -1 & \cdots \end{bmatrix}.$$

The first non-zero block corresponds to the INS position error states; the second block corresponds to the aiding sensor position error states. For our particular application, the aiding sensor will be the local position as computed by the radio network.

Given the covariance matrix of the (assumed independent) aiding sensor position errors,

$$R_p^\ell = \begin{bmatrix} \sigma_x^2 & 0 & 0 \\ 0 & \sigma_y^2 & 0 \\ 0 & 0 & \sigma_z^2 \end{bmatrix},$$

we now have all the information needed to perform a Kalman filter update.

3.3.3 TDOA Model

A TDOA measurement is equivalent to a range difference measurement (with a scale factor equal to the signal propagation speed, the speed of light in this case). The TDOA Kalman filter measurement is written as

$$z_{\delta r}(ij) = \Delta r_{AID}(ij) - [r(i) - r(j)] .$$

Here $\Delta r_{AID}(ij)$ is measured range difference (the time of arrival of the signal from Node *i* minus the time of arrival of the signal from Node *j* multiplied by the speed of light); $r(i)$ and $r(j)$ are the ranges computed using the filter's best estimate of INS position and the given positions of Nodes *i* and *j*.

Since each measurement is formed in the same way, we can consider each individually – the measurement matrix is a 1-by-*n* row vector. As before, it is derived as

$$h_{\delta r}^\ell(ij) = \frac{\partial z_{\delta r}^\ell(ij)}{\partial \vec{x}} .$$

If we initially assume that all positions are reported in the same local coordinate frame, the range between the filter's best estimate of INS position and the given position of Node *i* is simply

$$r(i) = \sqrt{\left(x_i^\ell - x_{INS}^\ell\right)^2 + \left(y_i^\ell - y_{INS}^\ell\right)^2 + \left(z_i^\ell - z_{INS}^\ell\right)^2} .$$

A MANET is mobile and ad hoc: nodes are always joining and leaving and rearranging themselves. This makes the modelling of node errors impractical in the Kalman filter. Therefore, in terms of states, the range equation can be expanded to

$$\begin{aligned} r(i) &= \sqrt{\left(x_i^\ell - \left(x^\ell - \delta x_{INS}^\ell\right)\right)^2 + \left(y_i^\ell - \left(y^\ell - \delta y_{INS}^\ell\right)\right)^2 + \left(z_i^\ell - \left(z^\ell - \delta z_{INS}^\ell\right)\right)^2} \\ &= \sqrt{\left(x_i^\ell - x^\ell + \delta x_{INS}^\ell\right)^2 + \left(y_i^\ell - y^\ell + \delta y_{INS}^\ell\right)^2 + \left(z_i^\ell - z^\ell + \delta z_{INS}^\ell\right)^2} \end{aligned}.$$

Then,

$$h_{\delta r}^\ell(ij) = \frac{\partial\{\Delta r_{AID}(ij) - [r(i) - r(j)]\}}{\partial \vec{x}} = \frac{\partial r(j)}{\partial \vec{x}} - \frac{\partial r(i)}{\partial \vec{x}},$$

using Node i as an example, we obtain the following equation.

$$\begin{aligned} \frac{\partial r(i)}{\partial\left(\delta x_{INS}^\ell\right)} &= \frac{1}{2}\left(\left(x_i^\ell - x^\ell + \delta x_{INS}^\ell\right)^2 + \left(y_i^\ell - y^\ell + \delta y_{INS}^\ell\right)^2 + \left(z_i^\ell - z^\ell + \delta z_{INS}^\ell\right)^2\right)^{-1/2} \cdot 2 \cdot \left(x_i^\ell - x^\ell + \delta x_{INS}^\ell\right) \\ &= \frac{x_i^\ell - x_{INS}^\ell}{r(i)} \end{aligned}$$

The y and z INS position error state expressions are completely analogous:

$$\begin{aligned} \frac{\partial r(i)}{\partial\left(\delta y_{INS}^\ell\right)} &= \frac{y_i^\ell - y_{INS}^\ell}{r(i)} \\ \frac{\partial r(i)}{\partial\left(\delta z_{INS}^\ell\right)} &= \frac{z_i^\ell - z_{INS}^\ell}{r(i)} \end{aligned}.$$

Likewise, the expressions for Node j, allows us to write the measurement vector as

$$h_{\delta r}^\ell(ij) = \left[\left(\frac{x_j^\ell - x_{INS}^\ell}{r(j)} - \frac{x_i^\ell - x_{INS}^\ell}{r(i)}\right) \quad \left(\frac{y_j^\ell - y_{INS}^\ell}{r(j)} - \frac{y_i^\ell - y_{INS}^\ell}{r(i)}\right) \quad \left(\frac{z_j^\ell - z_{INS}^\ell}{r(j)} - \frac{z_i^\ell - z_{INS}^\ell}{r(i)}\right) \quad \cdots\right].$$

The node position errors were not included in the state vector so they should be added to the measurement variances to optimise results. The variance of $\Delta r_{AID}(ij)$ should therefore include propagation errors (if significant) as well as the contributions of the node position errors.

Given the node position error covariance matrix, the range difference variance can be assumed constant (the least desirable option), it can be computed as the sum of the traces of the local level position covariance matrices for the nodes being differenced (a simple but sub-optimal solution), or it can be computed as the sum of the position variances along the line-of-sight towards the INS node (this is the best but most complex solution).

4.0 DEAD RECKONING MODELS IMPROVED TRACK DATA SHARING

The DR techniques are position prediction techniques to project current position based on acquired a priori knowledge. They are widely used in navigation systems for aircraft and ships, and are currently extending their application to car navigation systems based on GPS. Some car navigation systems combined wheels' odometric measures, with gyroscope measures and DR [18] to provide a fairly accurate estimate of position where GPS signals are not available, such as in parking lots and tunnels. Predictive computing for LBS [3] is used to overcome networking and computing problems, such as latency. According to this reference the name *dead reckoning* is an abbreviation of *deduced reckoning* implying that the present location is deduced or extrapolated from a known prior position. Due to DR sensitivity to changes in direction, speed and acceleration, predictions over too long period of times where these physical parameters changes exceed some thresholds, as during evasive manoeuvres, may result in poor performance [19]. However, in networked computer games and simulations, DR has proven to be an effective way to reduce lag caused by network latency and channel capacity issues. An extensive study [20] with simulation results shows the advantages of balancing or trading information management, data compression and error coding when exchanging tactical data over radio networks in order to optimize the exchange of end users' high value information.

4.1 Dead reckoning models for geographically distributed simulations

The Institute of Electrical and Electronics Engineers (IEEE) standardization provides a rich body of knowledge and terminology in the domain of distributed interactive simulations (DIS) [21]. DIS features can be exploited in the domain of sharing real-time (or quasi-real-time) accurate tactical and strategic information among geographically distributed participants located in and out an operational theatre. The success of such operations often requires that collaborative decision-makings result in prompt and accurate synchronized actions for optimal effects at low risk of fratricide/collateral damages and minimal cost. Here we focus on the challenge of improving the pervasive and continuous sharing of track data that accurately represents the dynamic movement of self-reporting blue-force units and sensed non-blue-force entities in theatre without creating undue communication traffics.

Furthermore, the Simulation Interoperability Standards Organization (SISO), that developed the High Level Architecture (HLA) framework, is progressing a Guidance, Rationale, and Interoperability Manual for the Real-time Platform Reference Federation Object Model (RPR FOM) document [22]. The RPR FOM document maps IEEE DIS Protocol Data Units (PDUs) into appropriate HLA objects and interaction classes as follows:

"*In general, individual PDU fields are mapped into corresponding class attributes or parameters. An individual PDU may be mapped across one or more HLA object or interaction class. This change in structure is designed to take advantage of the HLA's Declaration Management and Object Management. This capability can be used to limit network traffic in two ways:1- reducing the transmission of unchanged data, and 2- providing delivery only to federates which have expressed interest.*"

The IEEE and SISO literature on distributed simulations documents these two ways for limiting network traffic. The second way can be related to the notion of priority and importance of information for a given military operation that was alluded to in a previous paper [23]. The first way will be addressed here with a focus on DR, which is a method for estimating the position/orientation of an entity based on its previously known position/orientation and estimates of time and motion.

In several application domains such as avionics and defence and as described in [21], a first-order dead reckoning technique or model (DRM) provides a means for computing a predicted position $pp(t = t_0 + \Delta t)$ at a determined elapse of time Δt in the future from a current time t_0, i.e., at time $t = t_0 + \Delta t$, by assuming that an observed object continues its course from an initial position p_0 at time t_0 with a constant linear velocity v_0. A second-order model assumes that in addition to an initial position p_0 and initial linear velocity v_0 at t_0, a constant linear acceleration a_0 animates the object during the entire elapse of time Δt for a given prediction. The zero order DRM for a non-moving object is equivalent to setting the velocity and acceleration to zero. Consequently, one obtains the following equations for the static, constant linear velocity and constant acceleration (with no angular or bearing rate of change, otherwise another equation would be required) of a tracked object or simulated entity.

$$pp(p_0, v_0 = 0, a_0 = 0, \Delta t) = p_0$$

$$pp(p_0, v_0, a_0 = 0, \Delta t) = p_0 + v_0 \Delta t$$

$$pp(p_0, v_0, a_0, \Delta t) = p_0 + v_0 \Delta t + \frac{a_0 \Delta t^2}{2}$$

4.2 Potential gain of dead reckoning models for geographically distributed applications

This type of DRMs is used in distributed simulations to reduce communication traffic between geographically distributed participating computing nodes. By using DR, simulations are not required to report the status of their entities as often. When using such a strategy, a source node computes a high-resolution model at a high-update rate (e.g., new position calculated or sensed every 30 ms) to provide a high-fidelity reference for the represented entity. That same source node provides the initial values and subsequent updates to be used by an agreed upon specific DRM and its corresponding error threshold for such model and scenario. Furthermore, the source node runs the DRM model and measures the positional error between its high-resolution data and the output of the DRM. As soon as the error exceeds a prescribed threshold for a given entity and scenario type, the source node sends the required updates to other nodes that need the position of the concerned entity and the source resets its own DRM for subsequent error monitoring in a continuous process. The remote nodes compute the position of the entity using the data, provided by the source node, that specify the DRM model and parameters to be used. In addition to positional information, DRMs can be extended to predict the change in an object attitude, direction or orientation, i.e., for some objects like an helicopter or an armoured vehicle, end users may require timely information about the orientation of the object (going forward or backward) beside its direction along a path (indicated by the time history of its geolocation on a map).

Consequently, data about an entity DRM need to be sent only when required, i.e., when a threshold is exceeded. For a dismounted soldier this distance error can be set to one metre. A supplementary control may impose to send the high-resolution source data every minute. The price to pay is a manageable level of uncertainty due to the latency of the network [24]. It is manageable because one can anticipate such latency and compensate for it by adjusting the thresholds accordingly, e.g., if latency is less than half a second 90 % of the time then the selected threshold for an entity's DRM could be computed based on the entity's maximum acceleration and change of bearing that the entity of interest is capable of.

If the world model used for a tactical system requires 200 bits for the position and some 64-data bits for an entity description, then each update would require 264 bits. If a limited number of entities is assumed and the theatre area is converted to a planar grid, then 128 bits (of which 24 are for a unique entity identification number and description) could be sufficient for attaining the desired resolution. To specify a DRM identification number and corresponding parameters a system may require 8 bits for a static case, 32 bits for the constant linear velocity case and 64 bits for the constant linear acceleration one.

A simplified evaluation of the potential improvement in terms of radio-communications channel usage can be based on the following assumptions compared to sending positional updates every second. We make an exception for the static case for which the position is sent only at every minute. We assume that 20 such entities are part of our hypothetical scenario. The initial data exchange requirement for the static case could be 128 bits plus 8 bits (a tota1of 136 bits) that may require a resending after one minute. For the constant velocity case, we have 128 bits plus 32 bits, i.e., a total of 160 bits. Each time there is a change of course or velocity that causes exceeding the prescribed threshold another set of 160 bits is sent. We assume that one such change happens during the one-minute interval for a grand total of 320 bits for each of the assumed 40 such entities. Similarly the constant acceleration case requires that a total of 192 bits be sent initially and that a resending of an updated set of bits be sent every time the prescribed threshold is exceeded. Again we assume that one such change occurs during the one-minute interval for a grand total of 384 bits for each of the 40 entities with such behaviour.

From this simplified example with 100 entities (20 stationary, 40 at constant velocity and 40 at constant acceleration during the one-minute interval), the total data to be sent to all the remote computing nodes if we assume no DRMs is about 28 times the amount of data exchanged when using DRMs. So using DRMs reduces substantially the total amount of data required to maintain the accuracy of the dynamic entities evolving in the hypothesized operational theatre. In fact it costs only 3.5 % of the required traffic without DRMs, i.e., 46 kbits versus 1 308 kbits.

The testing and calibrating of DRMs need to be conducted using appropriate computer generated force (CGF) software and realistic scenarios for urban, rural and littoral operations in order to more accurately estimate the value of the proposed approach. Then its potential gain for improving the persistence and pervasiveness of accurate shared awareness in complex terrain would be revealed.

5.0 CONCLUSION

As a new generation of personnel develop sociological and cognitive skills required for successfully undertake missions of this century, being first responders, special operations experts or peacekeepers, their technology literacy would prove to play an important role as more technological aids will be provided to enhance their SA and decision making capabilities in complex geopolitical situations. This paper expanded on technological and procedure ideas to provide accurate and timely geocoded data that command and control systems and users' oriented aids required for enhancing SA, enabling self-synchronization and increasing mission success rate.

By providing improved collaborative geolocalization and more pervasive communications for moving assets and personnel, the proposed approach efficiently and robustly supports cooperative blue-force tracking (BFT). By adding networks of dispersed sensor nodes, the approach extends to the domain of sensing the non-blue force aspect of theatre entities and features that could be detected and then tracked. The addition of various sources of measurements (e.g., radio ranging and inertial) as inputs to a Kalman filters using the two strategies presented offers the advantage of making geolocation less susceptible to GPS denial. Given the increase in traffic due to the exchange of data for collating the measurements, own reporting and sensed data, the prediction strategy proposed, the DRM, ensures a better usage of the available network capacity. Then, it appears that the approach presented enhances the data necessary to improve shared SA.

All considered, efficiently and timely sharing appropriately geocoded data allows users' systems to present dynamic geolocation maps of the information of interest to concerned personnel. Such geocoded data allow to examine the time history and current state of pertinent information and to project what could happen next. SA improves when thousands of point reports and alert signals are transformed into coherent pictures designed to be more understandable by users. It is expected to increase confidence of decision-making personnel.

In conclusion, the choice of MANET protocols, hierarchical structures, localization algorithms, INS integrations and information management strategies support the hypothesis of improved BFT and shared SA in complex terrains. However more research and development activities need to be conducted in order to progress the potential of such advancements from concepts to capabilities. The following non-exhaustive list presents some examples of such furthering activities:

- Light-weight CCA-MAP localization algorithm
- Radio ranging techniques for MANETs
- MANET radio ranging experimentation
- Simulation and prototyping for the integration of MANET measures with INS
- SASNet simulation and prototyping with specific sensor types
- Cooperative ESM
- Information management, data compression and DRM tradeoffs using CGF

Pursuing research and development in this domain in an international forum would certainly help accelerating our progress towards the best-integrated solutions in support of the concerned communities. For example the integration of MANET, WSN, INS, GIS, IM and C2 has more to offer than current technological solutions proposed to end users, such as EPLRS, since such integration with other Canadian systems would provide unprecedented timely, persistent and pervasive theatre sensed precision data and information sharing that increase the level of SA to a point where it reduces fratricides, supports synchronization of actions and protects against unexpected attacks such as from improvised explosive devices (IEDs).

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