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Self-Aware/ Situation Aware

Integrated Handhelds for Dispersed Civil and Military Urban Operations

Successful response to fast-moving, life-critical situations – military combat, fires, disaster relief – usually depends on robust positioning capabilities and effective communications to provide commanders with comprehensive awareness of dynamic situations. Moreover, the systems providing this situation awareness need to be integrated and compatible with urban operations, and suitably automated. This article describes design of portable handheld equipment integrating GPS and other location technologies with "self-aware" radio networks that can automatically identify and locate all the members of a unit involved in such missions.

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Situational awareness usually underlies successful execution of team efforts in life-critical situations — whether they involve military operations, police and other first responder activities, or indeed many urgent situations in which the location and coordination of personnel and assets plays an important role.

Establishing and maintaining such awareness depends on reliable access to robust positioning and communications capabilities. Geolocation and information sharing, however, often prove problematic for key players involved in critical operations in dynamic environments in which GPS and communications are denied or interrupted.

Accordingly, military and public safety organizations can benefit from the emergence of low-cost, low-power GPS, geographic information systems (GIS), inertial navigation systems (INS) and smart radio equipment driven by a worldwide market for sharing commercial information on the move — fleet and cargo tracking, location-based services (e-commerce), just-in-time logistics, and so forth. Systems that integrate these technologies to provide information with appropriate time and positional relevance enable users to take decisions on the fly.

Such equipment, however, must lower — not raise — the workload on users, allowing them to focus their

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attention on the evolving situation. That is, wherever possible it needs to be automated, provide appropriately filtered and focused information, and be easy to operate. One concept that can help achieve this is the networking of "self-aware nodes" to develop a common view among participating entities or agents.

This concept supports a real-time, operational evolution of common intent with room for adaptation and self-organization. It also provides the essential landmarks for the synchronization, if not self-synchronization, of actions and tasks of a mission to reduce the risk of collateral effects and fratricide. For emergency operations, this means an increase in timeliness and effectiveness that would translate directly into saved lives.

Such integration relies on robust sources of information such as inertial measures, maps, and dynamic communications network topology. The geolocation and the adaptive network domains inform each other, in order to increase their respective performance in terms of speed, accuracy, knowledge and shared awareness.

In this concept, the proposed equipment is self-aware because it uses, exploits and memorizes information from diverse dependent and independent measures and sources, e.g., own position, radio spectrum availability, user authentication and role in a specific network. Then the networked system informs all participating agents and builds a distributed database that increases individual self-awareness and makes shared-awareness a robust reality.

In contrast, analyses of joint operations (those among agencies of a country) and coalition operations (those among countries) have shown that, although data are often available somewhere within the systems at play, the critical data are not necessarily shared appropriately and are often not transformed into end-users' knowledge. Exploiting the synergy among self-aware radios, geographic information and navigation systems, and command and control functions offers participating agents a more effective transformation of the available data into knowledge.

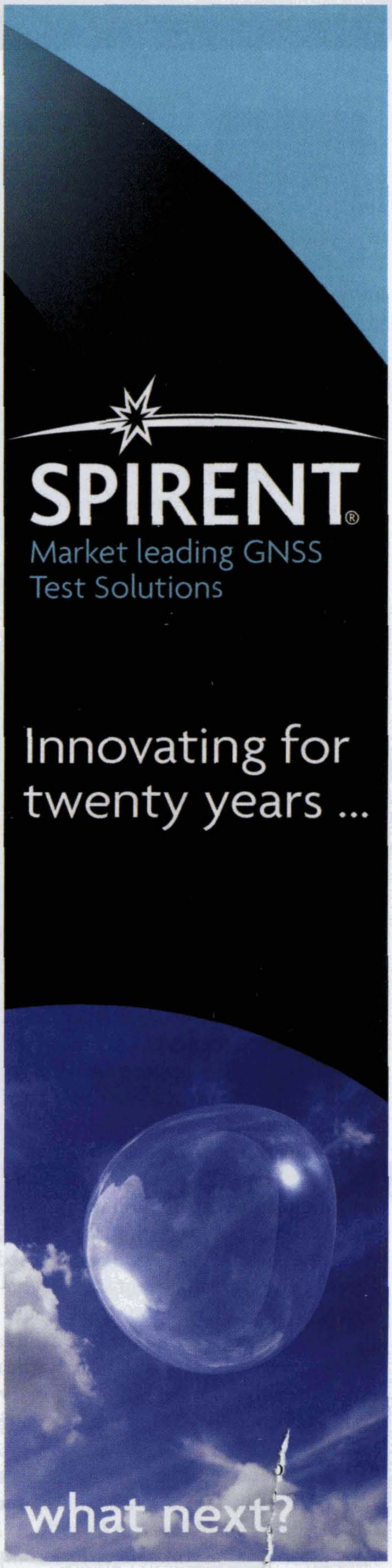
This is good news for decision-makers and coordinators. When geospatial information is combined with precise knowledge of the positions of transceiving equipment, a dynamic picture of moving assets may easily be drawn. This representation of the dynamic situation improves the ability of decision-makers and coordinators to assess situations promptly and to develop appropriate courses of actions — a must for successful operations.

This article will discuss the notional use of handheld, vehicle-mounted and base-station computer/transceiver equipment incorporating GPS, INS, GIS, and possibly including intelligence, logistic, and other data. The awareness of who, what, when, how, and why combined with the where — now and before, that is, the time history — leads to a better understanding of what is next and which courses of actions should be taken.

Equipment, Know Thyself

In 1999, Joe Mitola III and G.Q. Maguire Jr coined and defined the concept of a "cognitive radio." (See the articles by these authors cited in the "Additional Resources" section near the end of this article.) The same year Paul Labbé of Defence Research and Development Canada (DRDC) defined a similar concept: the self-aware equipment and self-aware radio. (See the 1999 article by Labbé cited in Additional Resources.) Combining these concepts offers the possibility to exploit dynamically the available radio spectrum in order to maintain proper connectivity, for example, in addition to multi-hop routing, using suitable spectrum chunks when signals are blocked by obstructions or jammed. Another example: INS cannot be jammed but GPS, satellite, and radio networks can, although some networks offer better protections than others.

In the following discussion, we will focus on the inertial integration aspect and the adaptive networking techniques for mobile units. Issues related to map



standards, GIS, radio coverage, technology in operational contexts such as C2 and middleware for interoperability are not covered.

Integrated Navigation. The well-understood limitations of GPS navigation and positioning in an urban environment can be mitigated through the addition of external information. In this section, we will outline methods that can be used to produce a flexible, statistically optimal, improved geolocation capability by combining GPS information with that from a microelectromechanical system (MEMS) inertial measurement unit (IMU), a radio transceiver, plus other sensor and non-sensor information.

The approach taken is that of the tried-and-true Kalman filter. IMU navigation data derived from integrated high-rate rotation and velocity rate data acts as the dead-reckoning basis of the Kalman filter formulation. Information from the GPS receiver, radio, and other sources are used to update the filter, reducing or slowing the growth of IMU errors.

The sidebar, "IMU Concepts," provides a brief, general summary of inertial navigation operation and challenges. Another sidebar, "Kalman Filter Concepts," describes the steps in filter processing.

Filter Measurements. The proposed sensor suite includes the MEMS IMU, GPS, LOng RAnge Navigation-C (LORAN-C), radio-network positioning, a digital compass, and a baro-altimeter.

Measurements that do not rely on aiding sensors can also be very valuable, especially after aiding sensor measurements have been lost. A commonly used measurement that can be signalled by analysis of IMU data or by the operator is the zero velocity update (ZUPT). The concept is simple: when the IMU is stationary, we know its velocity (zero) and can use this information to update the filter.

ZUPTs can be processed continually as long as the IMU is stationary. There are two possible ZUPT scenarios that can be implemented in the personal navigator:

1) They may be scheduled, requiring the operator to hold the IMU stationary for a short length of time. Unscheduled ZUPTs can be automatically detected and executed.
2) If the IMU can be boot-mounted, very short ZUPTs can be processed at every step, as the boot strikes the ground.

Sensor	Measurements
GPS	3D positions 3D velocities
Radio-network	3D positions
LORAN-C	2D positions
Compass	Heading
Baro-altimeter	Height
None (the IMU acts as a ZUPT detector)	Zero velocities

TABLE 1. Kalman Filter Measurements

IMU Concepts

Traditional IMUs are large, expensive, power-hungry devices comprised of orthogonal triads of accelerometers and gyroscopes. A personal navigator, such as we are describing, must be small, light, and power efficient.

In recent years, great advances in MEMS have led to the development of miniature accelerometers and gyros. These chip-sized sensors can be mass-produced at relatively low cost and meet the personal navigator size/weight/power requirements. MEMS IMUs are now being used in applications ranging from computer-game controllers to others that are more life-critical, such as automotive safety systems, military and commercial unmanned vehicles, and gun-launched munitions.

Unfortunately, the small size of the MEMS sensors comes at a cost: they exhibit errors that are orders of magnitude larger than conventional inertial sensors. These errors present special problems when using a MEMS IMU to build an INS or an inertial extension of GPS for geolocation as discussed later.

An INS is a dead-reckoning system, that is, its position, velocity, and attitude need to be initialized. Initial position is obtained from an independent source, a GPS receiver or terrain feature for example. Usually INS initialization takes place while the unit is stationary when the velocity vector can be set to zero.

Attitude initialisation (also known as alignment) is a two-step process as follows. In the first step, the orientation of the INS relative to the local level is determined by the accelerometers: when the outputs of the horizontal accelerometers are zero, they are assumed to be perpendicular to the gravity vector, however, any biases will lead directly to levelling errors: each milli-g (1 milli-g = 10^{-3} g_0 — g_0 is the gravitational acceleration experienced on Earth's surface) of accelerometer bias leads to a one-milliradian tilt error.

Requirements for space navigation are more in the range of a few micro-g (1 micro-g $=10^{-6}$ g_0). Requirements for urban and tactical navigation aided by GPS, radios and terrain features can be fulfilled by low-cost IMUs.

The second step requires alignment about the vertical axis. In a conventional system, the earth rotation rate can be used to identify east — where the component of Earth's rate is zero. Current state-of-the-art MEMS gyros have biases that are roughly equal to the earth rotation rate. Because earth rate cannot be reliably sensed, external information for heading (such as a digital compass) is required for alignment.

As long as the INS is stationary, the alignment can be maintained. Once the unit starts moving, however, it is no longer possible to separate the gravity (and earth rate signals) used for alignment from the accelerations (and rotations) arising from motion.

Sensor and alignment errors cause navigation errors to grow with time. The rate of growth is a function of sensor quality and alignment accuracy. External information is required to control the error growth. As indicated previously, the proposed integrated navigator uses a Kalman filter to accomplish this.

The vertical channel of any INS requires special attention. Due to positive feedback between computed height and gravity modelling error, the vertical channel is unstable in all inertial navigators. Consequently, external vertical control is required at all times and often includes a baro-altimeter (baro-altimeters should not to be used in a pressurized vehicle or compartment) that provides a reliable height reference in situations where neither GPS nor radio height is available.

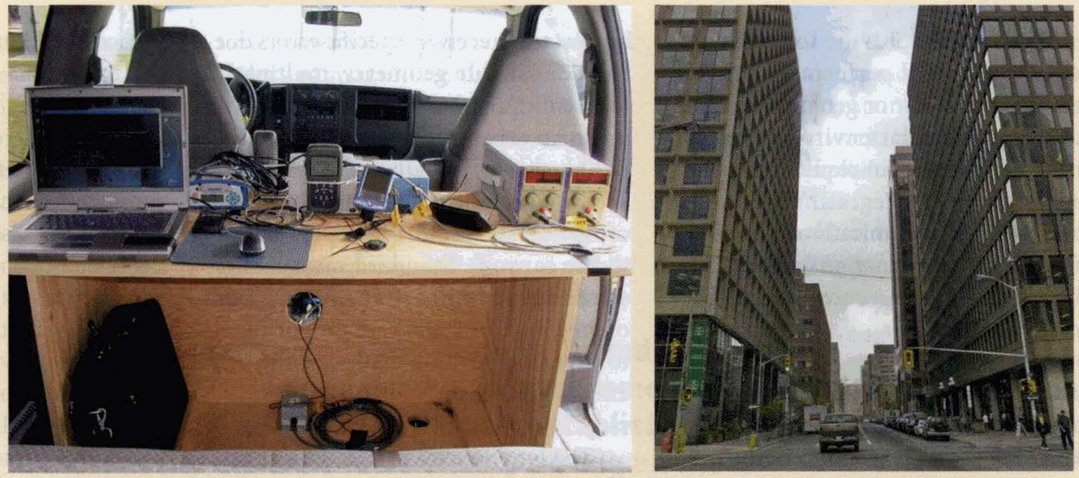


FIGURE 1 Van IMU-GPS test setup and Ottawa urban canyon

The measurements listed in **Table 1** provide a rich source of information for updating a Kalman filter and extending the accuracy of the IMU, providing pervasive geolocation and attitude under most foreseeable scenarios.

The proposed system has a very graceful degradation profile. In a typical scenario, where the user enters an urban canyon (where signal reflections, multipath, and blockage must be taken into consideration) then proceed indoors, degradation may occur as follows:

1) Outside the urban canyon, all measurements — GPS position and velocity, radio-network position, compass heading, altimeter height, and ZUPTs — will be available.
2) Upon entering the urban canyon, GPS positions (and to a lesser extent velocities) will be affected by signal blockage and multipath, the compass could be affected as well. GPS velocity is generally derived from the Doppler frequencies of the carrier signals, which are less affected by multipath than the code-based pseudoranges. In addition, carrier-based measurements are significantly more robust in indoor environments.
3) Upon entering a building, GPS positions will be further affected by blockage and multipath and will soon be lost. The compass would be affected.
4) Further inside the building, GPS velocities and positions will eventually be lost. Compass accuracy may be affected by local magnetic anomalies due to building materials and electrical equipment. A compass calibration at a location of interest may improve heading performance (to be investigated).

ZUPTs and altimeter height updates should be available at all times. Mobile ad hoc network technology (MANET), being local and adaptive, and LORAN-C, being high power, should be available most of the time except where intense interferences occur.

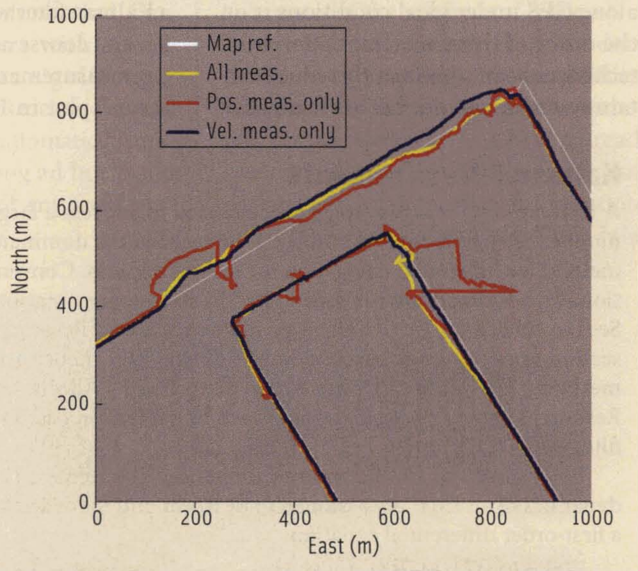


FIGURE 2 Filtering results with different measurements

Vehicular Trials

For the reported vehicular trials, a minivan was outfitted with a MEMS IMU, a handheld GPS receiver, and a digital compass. Several trials were conducted by driving the minivan through downtown Ottawa, Canada. **Figure 1** shows the layout of the van test equipment and an example of the urban environment. Data were processed post-trials, using a number of filter configurations.

Figure 2 shows a one-kilometer-square region that includes the selected urban canyon where the effects of signal blockage and multipath are most pronounced. This figure shows a reference track (whose most easterly leg appears to have a 30–40-meter offset), and three tracks from different Kalman filter measurement subsets. A high-precision reference system was not on board.

Of particular interest are the following observations:

- The run with GPS positions, velocities and course, compass heading, and ZUPTs (the yellow track) is much smoother than the positions-only run and the excursions are much smaller.
- The run with GPS position measurements only (red track) shows the largest excursions — up to almost 200 meters at one point.
- The run with GPS velocity (and course) measurements only (blue track) performs surprisingly well: it is still smoother and sometimes has smaller excursions than the all-measurement run.

These results provide some insight into the potential performance that a personal navigator or geolocator could achieve in a similar environment. We are seeking to obtain results for a personal handheld integrating pervasive geolocation, communications, and command & control functions as required for shared situation awareness in urban operations.

Accuracy Predictions

In a benign environment, we would expect the position accuracy of the Kalman filter to closely track the positions provided by the most accurate aiding sensor. The absolute accuracy of standalone GPS under ideal conditions is on the order of three meters. Differential techniques can significantly reduce certain systematic errors, but are ineffective against user receiver–specific errors due to poor satellite geometry, multipath, and so forth.

In an urban canyon or indoors, signal blockage typically results in poor satellite geometry, particularly in the cross-track direction (perpendicular to the canyon). Standard measures of satellite geometrical strength (dilutions of precision, or DOPs) are proportional to expected position errors. Multipath effects further degrade position accuracy.

The large errors in the "Pos. meas. only" (red) plot in Figure 2 are representative of the GPS position errors in an urban canyon. Combining IMU data in a Kalman filter with GPS position, velocity, and course as well as compass heading measurements, (e.g., the yellow, "All meas." plot in Figure 2), significantly reduces position errors. However, errors still exceed the requirements of indoor navigation.

This is where the positions provided by the radio network are critical. Measures from a local radio-network can be relatively precise as long as the anchoring references have sufficient positional accuracy to satisfy the target applications. (For further discussion, see the article by A. Savvides et al in Additional Resources.) Consequently, such measures would allow users to maintain position accuracy at levels adequate for most indoor navigation applications.

The tests described in the article by G. Lachapelle et al looked at GPS performance when signals were attenuated and reflected by a variety of building materials. It confirms the challenges of using GPS pseudoranges in an indoor envi-

Kalman Filter Concepts

A Kalman filter is a two-stage process used to address a large number of system control problems. It has been the dominant method for integrated navigation for several decades. Conventionally, a Kalman filter is formulated in state-space notation. See the publication by A. Gelb listed in the Additional Resources section for a thorough discussion of Kalman filter theory and methods. The report by Dale Arden also cited in Additional Resources describes a specific approach to navigation Kalman filter problem.

Following the development from these references, the dynamics of an IMU are assumed to be linear and modelled by a first-order differential equation:

$$\dot{\vec{x}}(t) = F(t)\vec{x}(t) + \vec{w}(t) \qquad (1)$$

where $\vec{x}(t)$ is the system state vector and $\vec{w}(t)$ is a random forcing function. *F(t)* is a model matrix often called the dynamics matrix. The discrete form is

$$\vec{x}_{k+1} = \Phi_k \vec{x}_k + \vec{w}_k,\ \vec{w}_k \sim N\left(\vec{0}, Q_k\right) \qquad (2)$$

The notation $\sim N\left(\vec{0}, C_k\right)$ means that all elements of the preceding vector have a Normal distribution with zero mean and a covariance matrix C, i.e., Q is the covariance matrix for $\vec{w}$. Given a starting estimate of the state vector and knowledge of its change in time (mechanised through the transition matrix, Φ_k), this recursive equation is used to propagate the states forward in time. This is the first stage of the Kalman filter process.

The second stage involves the use of external information to provide estimates of the states. True measurements are assumed to be a linear combination of $\vec{x}_k$ plus noise:

$$\vec{z}_k = H_k \vec{x}_k + \vec{v}_k,\ \vec{v}_k \sim N\left(\vec{0}, R_k\right) \qquad (3)$$

In equation (3), $\vec{z}$ is the measurement vector, *H* is the measurement matrix (defining the linear relationship between the states and measurements), $\vec{v}$ is the noise on the measurement. Again, *R* is the covariance matrix of $\vec{v}$. Actual measurements are formed by comparing INS data with external information (for example, GPS latitude minus IMU latitude). Based on the actual measurements the Kalman filter update is computed by the following equation,

$$\hat{\vec{x}}_k(+) = \hat{\vec{x}}_k(-) + K_k\left[\vec{z}_k - H_k \hat{\vec{x}}_k(-)\right] \qquad (4)$$

where the Kalman gain matrix K_k optimally weighs the measurements versus the linear transformation of the states.

The accompanying equations for the state covariance matrix are

$$P_{k+1}(-) = \Phi_k P_k(+)\Phi_k^T + Q_k \qquad (5)$$

for the propagation phase and

$$P_k(+) = P_k(-) - K_k H_k P_k(-) \qquad (6)$$

for the update phase. The signs inside the brackets indicate times immediately before (-) and after (+) a measurement update.

In an IMU-based Kalman filtering problem, errors in IMU position, velocity, and attitude are modelled as system states. IMU sensor errors (e.g., biases) are modelled as time-correlated "augmented" states. Errors states for other sensors may be added to the system states or more commonly to the augmented states.

Inspection of the covariance equations illustrates two important features: in steady state, the expected state errors will increase over every propagation interval and decrease when any measurement is successfully processed. Reduction in sensor state errors is often called sensor calibration. Reduction in the size of IMU sensor errors acts to slow the rate of navigation error growth during the propagation phase.

Aiding sensors, such as a baro-altimeter, should be calibrated. When GPS height is available, it provides an absolute height basis that can be used to calibrate the altimeter in order for the calibrated altimeter to provide more accurate heights after loss of GPS signals.

ronment and the potential usefulness of GPS velocity measurements, particularly when combined with inertial measurements. The results presented in Figure 2 suggest that a personal navigator inside a building will be able to navigate successfully with GPS velocities after GPS positions have been lost. We expect GPS positions to be lost first (loss of code lock); we expect GPS velocities to be available at much lower signal levels (phase lock).

While GPS and INS devices provide the individual or "self" location and tracking measurements, the mobile radio networking devices establish a global view of the dynamic relationship among all the nodes on the move.

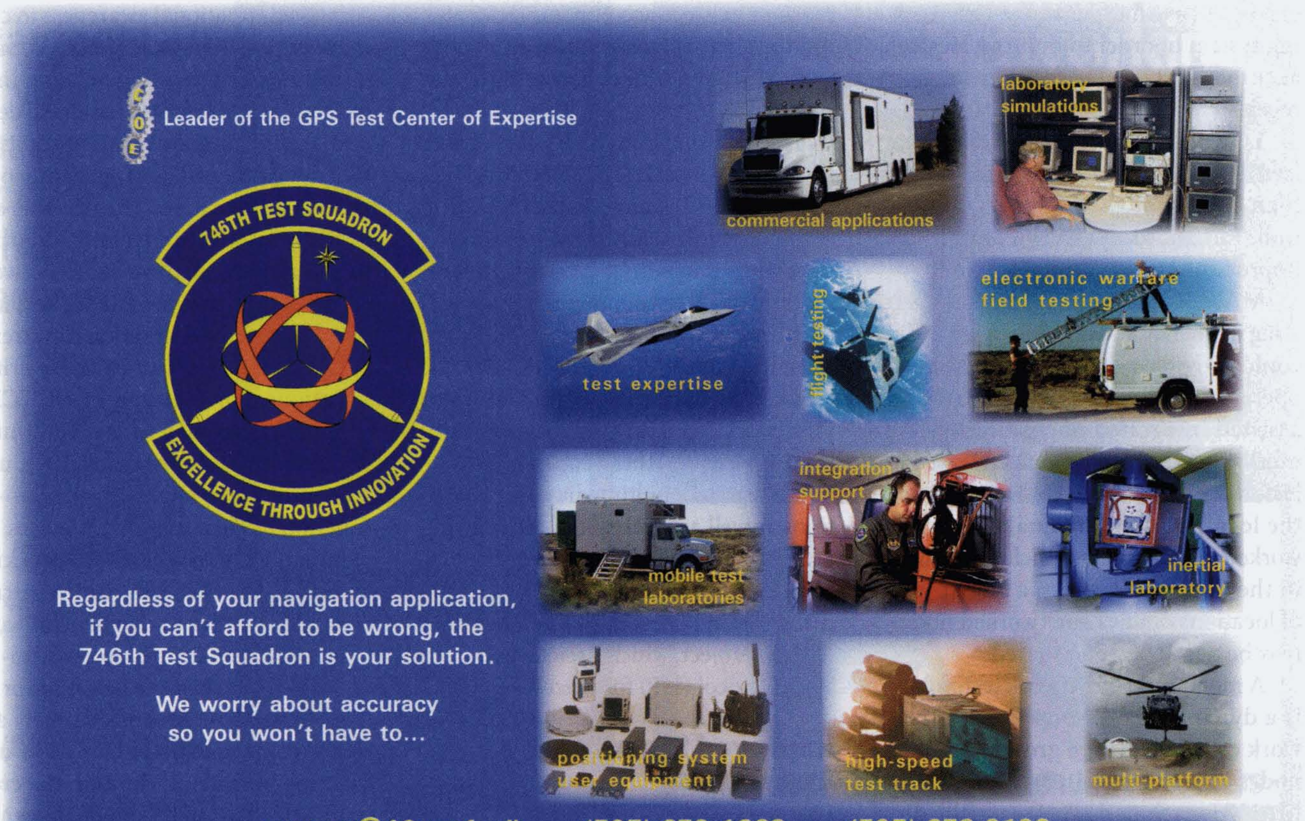
If all position measurements are lost, expected filtered position errors will start to grow. The rate of growth depends on the quality of the remaining dead-reckoning measurements. Excellent results using ZUPTs with a boot-mounted IMU have been reported by P. W. Kasameyer et al. However, the addition of measurements from a radio network and other means such as LORAN-C and terrain features would likely extend by several orders of magnitude the capabilities of low-cost IMUs, reducing the error growth below the level of that needed for most operational requirements.

Mobile Radio Networking

In mission-critical operations, a mobile radio network maintains communications among the parties involved in the operation and shares information, thus providing commanders with operational context that can significantly improve effectiveness. Recent advances in MANET enable the automatic formation of a network among ad hoc radio nodes in the absence of any fixed networking infrastructure.

Highly desirable for establishing communications among the operational personnel, such an intelligent self-forming radio network, offers information that can be exploited for enhanced situational awareness. While GPS and INS devices provide the individual or "self" location and tracking measurements, the mobile radio networking devices establish a global view of the dynamic relationship among all the nodes on the move. Complementing GPS-INS capabilities, such a communication relationship can assist us in deriving the awareness of the presence of "others."

Additionally, employing the distance- or angle-measuring capabilities of high precision radio signals, for example, ultra-wideband (UWB) or spread spectrum radio signals, the system can process and track location information of a networked radio node. This data



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can be fed as an input to the INS tracking system in order to improve location accuracy, especially under poor GPS reception, jamming or denial.

LORAN-C "provides a signal that is at least 10,000 times harder to jam than GPS" though it offers less resolution. Enhanced LORAN (eLoran) can improve on this accuracy.

MANET alone (depending on operating frequency and location of jammers) could provide a similar gain across an operational theater, giving a MANET-assisted integrated navigation system excellent jamming immunity. Nevertheless, by leveraging the network system, the locations of individual nodes networked neighborhoods including nodes in the vicinity, and even a global view of locations of all the networked nodes, may be developed and shared.

A mobile ad hoc network technology is a dynamic, multi-hop wireless network established by a group of mobile nodes on a shared wireless channel. In MANET, each node automatically discovers its neighborhood and establishes network routes with other nodes. Connecting nodes beyond one-hop radio reach or range is accomplished through multiple hops. Consequently, every node must also be capable of becoming a relay node if required.

The High Capacity Tactical Communications Network (HCTCN) MANET, developed and demonstrated by CRC in 2006, established advanced networking capabilities including network self-formation, self-healing, hierarchical routing, and automatic discovery of the presence of nodes and users. (See the sidebar, "Network Self-Form and Auto-Discovery," for further discussion of these concepts.) These capabilities provide integrated multimedia communications as well as improved node tracking and situational awareness over the network. Related efforts include the Tactical Information Distribution Enhancement (TIDE) project, which uses session initiated protocol (SIP) for voice-over-IP.

Improved Situational Awareness

The Hierarchical Optimized Link State Routing Protocol (HOLSR) and the Service Discovery (SD) capabilities described in the sidebar help the network provide improved situational awareness to commanders and personnel facing complex operations by providing position information of the integrated handheld device and associating a user's identity with that device as well as propagating other tactical information. They do this even in the most difficult terrain conditions in which non-adaptive radio networks usually fail to provide reliable services.

This improved situational awareness is especially important in safety-critical situations. For example, in HCTCN, a group of users may have a continuous coordination session where all the users communicate by applying a push-to-talk function on their handheld devices. The commander of the group needs to know all the nodes (persons) in the current network in order to decide who would be invited into the group push-to-talk session. The arrival of a new node or loss of an existing node sends a timely alert to the commander. This type of node tracking is achieved through the cross-layer information sharing between the routing layer and the SD function.

We should especially note that, like GPS signals, handheld satellite communications do not work well in buildings and infrastructures such as metro stations, urban, or natural canyons, or under adverse geometry or jamming. Conversely, MANET can get a signal through most of the time by adapting to the available connectivity and discovering new routing alternatives. The node tracking provides this advantage.

HOLSR routing identifies the removal of a node from its topology view and the arrival of a new node into its topology view. When a node *n* leaves the current network, routing layers of other nodes would find out that node *n* is removed from the topology table and inform the SD about the loss.

Upon being informed that node *n* is removed from the topology table, the SD would mark that node, monitor for its reappearance (as the node might be just temporarily out of radio reach or in radio silence), and eventually, after a prescribed observation time, the SD would confirm its absence by piggybacking a query into the HOLSR route update message. A response to the query might confirm that *n* is still reachable in the network, as well as its current IP address. Otherwise, the node is confirmed disconnected from the network.

When a node moves for a first time into or re-appears in the network or in a new cluster, it triggers a change in the HOLSR routing layer. This change prompts the node's SD function to piggyback an advertisement reporting itself, its user ID, IP address, and measures relative to other nodes (such as time-of-arrival and angle-of-arrival) estimates to be used to compute changes in topology and position). The user/commander in the current network can then optionally contact the new node immediately.

Alternatively, when a new node appears in the topology table, the SD component of a commander's node may send out a query request for the user ID according to the IP address seen in the topology table. This would let the commander or group conference chairperson be informed of a newcomer into the network without using bandwidth to set up an actual communication session with the node. The security scheme can be applied to authenticate the user ID and the node when they enter the network.

Without the tracking capability, the newly arrived node in the network is connected or known to others only when the node starts to communicate with someone in the network. Thus, more than several minutes may pass before the new node is known/heard in the network.

While the presence of the nodes and their user IDs can be automatically obtained for nodes within a cluster, a node may piggyback a query message going through the cluster head to search for a node in a different cluster/region of

the network. The auto-discovery mechanism can identify all of the user IDs and their address mappings in the network across all clusters, though the traffic volume control and security measurement would not permit every node to gather all the user ID mappings except for the specially authorized node.

Location Sharing. As mentioned earlier, the MANET's communication connections can be employed to exchange the location information of nodes. For example, in HCTCN, the GPS-INS readings, if available, are exchanged to allow the commander to view the location of each node marked on the map. This provides a networked view of global location information rather than a node only knowing its own location. Such capability presents an essential time-critical sharing of situational awareness, especially in operations where this makes the difference between mission failure and success, between fratricide and desired effect.

The possibility of combining geolocation (pervasive and persistent tracking of friendly "blue-forces") with GIS has a tremendous impact on the effectiveness of conducting a variety of operations where correctness and timeliness of information and decisions mean saving lives and securing people and assets.

Furthermore, the high-precision radio signals used in the MANET communications can also be employed to measure the distances or angles between the nodes. If approximated network distance metrics can be established, the location of the nodes can be computed using trilateration, multilateration, or other cooperative localization algorithms.

CRC has developed a cooperative algorithm that can compute the local map and merge local maps into a global map containing locations of the networked nodes. The computed map depicts the relative positions of the nodes in the network.

To translate the relative position readings into a required coordinate system, for example, GPS coordinates, anchor nodes that know their GPS coordinates are required. Given a minimum of three anchor nodes for a 2D space or four anchor nodes in a 3D space, the map with the relative position readings can be translated into an "absolute" map with all the coordinates aligned with the GPS coordinate readings. This location information can then be taken as one of the inputs into the Kalman filter of the INS to achieve a higher accuracy by compensating for GPS signal loss or other errors.

The capability to use the broadband front end of a digital radio to analyze the available spectrum and optimize frequency band allocation dynamically as function of an evolving scenario is not included in our discussion here. It is, however, a subject for current and future research activities at CRC.

Multiband Radios

Digital communications for mobiles impose unique challenges on wireless networks. The relative velocity between communicating nodes at low altitude may seriously impair information exchange, even at fairly good signal-to-noise ratios, due to fast fading and Doppler effects.

Radio-frequency (RF) passive and active devices and components are generally more efficient when operating frequencies are reduced from THz to MHz (due to ohmic and dielectric losses, resonant effects, dispersion and parasitic radiation). Although smaller components and nanotechnologies tend to alleviate this, the underplaying phenomena cannot be changed.

International and national frequency allocations notwithstanding, a similar tendency can be observed in propagation phenomena, although urban noise increases as the frequency decreases. However, the effective coverage at 150 MHz is superior to that at 1.5 GHz. (For additional details see the article by P. Labbé 1999 cited in Additional Resources.)

Reducing the mobile operating frequency by a factor of 10 extends the communication range by a factor of about five for a base station whose effective antenna height is 30 meters. If we assume that any of the radios can be used as a relay for routing in MANET, then the base station effective antenna height is the same as most participants with handheld devices, that is, about a meter.

If we assume an effective base station antenna height of one meter, one will obtain a range factor improvement of approximately four and six in exchange for reduction in operating frequencies by factors of 10 and 20, respectively. Moreover, this configuration better penetrates some underground structures, such as metro stations and caverns.

As a result the radio range extends from five kilometers to 20 and 30 kilometers, respectively. If the signal is less spread and uses less bandwidth, however, this approach may decrease the network performance in terms of low-probability of interception and channel capacity offered at the higher frequencies.

The effective throughput may also be affected by the fact that a larger coverage area on a single channel would increase the number of users sharing such channel. This can be circumvented by dynamically managing the available spectrum in order to optimize the services provided to the in-theatre participants.

Technology and Operations

The possibility of combining geolocation (pervasive and persistent tracking of friendly "blue-forces") with GIS may have a tremendous impact on the effectiveness of conducting a variety of operations where correctness and timeliness of information and decisions mean saving lives and securing people and assets. A self-aware radio informs its user about communication quality and geographical position, while providing similar information to fixed or mobile operations centers.

A unit in the field uses the radio to receive task orders and other information from an operations center or another unit. In return, the unit sends updates

on local observations, situation reports and requests for operational data.

Staff at the mobile center use the positions, situation reports, and qualitative data to improve the management of the communications assets, to plan and monitor courses of action, and to prepare operations reports for other agencies or for superiors. Exploiting the exchanged data and dynamic picture of blue-force tracking, the mobile operations center staff and task heads would be better able to optimally assign tasks to units for the desired coordinated and synchronized effects.

Dynamic Reporting of Position, Time, and Identity

There are specific requirements regarding the quality of information necessary to successful operations. Based on these requirements, we can define models to automatically update the position and identification among users and coordinating centers. Possible approaches include:

- Piggyback the information at each user transmission as an opportunity for a roll-call distributed database;
- Use thresholding techniques. First

Network Self-Forming and Auto-Discovery

The capability of network self-forming and auto-discovery contributes to the improved awareness of node presence in addition to the communication support it offers. The two key components of HCTCN, the HOLSR and the SD module, implemented the network's self-forming, self-healing and auto-discovery capabilities.

HOLSR extends the Internet Engineering Task Force (IETF) standard OLSR protocol to automatically organize nodes into clusters that belong to different hierarchies. It also establishes routes through the hierarchies. Similar to any link state protocol, HOLSR discovers the neighborhood of each node, forms the network topology view, and updates the neighborhood and topology automatically according to the movements of the nodes.

In HOLSR, to improve the network scalability, each node has a detailed topology view of its local cluster while the cluster head has a summarized topology view of other clusters. Thus a node has detailed routes for sending data to any node in its own cluster, and uses its cluster head for sending data to destinations outside its cluster. A node joins the cluster in its closest vicinity dynamically "on the fly" as soon as it moves into radio range of such vicinity.

Creating User Identity. The network topology information provided by HOLSR offers the opportunity to derive the presence of a user's node or a service (assuming that an authentication process is in place). The addresses of the nodes in the network and their topology information are collected in the topology database of HOLSR.

To identify a person or service, however, more than just the IP address is often needed: a fixed IP address assigned to each user would be hard for others to remember and impractical for the auto-configured MANET environment. Instead, we take the more suitable identifiers that are used by the communication applications to mark the person in the operations. For example, an application such as a voice or a video communication session service often dials a phone number or clicks a Uniform Resource Locator (URL) to establish the session with the destination party.

In this case, the phone number or the URL can be used to identify a specific user's node in a much more pellucid manner than the IP address. The phone number or URL can also remain the same from network to network, rather than changing it in different networks where the dynamic address configuration is performed.

In a multimedia communication session application, such as the one supported in CRC's HCTCN system employing IETF standard Session Initiation Protocol (SIP), the standard SIP URL is applied to identify a user's node and any SIP-enabled service node in the network. For example, a person named Joe Smith has a SIP URL joe.smith@unitA.ca and will use it in any of the rescue or combat missions in which he participates regardless of what MANET group he joins and what IP addresses his device assumes in the networks. This SIP URL then identifies the person of Joe Smith.

In HCTCN, anyone who wants to communicate with Joe Smith would only need to use a handheld device clicking on the entry of "Joe Smith" (joe.smith@unitA.ca) in the phone book interface of the device. A SIP session would be initialized using the SIP URL joe.smith @unitA.ca for voice, video, or multimedia communications. Therefore, the communication's ID, such as the SIP URL, serves two different functions for us: as the ID used by the communication application and the ID to identify a user's node when tracking its presence.

Using Network Topology. Now we come back to the question of how to utilize the topology view to determine if a person or a service node of interest is present in the network. Though the topology view of the routing layer only presents IP addresses of the nodes, the mapping between a user ID and the associated IP address will render us not only the presence of the user in the network, but also the user's topology and connectivity with other users and nodes.

Manually configuring the mapping between the user's ID and the associated IP address of the node is almost infeasible in an ad hoc environment. The SD function automatically maps the user ID to the associated IP address and presents the mapping to the network applications and users. The SD component is distributed on each node in HCTCN using cross-layer design. The user's ID, e.g., his SIP URL, is automatically identified from the application layer and mapped to the corresponding IP address in the network layer.

SD also disseminates the mappings into the network and collects the mappings of others from the network using the mechanism described below. In this way, a network automatically discovers the IP address for a given user ID without manually configuring any of the address mappings. Through this mapping, the user's presence and its topology relationship in the network are dynamically identified and tracked, using the address and topology information present in the HOLSR's routing database.

SD accomplishes the automatic discovery and mapping of user ID and IP addresses by piggybacking onto HOLSR routing messages. While HOLSR discovers and establishes the routes and network topology, it also derives the presence of the user's node. This cross-layer design technique, integrating network topology discovery and user ID mapping, has greatly improved protocol efficiency.

order thresholding techniques may refer to the physical size of the object tracked, its dynamic including maximum speed and acceleration, and finally the type of accuracy required for a task, e.g., define a sphere for the acceptable error. The model applied by end-user information systems can be computed locally in order to predict when some thresholds will be exceeded (time and location).

- Apply a time threshold that prompts action after a given time without an update; and
- Implement a dynamic parameter threshold that responds to changes in distance, altitude, speed, direction, or attitude.

These techniques ensure proper dissemination of available information in a manner that makes efficient use of wireless capacity. They are cost-effective with respect to channel, bandwidth, and computer use. Furthermore, they increase the timeliness and accuracy of the common information shared by mobile units and managed by coordinating centers.

During the exchange of information between the units (teams) and the coordination center, the radios continuously provide current position and time. At the operations center, a priori information about each team has been recorded: departure time, position, and name of the individuals in the team, assets used (including transceiver codes or URL), destination and estimated time of arrival at a location.

This information is also provided to the mobile team. If the estimated time is exceeded by a given interval, the team will report the current situation to the coordinator.

Conclusions and Recommendations

The integration of GPS, INS, radio and GIS into handheld, mobile and fix equipment for dispersed civilian, interagency, and military operations can bring about a significant improvement in mission success. It can also reduce undesired effects as the result of an unprecedented quality and timeliness of shared-situation awareness and an ability to synchronize efforts to deliver the right, but simultaneously timely and precise, effects.

In the extremely dynamic and complex reality of current and future operations, the proposed concepts — aided by pervasive and persistent intelligence, surveillance, and reconnaissance — represent the ultimate system-of-systems paradigm. With such systems, humans and machines are in better position to transform collected data into critical knowledge to establish and maintain cost-effective paths toward the desired end states.

To achieve the promised gains of this technology for effective network enabled operations one must realize the following:

- ensure robust networking of people and assets
- deploy sensors to report on the dynamic environment where an operation will be conducted (timely, pervasively, and accurately tracking blue, red, and neutral force elements and assets up to a single individual or asset, both for blue-force and target tracking)
- develop and adopt a shared information management strategy for exposing and sharing pertinent data to be transformed into information and critical knowledge
- train staff to contribute in transforming such data and information into the knowledge required to support the required decision processes
- share the development of a common intent, and ultimately
- exploit the networked people and assets to develop courses of actions and execute them effectively to meet goals, and
- synchronize actions for effects.

Combining information about the networks and the position of equipment positions relative to GIS and intelligence information in a meaningful operational context and its time history would significantly improve a large variety of operations. It would be easier to assign priority based on time, position and operations parameters, because all the necessary data and knowledge would be available to each network node or mobile unit.

In summary, the integration of this suite of communications, positioning, and mapping capabilities into handheld (or onboard) computer devices for dispersed civilian and military urban operations offers unprecedented information-sharing and network-management opportunities. It also enables timely shared awareness for all participants either at command centers or in the theater of action.

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DRDC is an agency of the Canadian Department of National Defence responding to the scientific and technological needs of the Canadian Forces. Its mission is to ensure that the CF remains scientifically and operationally relevant. The agency is made up of seven research centres located across Canada with a corporate office in Ottawa. DRDC has an annual budget of $300 million and employs 1500 people. With a broad scientific program, DRDC actively collaborates with industry, international allies, academia, other government departments and the national security community. More information about DRDC is available at <http://www.drdc-rddc.gc.ca>.

The Communications Research Centre Canada (CRC) is the Canadian government's primary laboratory for research and development (R&D) in advanced telecommunications. Under its four research branches (Terrestrial Wireless, Satellite Communications and Radio Propagation Research, Broadband Network Technologies and Broadcast Technology), CRC specializes in taking an interdisciplinary approach to longer-term R&D in wireless systems, radio fundamentals, communication networks, photonics, and interactive multimedia. More information about CRC is available at <http://www.crc.ca>.

Manufacturers

The sensors used for the urban canyon tests quoted in the paper are the DAGR (Defence Advanced GPS Receiver), from **Rockwell Collins, Inc.**, Cedar Rapids, Iowa, USA; SiIMU MEMS IMU (now called SiIMU01), from **BAE SYSTEMS Inertial Products Division,** Plymouth, Devon, United Kingdom; and the C100 digital compass from **KVH Industries, Inc.**, Middletown, Rhode Island, USA.

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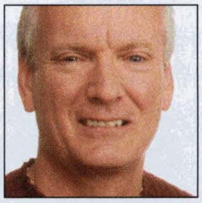

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