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This paper discusses research efforts at the Naval Research Laboratory (NRL) in the area of environmentally adaptive navigation and dynamic mission planning. Presented in this paper is the system architecture being developed for the accomplishment of objective based dynamic navigation. A simulator is being constructed that incorporates this architecture and its design is presented. This simulator will enable the future development of specific mission behavior modules.

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OBJECTIVE BASED DYNAMIC NAVIGATION PLANNING

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Abstract

This paper discusses research efforts at the Naval Research Laboratory (NRL) in the area of environmentally adaptive navigation and dynamic mission planning. Presented in this paper is the system architecture being developed for the accomplishment of objective based dynamic navigation. A simulator is being constructed that incorporates this architecture and its design is presented. This simulator will enable the future development of specific mission behavior modules.

I. Introduction

Objective based dynamic navigation planning addresses the need for adaptive planning and execution of environmental surveys. In general the objective of a survey is not to simply turn a sensor on and to have the vessel that is carrying the sensor navigate through a series of waypoints. Rather, the typical objective is to use the sensor to characterize the environment in some fashion; for swath type sensors (sidescan, video, bathymetry, altimetry, etc.) the objective is often to achieve full area coverage of a terrain. The design of a survey planning and execution system should thus be built around the objective of a particular survey using realistic system/vessel models for survey planning or in situ assessment of sensor/vessel performance for survey execution.

The research exhibited here is part of the Environmentally Adaptive Navigation (EAN) effort at the Naval Research Laboratory that primarily focuses on adaptive navigation. The rational behind this focus is that given an estimate (or in situ measurement) of a particular sensor's characteristics, the problem of achieving the stated mission objective typically becomes a problem of deploying the sensor at the proper positions and orientations – i.e. vessel navigation. In particular, this research focuses on achievement of mission objectives with fully autonomous vessels without the benefit of human judgment to contend with unforeseen circumstances. EAN is building on the previous AutoSurvey [1] work at NRL and is concentrating on swath type sensors at this point in the research.

The present research effort is the development of an EAN simulator. The goal for this simulator is to provide a flexible and generic platform for objective based planning of surveys with multiple types of vessels and sensors, and will encompass the AutoSurvey algorithms as part of its initial development. The AutoSurvey system generates adaptive navigation lines for bathymetric surveys within a defined boundary and is being transitioned to the NAVOCEANO hydrographic survey fleet. AutoSurvey provides only one of the many intelligent behaviors that will be required to optimally and autonomously conduct a full swath sensor survey. The architecture of the EAN system discussed in this paper strives for the ability to easily incorporate new system behaviors as they are developed.

The EAN simulator will also provide an excellent tool for planning swath sensor surveys. It is designed to take into account the sensor footprint on the terrain being surveyed, and thus its accuracy in predicting sensor coverage and time in survey will be better than traditional flat bottom or rule of thumb methods. This will allow survey planners to get a better idea of the required direction, shape and spacing of the survey lines required to meet the mission objective. In doing so, time at sea and survey distance can be minimized, and survey area coverage can be optimized. A secondary function of this research is the study of various coverage patterns and maneuvering techniques and their effect on survey coverage and time-in-field efficiency.

This next section of this paper provides some background on the need for environmentally adaptive navigation and discusses the primary design objectives of the EAN simulator. Section III discusses the system architecture and functional system design to achieve an objective based adaptive navigation system. Finally, Section IV summarizes the EAN simulator development and discusses future planned efforts.

II. EAN System Background

Environmentally adaptive navigation for swath sensors is of particular importance due to the variations that can occur in a sensor's achieved coverage area. Swath sensors typically have a fixed angular swath that translates to a variable footprint, the size of which depends on a multitude of factors. For a vessel traveling in level flight, variations in the distance from the vessel to the terrain cause a change in the swath width; the greater the altitude over the terrain, the greater the swath width. Variations in swath width are also experienced for constant altitude (terrain following) vessel flight due to rough terrain, crabbing, and occlusion.

Clearly, adaptive navigation is needed to optimize vessel deployment, i.e., to ensure full area coverage and to minimize wasted time. Ideally, swath sensor operations would utilize dynamic mission planning during the execution of a deployment. Dynamic mission planning utilizes adaptive navigation based on the in situ assessment of mission objective accomplishment as realized by the actual vessel sensor performance. This is obviously preferred over pre-mission planning, because decisions are made based on current, local sensor data instead of based on predicted data from models or databases and assumed sensor performance.

Mission planning for a swath sensor based survey is typically accomplished using greatly simplifying assumptions on the vessel, sensor and area terrain, and generates a series of evenly spaced parallel lines. Consequently, significantly better pre-mission planning can be achieved using adaptive navigation that incorporates better models of sensor and vessel performance as well as the best knowledge available on the area terrain.

Because the placing of the vessel/sensor in the desired location and orientation is fundamental to successful accomplishment of most phases of survey/search operations in general, the focus of the EAN system has been primarily on adaptive navigation. The architecture of the system was designed to facilitate the study and development of other survey/search related operations, including obstacle avoidance and continuation of a mission after unavoidable interruption (i.e., deviation from the planned track). The design goal of the EAN simulator was to create a suite of software modules that work together to simulate realistic data collection surveys in which the primary sensor system is swath based.

From the outset, the thinking on the EAN project was to go beyond a simple simulator implementation of AutoSurvey and to create a portable UUV data collection and navigation system whose architecture would lend itself to the incremental integration of new capabilities.

The system was also specifically designed to provide a platform to develop, implement and test new dynamic mission planning algorithms. While the primary objective of the present EAN development was the development of a simulator, a flexible architecture goal was pursued to facilitate transitions to vessel control systems. This design goal was to be accomplished by the clear delineation of specific system dependent and independent functions. Key algorithms such as next line generation and obstacle avoidance were to be part of system independent libraries, while access to actual sensors, motors, and communications equipment (or their simulated counterparts) were to be handled by a set of operational application program interfaces (APIs). A transition from the simulator to a physical system would thus involve changing the data path of the "sensor driver" and the "navigation driver" modules from simulated data to physical, real world data.

Key design features of the EAN simulator include:

- Generation of more realistic sensor swath coverage estimates by using better models for the environment, vessel and sensor:
  - o Utilization of a digital terrain map (DTM) of the area
  - o Simulated survey vessel performance bounded by the target vessel's attributes – bounded turn and acceleration/deceleration rates. The simulated vessel should not be allowed to execute maneuvers that a real vessel could not. Vessel flight modes should include level flight or terrain following. A generic vessel model is desired that can easily represent any target vessel given a defined set of maneuvering characteristics.
  - o Sensor model that includes maximum slant ranges, occlusion

detection and sensor orientation/position with respect to the terrain map. A generic sensor model is desired that can easily represent a large variety of swath type sensors with just a change of parameters.

- 3d graphic representation showing the survey area, the ships progress, current sensor field of view, and current accumulated survey statistics
- The ability to use a variety of vessel navigation methods including parallel, uniformly spaced, preplanned lines and lines that are adaptively generated using the AutoSurvey [1] algorithms.
- The ability to easily integrate new behavior modules required to accomplish specific mission objectives
- Assessment of mission performance in terms of required mission time and achieved sensor area coverage.
- The ability to generate track line waypoints that could be used for an actual vessel survey.
- The ability to run the system on a single machine, or in a distributed mode over a network.
- A system architecture that lends itself to migration, in whole or in part, into physical vessel systems. By replacing modules such as the swath sensor simulator, vessel motion simulator, etc, with their physical counterparts, the transition can be made in an incremental manner.

III. Architecture and Functional Design

The design of the EAN simulator is described in the following subsections. The design's conceptual and functional issues will be discussed as well as those that concern the implementation of the system.

A. System Architecture

1. Objective based conceptual Architecture

Figure 1 below illustrates the conceptual view of the system, from a decision/thought process point of view. Figure 1.a is a general system that may or may not include navigation. Figure 1.b is one step less general and is focused on navigation. The main idea is that the autonomous entity can determine its next action, given its state at some point in time, based on its perception of the environment, and a toolbox of goal oriented algorithms. The action/sensor feedback loop guides the autonomous entity towards its goals.

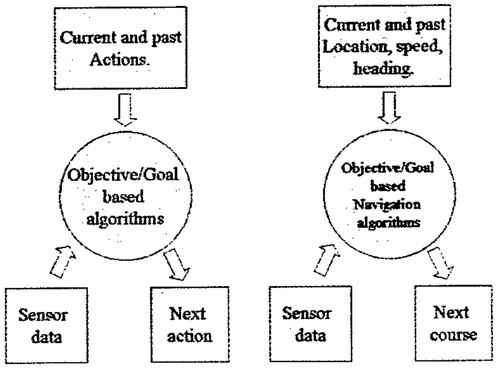

Figure a. Figure b.

Figure 1. These two figures show the overall conceptual view of the EAN system. Figure a. shows the conceptual view of a multipurpose system, while figure b. shows the navigation system.

In its current state the EAN simulator would most closely match Figure 1.b with the understanding that there is only one goal based set of algorithms, those of the AutoSurvey library. A logical progression for the system is to develop the ability to avoid obstacles and to optimally recover the data missed during the obstacle avoidance maneuver. Other functionality such as a power saving mode, or a feature-seeking mode, would enhance the value of the system. These functions would all be system independent to the extent that they can be modeled based on generic sensor types (swath, point, profile, etc.) as opposed to specific system interfaces and data formats. Figure 2 shows a conceptual flow diagram incorporating these features.

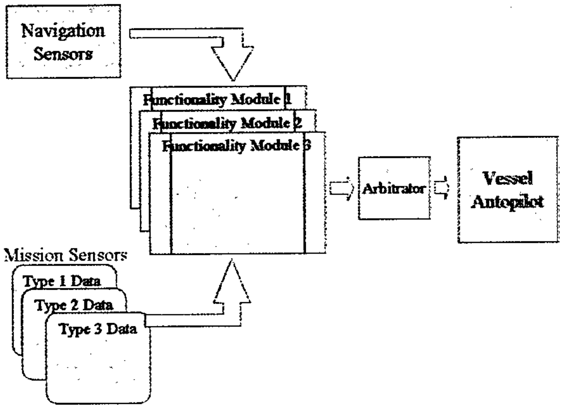

Figure 2. This figure shows the interaction of several generic functionality modules. The Arbitrator module sorts out any conflicts so that the input to the Autopilot is a coherent set of navigation objectives.

Note that in Figure 2 vessel positions and sensor data are concurrently available to each different type of functionality. The *Arbitrator* module resolves any conflicts that may arise from the different functionality modules so that a coherent stream of positions is passed to the *Autopilot*.

2. Mission Objectives Arbitration

Since multiple navigation objectives may exist at any given time, an arbitration scheme is required to choose the correct system behavior. A subsumption approach is taken in the EAN system design for the arbitration. The architecture shown in Figure 2 is based on Rodney Brooks' Subsumption Architecture [2]. Subsumption, as it was originally labeled, was introduced as a method to control mobile autonomous robots that operate in an unstructured environment. Later articles refer to it as Behavior programming.

Subsumption methods have been used effectively to control robots in various settings where multiple behaviors are needed to produce the desired functionality. MIT's Allen robot [4] was programmed to wander, seek out distances far from it, and avoid objects. A more complex functionality was achieved by using more behaviors in MIT's Herbert robot. It was able to operate into cluttered office spaces while people were present. Its purpose was to go in to offices and collect empty soda cans. By combining various behaviors such as wandering, wall following, obstacle avoidance, can recognition, and grasping, Herbert was able to do useful work in a changing unstructured environment. It did not use world models and there was minimal inter-behavior communication. Most of the inter-behavior communication was accomplished by using the environment as the information transmission medium.

The above examples describe systems of opportunity, sometimes referred to as reactive systems. The systems work well because their hierarchy of responses to sensor inputs is set up well for the environment they inhabit. Since there is no modeling of the environment or any part of it, there can be no optimization. Some hierarchies may be more effective than others, but because of the lack of a modeling structure, there are no preplanned events.

Conversely, cognitive systems use a world model on which to base their decisions. The world model can either be pre-programmed or built with sensory inputs. If the model is correct and can remain updated, and the computing equipment has adequate speed for the given task, system events can be planned with a degree of optimization.

There is no requirement that a system be all reactive or all cognitive. Ferber [5] describes a hierarchy of modules for an explorer robot based on a subsumption architecture in which the more reflexive modules, like obstacle avoidance and replenishing energy, can subsume the cognitive behaviors, like making maps and exploring.

3. Subsumption Based EAN Architecture

Figure 3 shows the EAN survey functions as a similar hierarchy. As in Ferber's explorer robot, the more reactive behaviors dominate the cognitive behaviors.

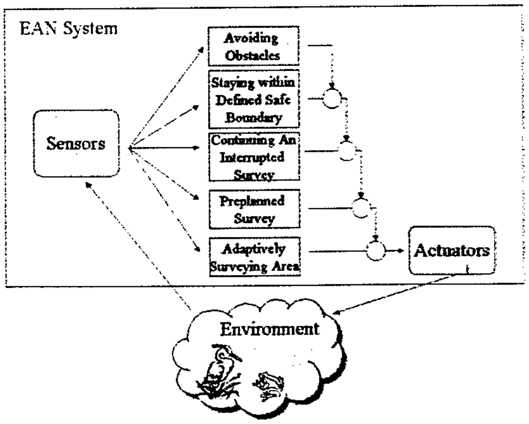

Figure 3. Model of the EAN system based on subsumption architecture. Note that the more reactive modules such as avoiding obstacles have precedence over the cognitive modules.

EAN is set up using a subsumption like architecture. Although subsumption is usually associated with reactive systems, in EAN some of the behavior modules will be cognitive, e.g., the Autosurvey module. The more reactive modules will be higher in the hierarchy than the cognitive modules. The overall functionality will be that of a system that spends most of its time and resources executing primary goal modules, i.e., the survey control routines in the AutoSurvey module. But when the occasion arises, the more reactive modules (e.g., obstacle avoidance) will subsume the goal modules. As in other applications of subsumption, all modules will execute in parallel and each will have access to the sensor data that they need.

The interior architecture of the various behavior modules of EAN may or may not be subsumption based. Because the obstacle avoidance module is by nature reactive, it will likely be subsumption based, while the more cognitive AutoSurvey module will not. Thus, in cases where needed, subsumption will be nested.

The EAN system behavior hierarchy will be static during actual surveys, thus increasing system predictability. The system designers will establish the initial hierarchy, but a statistical hierarchy-arranging scheme similar to that used by Maes [3] for walking robots will be investigated. The effectiveness of hierarchies derived from several different survey scenarios will be compared.

B. System Functional Design

The EAN simulator is a suite of software modules that work together to create a swath sensor simulation system, including vessel and sensor simulation modules. The modules are arranged into four distinct levels of abstraction. In general, all modules in a particular level are related to one another either by function, or by attribute. By using levels, the software can be constructed and tested in an incremental manner. This methodology can also be used to increase the portability of the system.

1. Advantages and Disadvantages of the Multi-Level Approach

The main advantage of arranging software in levels is complexity reduction due to abstraction and modularity [6]. By hiding the details of operation from level to level, the intra level complexity is reduced. In general, upper levels deal with conceptual issues while lower levels handle the mechanics of getting the work done. Portability and ease of development and testing are also distinct advantages of multi-level design.

Because of the distinct separation of the various software modules, this approach may not lend itself to embedded systems, or to systems that are limited by memory or speed. The inter-module communication protocols cost the system time when compared to making direct calls. The hiding of details by levels of abstraction has a similar effect in that it increases the average height of the runtime stack, thus requiring more time and memory. Because of the increased average stack height, more time is spent managing the parameters associated with module calls than would be spent in a comparable tightly coupled system.

2 EAN Levels

The EAN software is arranged into four distinct levels. It is similar to the UNIX system layout in that there is one level that is system dependent, Level 4. One of early design goals was to create an architecture in which there existed clearly defined API's and a separation of system dependent and independent modules. The separation of dependent and independent functions is described in more detail in the EAN level 3 discussions. The separations, or levels, were to be hierarchical in nature, i.e., Level 1 modules rely on Level 2 modules, Level 2 modules rely on Level 3 modules and so forth. The big difference between UNIX and the EAN system is that much user interaction and processing occurs at the system dependent level (Level 4) in EAN, whereas in UNIX the system dependent layer is the furthest removed from the user. So in this regard the EAN architecture is somewhat like an inverted UNIX structure.

Figure 4 shows generic Level 1 and Level 2 modules. The Level 1 module contains algorithms that are designed to generate navigation waypoints that achieve certain objectives given the navigation data and the mission sensor data. The function of the Level 2 module is to validate the incoming data to ensure that it complies with the assumptions that are made by the Level 1 algorithms about the data. For complex Level 1 algorithms, many assumptions about the incoming data may be required and a violation of any of these assumptions could cause the module to fail, or worse, to generate undetected erroneous results.

While it would be desirable to have the Level 2 modules strictly system independent, this is not practical for more complex sensors. Consequently, the Level 2 task of data validation has been divided between both system dependent and system independent tasks.

In particular, a data validation task such as ensuring that the data meets certain quality constraints is very likely to be specific to a particular sensor.

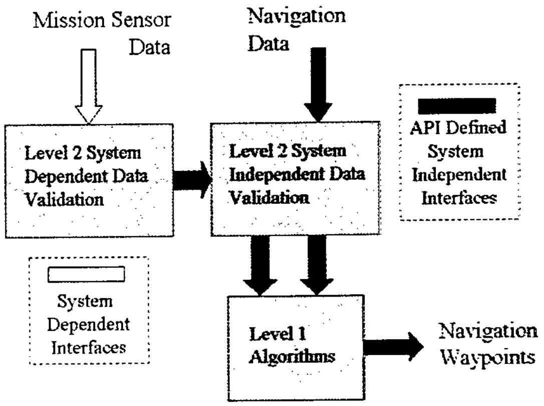

Figure 4. Level 1 and Level 2 Modules. Level 1 modules generate navigation waypoints given navigation data and mission sensor data. Level 2 modules validate the incoming data to ensure that it complies with the assumptions made by the Level 1 algorithms. The blue interfaces are system independent, API defined interfaces. The yellow interfaces are system dependent.

Figure 5 shows an example of a generic Level 3 module. Level 3 modules incorporate the Level 1 and system independent Level 2 modules. Each Level 3 module is assigned a specific goal oriented task. Each module requires navigation data (position, orientation, time, etc.) and one or more mission sensor inputs. The Level 3 modules include functionality for:

- Acquisition of navigation and mission sensor data; event-driven, either at periodic intervals or continuously
- Event detection software that detects (using mission sensors and/or navigation data) when it needs to go active. Certain activities, such as end-of-line turn computations, go active only when specific events occur. Other Level 3 modules, such as obstacle detection, would be continuously active, but would only generate navigation waypoints when certain events occur. Conceivably there could be Level 3 modules that combine both event driven and continuous operations in order to meet their objectives.
- Execution of the Level 2 and Level 1 modules when required. A Level 3 module could contain several Level 1 modules that are executed either sequentially or in tandem.
- Passing of generated waypoints to the arbitration module

The Level 3 modules are designed to be system independent. While their interfaces to the associated mission sensors will likely be tailored to the specific type of sensor, they will not directly contend with the interface complexities of specific pieces of hardware.

Figure 6 shows EAN Level 4, as well as the autopilot, mission sensors and navigation sensors that are external systems. Most importantly, Level 4 adds the arbitration module that determines which set of Level 3 generated navigation waypoints is to be passed to the autopilot for execution. Level 4 also includes the translators for the navigation sensors, mission sensors, and the generated navigation waypoints. The translators serve strictly to convert the device independent data streams used by Level 3 to the system specific data streams required by the external systems. The translators are associated with Level 3 instead of Level 4 since many Level 3 modules may utilize the same sensor inputs and duplication of the associated translator is not desired.

It is important to note that this system has been specifically designed to be waypoint centric – i.e., the output of each Level 3 module is a set of positions that the vessel is intended to reach. This approach was taken since mission objectives necessarily dictate that the vessel be at specific positions and orientations in order to accomplish mission tasks. While direct vessel control (heading, speed, attitude, etc.) may be suitable for certain reactive behaviors such as obstacle avoidance, it does not lend itself well to the more cognitive oriented objective based navigation. A waypoint-based system however, is suitable for both reactive and cognitive behaviors. This architecture lends itself directly to the inclusion of position 'qualifiers'. Simply arriving at a position may not be sufficient depending upon the specific task. Position qualifiers could include such things as time, orientation and maneuvering aggressiveness.

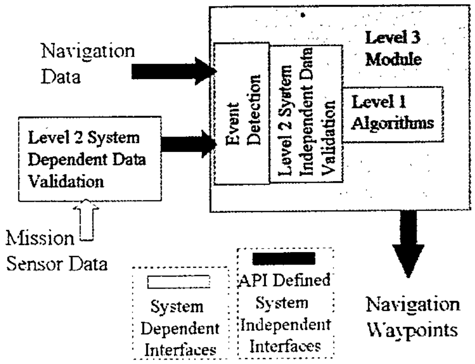

Figure 5. Level 3 Module. The Level 3 module incorporates Level 1 and 2 modules. The Level 3 module also includes the necessary mechanisms to pass data into and out of the Level 3 module and to execute the Level 1 and 2 modules at the appropriate times. The blue interfaces are system independent, API defined interfaces. The yellow interfaces are system dependent.

The full EAN simulator also includes modules for the autopilot, the vessel and the mission sensors. The autopilot module receives the waypoints from Level 4 and position data from the vessel module and generates the appropriate heading, speed and depth/altitude commands for the vessel module to execute. The vessel module realistically simulates the motion of a vessel and generates the navigation sensor outputs. The mission sensor modules uses archived environmental data and the navigation data from the vessel module to generate realistic sensor data. As can be seen from Figure 6, EAN Level 4 should be readily portable from a simulator environment to a real vessel.

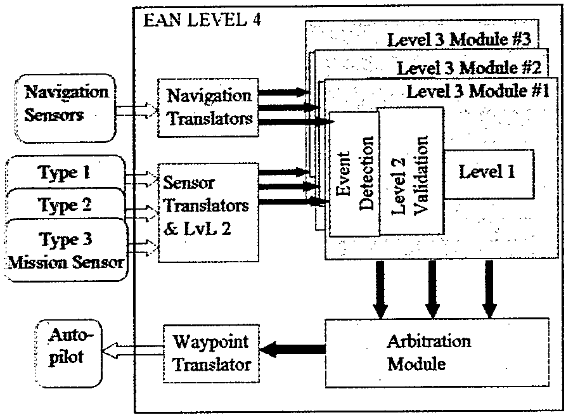

Figure 6. System Level 4. Level 4 includes all the Level 3 modules, the arbitration module, and system specific interfaces to navigation sensors, mission sensors and the autopilot.

IV. Summary

This paper presented the architecture and design of the Environmentally Adaptive Navigation (EAN) simulator system that is being constructed at NRL. The EAN simulator has been implemented in four distinct levels of software. This design has parallels to that of the design of the UNIX operating system. The function of the levels can be briefly described as follows:

- *Level 1* - A basic set of machine independent algorithms are used to generate navigation waypoints based on sensory data and some stated objective.

- ***Level 2*** – Performs input data assumption enforcement to ensure predictable Level 1 operation.
- ***Level 3*** – Incorporates the Level 1 and 2 modules and the necessary mechanisms to execute and to interface them to the external data streams.
- ***Level 4*** – Provides data translation between external devices (or their simulated counterparts) and the device independent Level 3 modules. Level 4 also provides arbitration between competing Level 3 objectives.

A partial simulator system has been completed that incorporates the AutoSurvey library and a few other simple Level 1 modules. Work continues to refine the Level 2 modules and to develop the remaining Level 1 behavior modules that will be required to autonomously execute an entire swath survey in an optimal fashion.

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