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A Unified Framework for a Robust Conflict-Free Robot Navigation

S. Veera Ragavan, and V. Ganapathy

Abstract**—** Many environment specific methods and systems for Robot Navigation exist. However vast strides in the evolution of navigation technologies and system techniques create the need for a general unified framework that is scalable, modular and dynamic. In this paper a Unified Framework for a Robust Conflict-free Robot Navigation System that can be used for either a structured or unstructured and indoor or outdoor environments has been proposed. The fundamental design aspects and implementation issues encountered during the development of the module are discussed. The results of the deployment of three major peripheral modules of the framework namely the GSM based communication module, GIS Module and GPS module are reported in this paper.

Keywords**—**Localization, Sensor Fusion, Mapping, GIS, GPS, and Autonomous Mobile Robot Navigation.

I. INTRODUCTION

AUTONOMOUS MOBILE ROBOT NAVIGATION methods and systems are usually environment and /or system specific, characterized by unique constraints and cannot be readily generalized. There has been resurgence in the development of Service Robots capable of missions in complex dynamic environments [1]. The value of the stock of professional Service Robots is estimated at $3.6 billion. About 25,000 units of Service Robots were installed for professional use up to the end of 2004. All of them were however highly industry, environment and task specific [2]. This highlights the push for the development of general multipurpose Service Robots and hence the need for a General Unified Framework on which these mobile robots can be built upon. In this article a Unified Framework for a Robust Conflict-free Robot Navigation System that can be used for either a structured or unstructured and indoor or outdoor environments has been proposed.

Robot Navigation is guiding a mobile robot to move to a desired goal, along a planned path in an environment characterized by a terrain and a set of distinct objects (such as obstacles, milestones, waypoints and landmarks). Motion planning is often designed to optimize specific performance criteria and to satisfy constraints on the robot's motion. The behavioral complexity and diversity of environments and the large number of objectives and constraints make the mobile robot navigation problem ill posed.

Moreover, physical platforms and sensor suites vary significantly from system to system, complicating further the task of generating a unified framework for sensing and control. While an Autonomous Mobile Robot Navigation problem can be decomposed into a number of smaller sub problems like robot localization, goal specification, goal recognition, motion planning, and sensory perception etc. the crux of handling all these sub problems as elaborated in Sections II – V, lies in handling issues related to Localization, Sensor Integration, Behavior Fusion and Framework Design.

Sensor Integration is concerned with the synergistic use of multiple sources of information. Data from sensor measurements have problems like noise, errors and inadequacy for a complete perception. More often it is the case that one cannot have a complete view of the world based on data from a single sensor. These aspects contribute to the reliability and increase the uncertainty in the system.

Behavior Fusion combines deliberative and reactive approaches. Earlier work used Hybrid Frameworks and enhanced topological maps that incorporated reactive behaviors in order to improve the robustness of mobile robot navigation [7]-[8]. Recently an increase and variety in the use of AI techniques for behavioral fusion for deliberative approaches can be seen [14].

With multiple sensors deployed, the requirements on system architecture become very demanding. For example if a single processor is used, perceptual processing will kill a resource starved Mobile Robot and will lead to severe latencies and failures in real-time control. This calls for decentralized Parallel Processing. However, if multiple processors are used, the processing times may vary from one sensor to the next and so some loose asynchronous coupling mechanism must be employed.

To integrate data from disparate sources meaningfully often requires information on Sensor data i.e. *Metadata*. Metadata is fundamental requirement to obtain a single coherent data interpretation. There is no single standard which reasonably addresses this issue [15].

Further modular design methodology is the prerequisite, since perception, planning, and control are the only problems currently being studied, and the system design is expected to change rapidly [5].

A Unified Framework that represents and provides tools to manage all these different problems has been proposed in Section II. None of the frameworks described until now

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S. Veera Ragavan (e-mail: veera.ragavan@eng.monash.edu.my) and V. Ganapathy (e-mail: velappa.ganapathy@eng.monash.edu.my) are with the School of Engineering, Monash University at Sunway Campus, Malaysia.

achieves this objective for different types of applications and scenarios and research is still at its infancy.

Experimental validation of the framework is discussed and the results of the deployment of three major peripheral modules of the framework namely the GSM based communication module, GIS Module and GPS module are reported in Section VI of this paper.

II. THE UNIFIED FRAMEWORK FOR A ROBUST CONFLICT-FREE ROBOT NAVIGATION

A. *Survey*

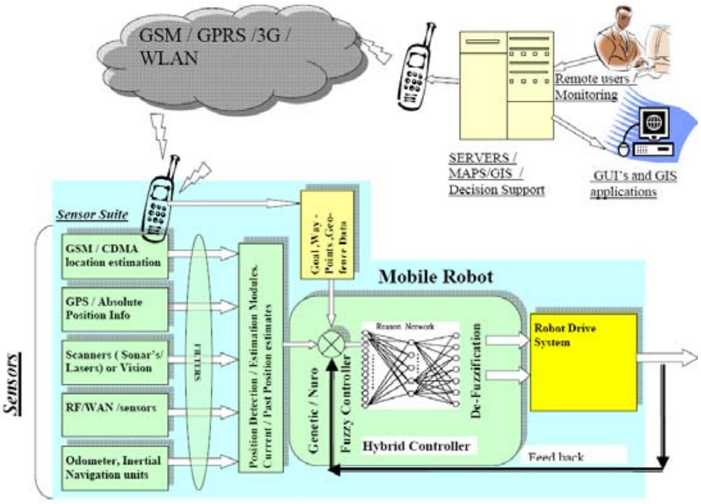
A survey of the vast body of literature in mobile robotics leads us to conclude that while many techniques that perform robust robot navigation in appropriately constrained environment exist, none of these appear to have been designed to work when the constraints are relaxed and obviously not in general environments[5].

Another problem with the research efforts has been the individualized nature and limited scope of the published work. Most researchers take a specialized sub- problem (such as robot localization) of the mobile navigation problem and then propose a solution for that. However, a higher level implementation that uses the proposed technique for solving the sub-problem in conjunction with other algorithms required for performing robust robot navigation is often missing. This we believe has lead to very little research work in the area of generalized autonomous mobile robot navigation.

B. *Generalized System defined*

Generalized autonomous mobile robot navigation systems are capable of performing all the various robot navigation related tasks in a robust and efficient manner without placing any constraints on the characteristics of the environment or the robot. Typical robot navigation tasks include robot localization, goal specification and recognition, motion planning, obstacle avoidance, and sensor fusion.

The difficulty in creating such a generalized robot navigation system is apparent. We do not propose to create such a system, but instead propose a frame work that can be used for creating a navigation system for any environment specified. While this navigation system may still be environment dependent, it is hoped that the frame work will provide the designers with an easy and efficient methodology for adapting the navigation system to changes in the environment.



A Unified Framework for a Robust Conflict free- Mobile Robot Navigation System

C. *The Operating Environment*

The operating environment of a generalized mobile robot navigation system can include:

- Outdoor and indoor locations
- Structured and Unstructured environments
- Rough and smooth terrain
- Stationary and moving obstacles
- Structured and unstructured landmarks
- Single or multiple robots
- Sensor Suite with assorted sensors models and types

D. *Assumptions*

No assumptions are made on the a priori knowledge about any of the features mentioned above. A generalized system must be able to perform navigation when the environment and all its characteristics are completely known (either a priori or through learning) and when they are completely unknown.

E. *Unified Framework Defined*

We define a Unified framework as a general methodology that allows easy adaptation of a mobile robot navigation system to changes in the constraints and assumptions associated with the operating environment. The primary task of a generalized framework is to create a navigation system that can perform robot localization (absolute or relative), multi sensor fusion, motion planning given the characteristics specifying the environment. This environment can possess any subset of the characteristics associated with generalized mobile robot navigation system.

F. *Information Storage and Exchange*

A framework provides a presentation for storing information acquired about the system, either through prior knowledge or while performing navigation. It also provides a set of tools for updating information stored in this representation. Along with the representation and the tools there also exists a methodology that defines how the tools can

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be used to update the representation

G. Problem Decomposition

The Autonomous Mobile Robot Navigation problem can be decomposed into smaller sub problems that deal with robot localization, goal specification, goal recognition, motion planning, and sensor fusion. Various methods and techniques have been proposed for solving these problems in different environments.

H. Core Areas and Modularity in Design

We do not propose to cover all the problems, but instead concentrate on three primary areas that the frame work will leverage upon to create a Conflict-free Robust Navigation System:

- Localization
- Sensor Integration,
- Behavior Fusion

It can be seen from the figure above that the frame work is sufficiently modular to handle the hardware and software aspects of a unified framework.

I. System Architecture for the Framework

The Choice of an Open Distributed System Architecture as the best for this Unified Framework is not debated here.

As it can be clearly seen, while the framework unifies the diversity, the success and coherence of the Distributed system architecture lies in its open heart. This places undue stress on the selection of a Communication Layer.

The Distinguishing feature of this Framework is the true mobility leveraged through the Mobile Communication Network. With the GSM/GPRS communication as the network platform, Mobile Robot graduates to a Borderless Tele-robot. With the price of GSM/GPRS modules and data call charges reducing by the day, it is only logical that the mobile robots will always remain connected.

J. Advantages and Features

With the GSM/GPRS communication platform of choice all the advantages accruing out of the combination is extensive and is not discussed here. The main advantages of the architecture in the context of Mobile Robot Navigation are as follows:

1. Permits outsourcing of computation intensive processes to Remote Servers and Decision Support Systems through open and secure Protocols.
2. Mobile Robot can poll for Issue Based Support. E.g. map request, location estimation, an optimal path plan, waypoints and Landmark assistance from GIS server.
3. Regular and periodic data archival and historical data request. A major advantage for training and dynamic learning.
4. Enjoy location based services etc., based on the current location e.g. Robot Refueling location, Ubiquitous computing.
5. Dynamic task scheduling and route / reroute plan (like radio traffic, meeting and coordination info etc.)
6. Over the air firmware upgrade- freely reprogrammable remotely. (E.g. go to location A as Lawn tending robot and upgrade firmware (excluding the generic application layer) while at A to become golfer's companion and go to location B.)
7. Web enabled and networked sensors can be hooked to provide additional support. E.g. Receive a basement car park flood alert.
8. GSM localization using Cell ID and other statistical location estimation services - can compliment absence of GPS position estimates. E.g. in basement car parks etc.
9. More robust connections and always "ON" network support.
10. Cost effective, multiple data transmission options with fallbacks without programming overhead. E.g. Small amounts of data can be transferred through SMS text messages to the mobile robot and larger packets through GPRS, data call, Bluetooth etc.

III. LOCALIZATION PROBLEM

Exact knowledge of the position of a vehicle is a fundamental problem in mobile robot applications. In search for a solution, researchers and engineers have developed a variety of systems, sensors, and techniques for mobile robot positioning. This relevant mobile robot positioning technologies that are used for localization is classified into seven categories [11]. They are Odometry, Inertial Navigation, Magnetic Compasses, Active Beacons, Global Positioning Systems, Landmark Navigation and Model Matching.

Global Positioning System (GPS) provides continuous positioning information, anywhere in the world under any weather conditions so long as the receiver has a direct line of sight to the sky.

GPS [12] consists, nominally, of a constellation of 24 operational satellites. For the purpose of this paper, a commercial GPS device was used to periodically obtain relevant GPS information.

Apart from providing positional information, GPS also provides a host of other useful information like accurate time, speed and bearing during traveling motion. This also helps in synchronizing sensor system clocks [13].

IV. SENSOR INTEGRATION / FUSION

A. Sensor Integration

Sensor integration is concerned with the synergistic use of multiple sources of information. Sensor fusion is a major component of sensor integration, merging multiple inputs with a common representation. Sensor Data fusion cannot be viewed in isolation. The Fusion of data can be done in multiple stages, across multiple layers or at different hierarchical levels [3]-[4].

More often one cannot have a complete view of the world based on data from a single sensor. Apart from issues of data inadequacy for a complete perception, data from multiple sensors have problems like noise and errors. These aspects contribute to the reliability and increase the uncertainty in the system. A poor fusion result can result in catastrophes and be worse than single sensor perception.

B. *Classification of Integration Techniques*

Sensor Integration techniques are broadly classified in two categories: Low-level fusion where direct integration of sensory data, results in parameter and state estimates and High-level fusion where indirect integration of sensory data in hierarchical architectures, through command arbitration and integration of control signals suggested by different modules results in higher level estimates and deliberations. In the "gray" area between the two classes are architectures that synthesize command and control signals directly from sensory input—often without explicit construction of environmental models.

Fusion of sensory information between layers is achieved as the high-level layers draw information from lower-level layers to synthesize their own estimates and decisions. The translation of sensory input into layer decisions (the synthesis of reactive and deliberative behaviors) have been demonstrated using Potential Fields for obstacles, Rule-based Expert Systems, Fuzzy Logic, Neural Networks and Genetic Algorithms

C. *Classification based on Sensor Types*

Sensor Fusion can also be categorized into three classes: Complimentary sensors, Competitive sensors, and Cooperative sensors. Complimentary sensors do not depend on each other directly but can be merged to form a more complete picture of the environment and is relatively easy to implement since no conflicting information is present. One example is a Remote Web Camera covering disparate geographic regions. Competitive sensors provide equivalent information about the environment usually for redundancy. For example, a configuration with three identical sensors can tolerate the failure of one unit. This is a general problem that is challenging, since it involves interpreting conflicting readings.

Cooperative sensors work together to drive information that neither sensor alone could provide. An example of cooperative sensing would be using two video cameras in stereo for 3D vision. This type of fusion is dependent on details of the physical devices involved and cannot be approached as a general problem.

D. *Survey*

Just as we have multiple options and requirements for data fusion, we also find different solution approaches for this problem. Researchers use statistical analysis like mean, average, median, standard deviation, correlation and variance (the Kalman Filter Algorithm) or heuristic approaches to manage the uncertainty, such as probabilistic models based on Bayesian Networks or uncertainty sets, possibility models based on Fuzzy Logic and Dempster-Shafer theory, or learning algorithms based on Neural Networks and Evolutionary Algorithms, and Hybrid Systems. None of the frameworks described until now achieves this objective for different types of applications and scenarios and research is still at its infancy.

E. *Hardware and Design Constraints*

With Multiple sensors deployed, the requirements on system architecture become very demanding. If a single processor is used, perceptual processing will kill a resource starved Mobile Robot and leads to severe latency and failures in real-time control and calls for decentralized Parallel Processing. However, if multiple processors are used, the processing times may vary from one sensor to the next and so some loose, asynchronous coupling mechanism must be employed.

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F. *Fusion Issues and Standards*

The Distributed Sensor nodes must be synchronized. This can be done internally (through synch pulses) or externally (through synchronization). GPS easily provides the capability to allow the external synchronization of clocks at major nodes within a network to better than 100 ns in time and 1/10 in frequency [13].

Integrating data from disparate sources needs information on Sensor data i.e. Metadata. Metadata are fundamental inputs necessary for data fusion like Geometric reasoning, transformation data, timestamps and timeliness of input data, geospatial info which are needed for a single coherent data interpretation. There is no single standard which reasonably addresses this issue [15].

G. *Design and Implementation Issues Anticipated –Data Representations, Storage and Exchange*

Storing information acquired about the system, either through prior knowledge or while performing navigation. Updating information stored needs tools and pre defined methodologies for use and updating the existing representations. Thus it necessitates creation and provision for a formal data fusion module in the framework that maintains and provides tools to manage all these different problems.

V. BEHAVIOR FUSION

A. *General Behavior-Based Control*

Questions regarding representation and behavioral organization are of pivotal concern in AI and robotics. Control architectures provide a means of principally constraining the space of possible solutions, often focusing on particular representational or planning methodologies, in order to render practical problems achievable. A variety of architectures with different underlying principles have been proposed and demonstrated for robot control.

B. *A brief Survey on Behavior-Based Control*

Behavioral fusion combines deliberative and reactive approaches. Earlier work in hybrid systems includes that of Murphy et al. [7] who developed the Trulla Hybrid Framework and Ryu and Yang [8] who utilized an enhanced topological map that incorporated reactive behaviors in order to improve the robustness of their mobile robot navigation.

David Mulvaney et al. [9] used a reactive navigation system to acquire waypoints as inputs for later deliberative planning. The deliberative navigation system also incorporates exploration to allow additional waypoints in the robot's environment to be discovered if time permits thus reducing both the computation time and memory requirement.

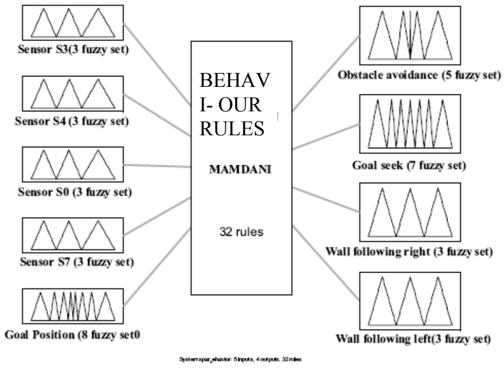


Fig. 1 Sample Framework for Behavioural Fusion [14]

C. *Proposed Approach for Behavior Fusion*

Recently an increase and variety in the use of AI techniques for behavioral fusion approaches can be seen [14]. To accomplish this, we have proposed a hybrid framework using Probabilistic and AI techniques. Use of a Hybrid Controllers is seen as a major flexibility and advantage. The additional computational overhead can perhaps be offset by outsourcing other tasks as such provisions already exist in our framework.

VI. EXPERIMENTS

Experimental validation of the framework began with building simple prototype and peripheral support modules and integrating them to core modules. The following Modules have been developed and integrated.

1. GPS based Position estimation and detection modules
2. GSM/GPRS based Communication Modules
3. Global Information Systems (GIS) and Mapping Systems

For the purposes of testing the Modules the GPS and communication modules were deployed on a car and driven around. The details of the tests and results of the individual modules tested are given below.

A. *GPS for Absolute Position and Time*

Experiments were done to verify the following general claims using Motorola M12+ oncore © GPS modules and to acquire real time data from deployed guided vehicles.

- Obtain exact location (longitude, latitude and height co-ordinates) accuracy range of 20m to approx. 1 mm.
- Ability to obtain precise time (Universal Time Coordinated, UTC) accuracy range of 60ns to approx. 5ns.

Real time GPS information was obtained by fitting it on a guided vehicle and accuracy measurements through manual deployment. The log was taken at different times of the day and at various venues. The raw format of the log was transferred to a computer.

The experimental set up used to evaluate the units is shown below.

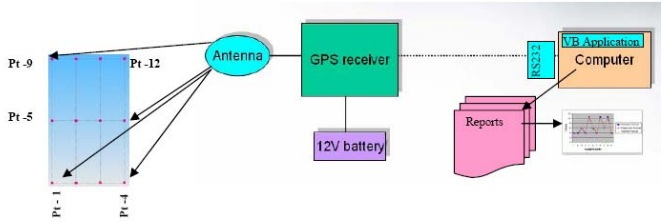


Fig. 2 Experimental set up for GPS Error Estimation

A rectangular grid with 12 points was used to check the error distribution. The distance and bearing between two Latitude/Longitude was calculated using Haversine, Vincentry ellipsoid and Rhumb Line formulae. Experiments show that localization errors of sampled readings ranged from 3 to 20 meters.

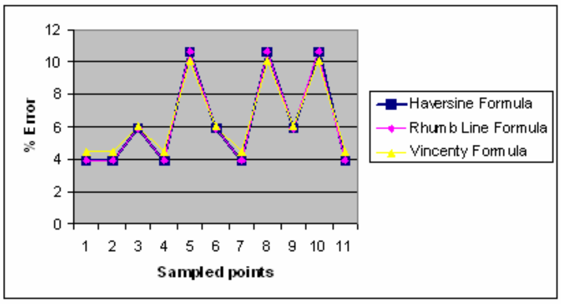
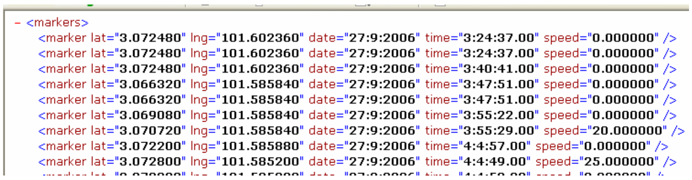


Fig. 3 GPS Error estimation

A Visual Basic application was developed to provide two output files [10]. The first is raw data in CSV format which contains real-time track report of the deployed GPS unit at predefined intervals. Reported data includes positional data, time, date, speed and distance traveled and other sensor data. The user can use Microsoft Excel to view and analyze.

The second one is an XML format file which is in a form ready for export to GIS applications. This file can be viewed currently in historical fashion in map through map servers like Google Earth© through its API. This integration will allow the plotting of coordinates on Google Earth hence revealing the path and position of the Deployed GPS Unit.



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- <markers>
    <marker lat="3.072480" lng="101.602360" date="27:9:2006" time="3:24:37.00" speed="0.000000" />
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```

Fig. 4 XML output from the VB application

B. *GSM based Communication Modules*

The Communication server has a Data Receiving and Transmitting Module (DRTM) developed as two independent plug-in modules that can send and receive SMS text messages. Due to SMS text message size limitations, six Location records and On-Board sensor Info are time tagged and sent as one SMS packet for bandwidth optimization. The modules are Windows based and not platform independent as yet.

C. *GIS as Mapping and Decision Support Systems*

The GIS application was developed and implemented using JavaScript, HTML, XML and Google Map© API's [6]. A sample plot of the XML data obtained above is shown here.

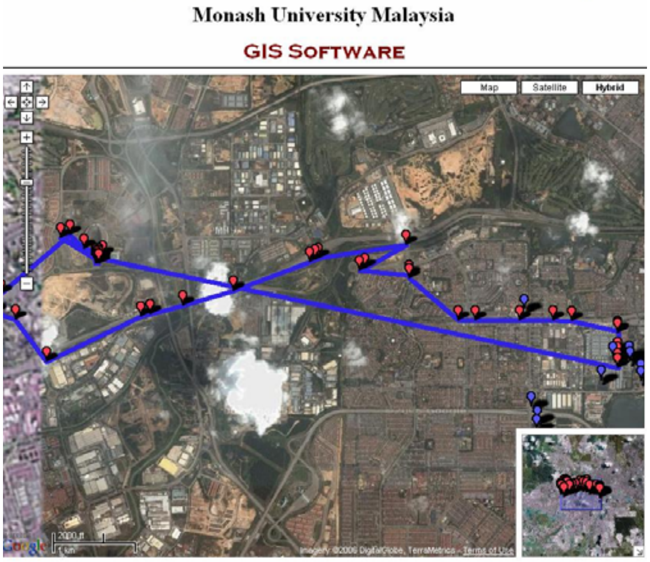

Fig. 5 Historical Replay of Mobile unit's path which can be used as trip info for future trips

From GIS higher level deliberations can be generated by "Just Clicking" on the Map. For example

- path ,
- waypoints, rerouting
- goal info etc.

A XML file of these deliberations for example in this case absolute position info can then be transmitted to the Mobile Robot through the DRTM Module developed above.

GIS can also be used as a Data Base tool to store Geo spatial info gathered. These can be provided as a High level Location assistance or Issue based Decision Support. E.g. provide snapshots or 3D-Laser scan template info for Exteroceptive based Localization [16].

D. *Experimental Framework - Results*

While it will be long before Robots or AGV's can freely navigate in public domain, the success of the above modules prove that a General framework can developed. It can be seen as a first major step in achieving the goal of Autonomous Robot Navigation.

VII. CONCLUSION

We have aimed to acquaint the reader with the issues faced in autonomous mobile robot navigation. The autonomous mobile robot navigation problem can be decomposed into smaller sub problems. Various methods and techniques have been proposed for solving these problems in different environments. The complexity of the navigation problem increases with uncertainties in the environment and multiple sensors. Current techniques fail to perform robot navigation in minimally constrained environments given uncertainties arising due to the above mentioned factors.

We believe that while it is very hard (if not impossible) to find a single robust technique for robot navigation that will perform well in minimally constrained environments with varying characteristics, a generalized framework approach can select from a repertoire of such methods based on the environment the robot is currently operating in. To accomplish this, we have proposed a hybrid framework that is modular, scalable and dynamic. The successful deployment of three major peripheral modules namely the GSM based communication module, GPS Module and GIS Module can be seen as a major Milestone in the development of the framework as GPS module, Communication Layer and Decision Support Layers are preconditions to success of the framework.

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