

SMART CHARTS, SMART BRIDGE: OBSERVATIONS OF THE SHIPBOARD PILOTING EXPERT SYSTEM

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INTRODUCTION

Safe navigation in restricted waters continues to be a perennial concern for ship owners, operators, navigators, and citizens. Much research has been conducted in order to determine the most efficient and effective methods for improving the safety of navigation and for training ships' officers and pilots ([1-11]. The impetus for much of this research stems from reports that a majority of maritime collisions, ramming, and groundings occur in harbour or harbour approach waters, and that approximately 80% of these accidents are due to human error [12]. Consequently, over the past decade, there has been increasing interest in decision aids designed to allow humans to perform well in stressful and information overload situation [13], particularly during ship transits in restricted waters [10, 14].

Decision aids improving the safety of navigation and supporting the cognitive skills of piloting--maneuvering, collision avoidance, and the practice of good seamanship--are of substantial interest [6, 7, 10]. These decision aids can be standalone systems or embedded within an integrated bridge system or Electronic Chart Display and Information System (ECDIS), and can exhibit the properties of a real-time knowledge based control system [11].

Following the March 1989 EXXON VALDEZ oil spill, Rensselaer Polytechnic Institute (RPI) began the development of an embedded real-time knowledge based control system designed to provide recommendations and alternatives to ship's pilots and masters navigating in close waters. This Shipboard Piloting Expert System (SPES) is an embedded software module within the Sperry Marine, Inc. Exxbridge integrated bridge system [15], which was built by Sperry Marine, Inc. for Exxon

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Shipping Company tankers. The SPES was developed with funding from the US Department of Transportation, Maritime Administration and the US Coast Guard, with cost sharing from Exxon shipping Company, Sperry Marine, Inc., and the National Oceanic and Atmospheric Administration; and with the cooperation of the Southwest Alaska Pilot's Association. This paper describes the SPES and its integration with the ExxBridge integrated bridge system; it also describes results from a two-year operational assessment of the SPES, as well as future directions for the system.

2. BACKGROUND

Most vessels navigate with three people on or about the bridge: the watch officer, the helmsman, and a lookout. Some shipping companies have eliminated the lookout in normal navigational circumstances, with good visibility. At night or in conditions of poor visibility, a lookout is added to the team. New technology has also been introduced to assist the vessel's navigational watch team: integrated ship's bridges, vessel traffic services, electronic chart display and information system (ECDIS) [17, 18], real-time tide, current and environmental information [19], and real-time intelligent embedded piloting systems [11]. This paper focuses on two of those technologies--integrated bridges and shipboard piloting expert systems--and discusses the capabilities and contributions of an intelligent piloting system embedded within an integrated ship's bridge.

2.1 Integrated Bridges

Integrated bridge systems are being developed by a number of nations--the United States, Norway, West Germany, Japan and the United Kingdom. These integrated systems project the wheelhouse as the operational centre for navigational and supervisory tasks aboard the ship; in many cases, these bridges become "ships operations centers," incorporating controls and monitors for all essential vessel functions--navigation, engine control, and communications. In the integrated bridge, many routine navigational tasks, such as chart updating, position plotting, and steering may be automated [16].

Single-handed bridges--those on which the watch officer serves also as a helmsman and a lookout--are also being introduced by some non-US flag shipping operators, and the certificating authorities of some nations have permitted some vessels to operate in this manner, provided they have some automated equipment. Many other vessels operate in this way without permission, even in restricted waters. In most cases where integrated and single-handed bridges are introduced, bridge equipment is automated and decision aids are added. However, decision aids which have been developed within the context of these systems have often been standalone systems, not integrated with existing bridge designs [20].

Some empirical research shows that officers serving single-handed watches aboard such "Ship of the Future" bridges have been significantly better at maintaining the vessels' course than have traditional watches aboard conventional

bridges. These improvements were attributed to attentive ergonomic design and the provision of robust decision aids. They were also reported to have been accomplished with no accompanying information overload [6, 21]. These results suggest that introduction of bridge automation can be effective in combatting shipboard stress and fatigue, by removing the non-critical monitoring task for the human decision-maker. However, some researchers have suggested that integrated bridge systems may be distracting enough to degrade performance on the most critical task: keeping the vessel on course while avoiding collision [6, 19].

Thoughtful introduction of bridge technology can work to alleviate stress and fatigue on watch by embedding simulation and functional team training capabilities in automated systems, so as to provide non-distracting, stimulating exercises [19]. A number of benefits could easily be hypothesized from such introductions. The integration of data and planning, long a goal in complex decision-making domains, might lead to the reduction of "competent errors"--errors committed by trained and competent crew members operating in error-inducing systems [22]. Enhanced vessel safety and ship-shore team performance enhancements are additional benefits. Wise and prudent application of advanced integrated bridge system technology and (perhaps more importantly) "lessons learned" offers the opportunity for better equipment performance, better and more reliable automation, as well as increased redundancy (and reliability) of vital systems.

2.2 The Importance of Integration

Integrated navigation systems, incorporating all elements required for safe vessel navigation, must input and process asynchronously real-world events as they occur, and generate output relevant to the vessel's safe navigation. Such requirements pose substantial challenges for current merchant vessel shipboard systems. Several earlier "Ship of the Future projects" were successful demonstrations of a single advanced technology, concept, or prototype. However, "leap ahead" capabilities for next generation merchant vessels require the integration of diverse technologies and knowledge bases in order to enhance the safety of navigation, and to transform shipboard operations, performance, and environmental protection of organizations in the future. Proliferating black boxes of navigational equipment aboard the bridges of current and next generation merchant vessels will not enhance the safety of navigation, and, in fact, may prove a detriment to safe navigation. Instead, integrating equipment, knowledge, and displays so as to enhance the decision making effectiveness of the mariner offers the opportunity to simultaneously enhance the safety of navigation and the performance of the shipboard crew.

3. THE SHIPBOARD PILOTING EXPERT SYSTEM (SPES)

The SPES is an embedded software module in the *Exxbridge* integrated bridge system developed by Sperry Marine, Inc., for Exxon Shipping Company [15]. The SPES communicates with the ExxBridge via the SEANET shipboard local area network (LAN), the spine of the ExxBridge integrated bridge system. Real-time

SEANET information flows into the SPES, is processed by the SPES software, and SPES output is forwarded to the ExxBridge display consoles via the SEANET. The SPES reasons about the data available to it from the SEANET, determines the implications of the data, and provides vessel and bridge management recommendations to the bridge watch team.

The SPES software was built in Common Lisp, KEE (Intellicorp's Knowledge Engineering Environment, an expert system shell), and Common Windows, running atop the Unix operating system on Sun workstations. This software core interacts with three applications: (1) a set of interface routines which permit communication between the SPES and the Sperry Vessel Management System (VMS); (2) a set of electronic charts, providing a real-time plan view of the vessel's position in the waterway; and (3) the SPES. A full description of the SPES design is given in [11].

3.1 Sperry Marine's ExxBridge Integrated Bridge and the SPES

Exxon's ExxBridge Integrated Bridge System (IBS) program is one example of integrated ship's bridge programs being effected throughout the world. The ExxBridge hardware and software integrates bridge shiphandling and navigation equipment into a consolidated workstation, with user control and display functions handled via a large touch-sensitive display. Functionally, the ExxBridge hardware and software design:

- records pertinent voyage, alarm, and operations data, aiding casualty investigations, and incorporating vessel characteristics for advanced control algorithms, and vessel and voyage efficiency analyses;
- provides an on-board simulator at sea for frequent training, practice, and drills; and
- insures operator attention and participation in all operations by providing a cascading advisory, warning, and alarm system.

The ExxBridge hardware includes:

- a **maneuvering display** which consolidates display and control of shiphandling and maneuvering data; and
- a **navigation display** which provides an electronic chart-based display consolidating a plan view of the harbour with overlaid chart, radar, and target data.

Figure 1 details the ExxBridge hardware configuration.

With the development of the SPES, additional software and enhanced functionality are added to the ExxBridge. A Sun workstation is added to the 80x86-based ExxBridge processor suite to facilitate real-time information processing, although no additional displays are added to the ExxBridge with the deployment of the SPES. Instead, the SPES reasoning and recommendations appear to the user as

overlays on the ExxBridge electronic charts, or as additional software "windows" on the ExxBridge displays.

SPES output displayed includes alarms of potential collision and grounding situations; on-line voyage plan data, including wheel over points, voyage plan waypoints, local aids to navigation, and parallel index points; and recommended alterations to voyage plans to avoid potential collisions or groundings. ExxBridge voyage plans are displayed graphically, and on-line voyage plan details are provided as both text and chart graphics. SPES collision and grounding alarms, and SPES-recommended alterations to the voyage plan in response to alarm or alert conditions are also presented as both text and chart graphics.

SPES alerts and alarms are the system's primary output. Alerts are defined as information and recommendations warning of incidents, objects, target, or situations of potential concern (i.e., an approaching vessel with a closest point of approach (CPA) of less than 2 miles who is 8 miles away). Alarms are defined as more serious warnings of incidents, objects, targets, or situations which are of immediate and grave concern (i.e., an approaching vessel with a CPA of less than 1 mile, in fog; risk of grounding or collision with an object 5 miles away, etc.) Advisories are also generated by the SPES, and are separated into the following four categories:

- 1) Current Track - information and recommendations about current position and related local piloting knowledge,
- 2) Underway Conditions - information and recommendations related to the current function of the ship (i.e., docking, participation in a traffic separation scheme) and its required/recommended VTS contacts,
- 3) Next Track - information and recommendations about the vessel's next track, including future transit points, based on the current situation, and
- 4) Weather/Visibility/VTS contacts - information and recommendations about current weather and visibility restrictions.

ExxBridge voyage plans, which were developed for the ExxBridge by Exxon ship masters, are a primary source of information to the SPES. They indicate the desired vessel track and desired rate of advance over the set of voyage legs planned for a particular harbour transit. SPES treats the ExxBridge voyage plan as the basis for recommended plan alterations. Voyage plan alterations can originate from SPES-generated recommendations or by manual entry by the ExxBridge user. Ultimately, the ExxBridge user enters and executes a particular voyage plan alteration via the operator interface at the ExxBridge displays. The SPES is notified whenever the operator elects to execute a voyage plan alteration via real-time SEANET messages.

SPES-generated voyage plan alterations are transmitted as recommendations to the ExxBridge user. When the SPES recommends a voyage plan alteration, the user may either accept it, reject it, or modify it and then accept it; thus, acting upon a SPES recommendation is similar to the process required to manually generate voyage plan alterations with the ExxBridge. The SPES is always notified (via

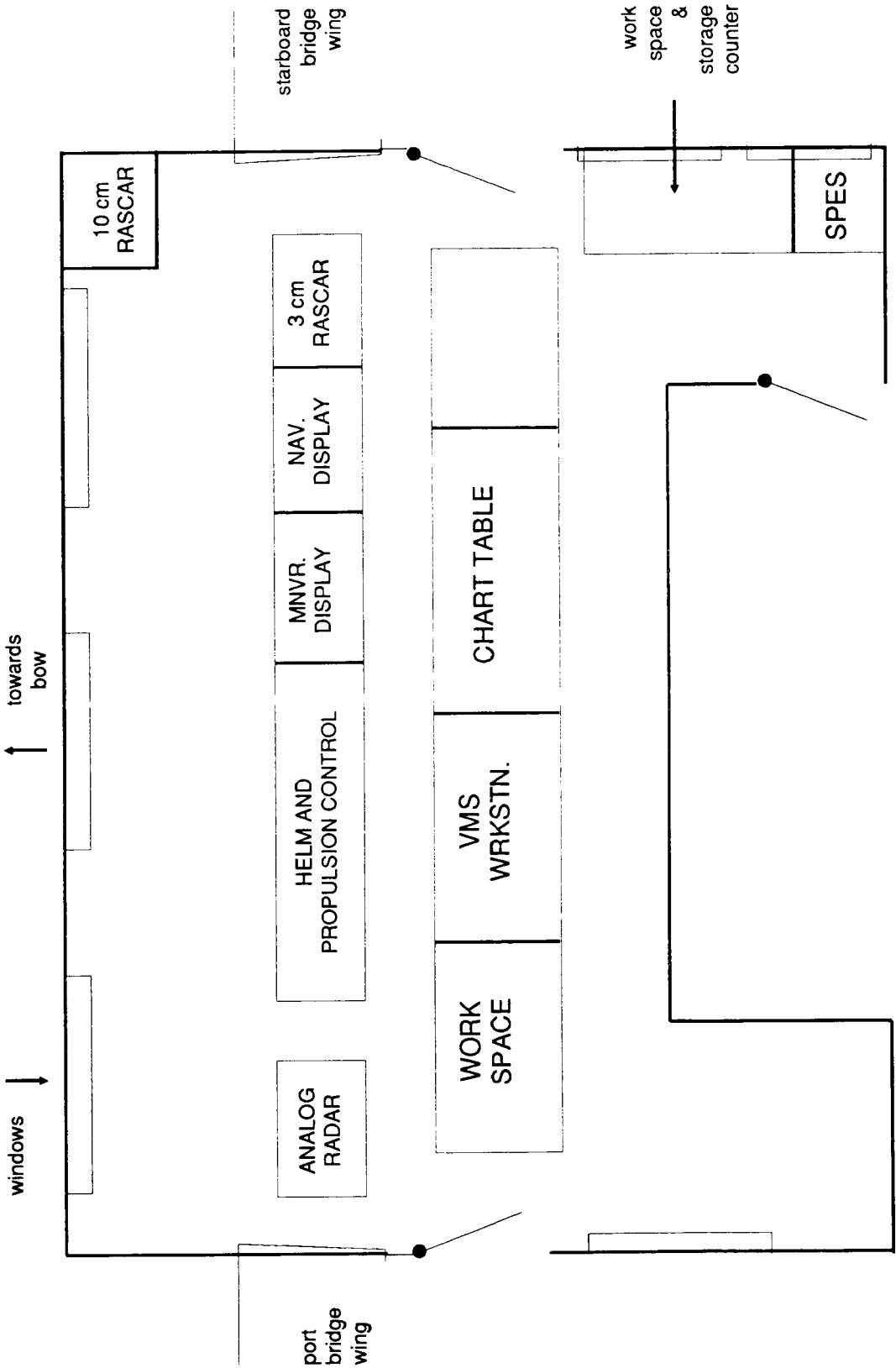


FIG. 1.- Physical Layout of EXXON BENICIA Bridge Equipment.

SEANET) when a plan alteration has been instituted by the ExxBridge operator. This approach covers operator acceptance of a SPES plan alteration, a plan alteration developed manually by the operator, or a plan alteration recommended by SPES and manually modified by the operator.

3.2 Example of ExxBridge-SPES Operation

Consider the following example as illustrative of combined ExxBridge-SPES operation. The EXXON BENICIA is inbound in Prince William Sound, in the inbound Traffic Separation Scheme (TSS), following the inbound voyage plan to the Alyeska Terminal. The vessel is currently south of the pilot station (Fig. 2). The captain is on the bridge with the bridge watch team. The current voyage plan was previously developed by the BENICIA's crew, and the SPES has been programmed with this plan.

Based on the VHF radio traffic, the BENICIA anticipates an outbound laden tanker, following the outbound TSS; in addition, the vessel encounters local small boat traffic, primarily fishing boats and local ferries. The SPES detects and tracks the outbound tanker, but does not generate an alarm since the two vessels are following their respective TSS. This is determined by comparing the other vessel's course made good to the appropriate TSS track for the vessel's current position. During the time that the outbound tanker is tracked by the BENICIA's radar, the SPES continuously monitors it. If the vessel departs the outbound TSS and poses a potential risk to the BENICIA, the SPES immediately raise an alarm. This triggers an aural alarm in the ExxBridge displays and overlays the target's marker on the ExxBridge chart display with a red triangle signifying danger. In addition, courses to steer, and times to turn, updated in 15-24 second reasoning cycles, are provided in order to steer the vessel clear of danger.

As the outbound tanker passes the BENICIA, a cruise ship is noted approaching on the starboard quarter. The cruise ship is tracked on radar, and the SPES monitors the track data from the BENICIA's radar and recognizes a crossing situation unfolding. While the watch officer is monitoring the situation on the radar display, the cruise ship's range decreases to less than 8 nautical miles. At this point, the SPES's situation assessment function recognizes a potential collision risk if both the target and the BENICIA maintain their respective course and speed.

The watch officer's attention shifts to the ExxBridge navigation display next to the radar console as the SPES's recommended action is plotted on the ExxBridge electronic chart. When the alarm sounded, the captain reviewed the ExxBridge's overhead repeater display and noted the SPES's recommendation to alter course to starboard, which corresponded with the captain's and pilot's plan to go around the cruise ship's stern while still inside the inbound TSS. The pilot advises the captain to execute a voyage plan alteration similar to the SPES's recommendation; the captain reminds the watch officer to monitor the cruise ship's course and speed, as the cruise ship is preparing to drop off a pilot. The BENICIA is in hand steering mode, so the SPES's recommended plan alteration is accepted using the ExxBridge navigation display touchscreen, which silences the acoustic alarm and sends an alarm acknowledgement to the SPES. As the BENICIA swings right, the SPES continues to monitor the situation but does not issue new alarms for the cruise ship

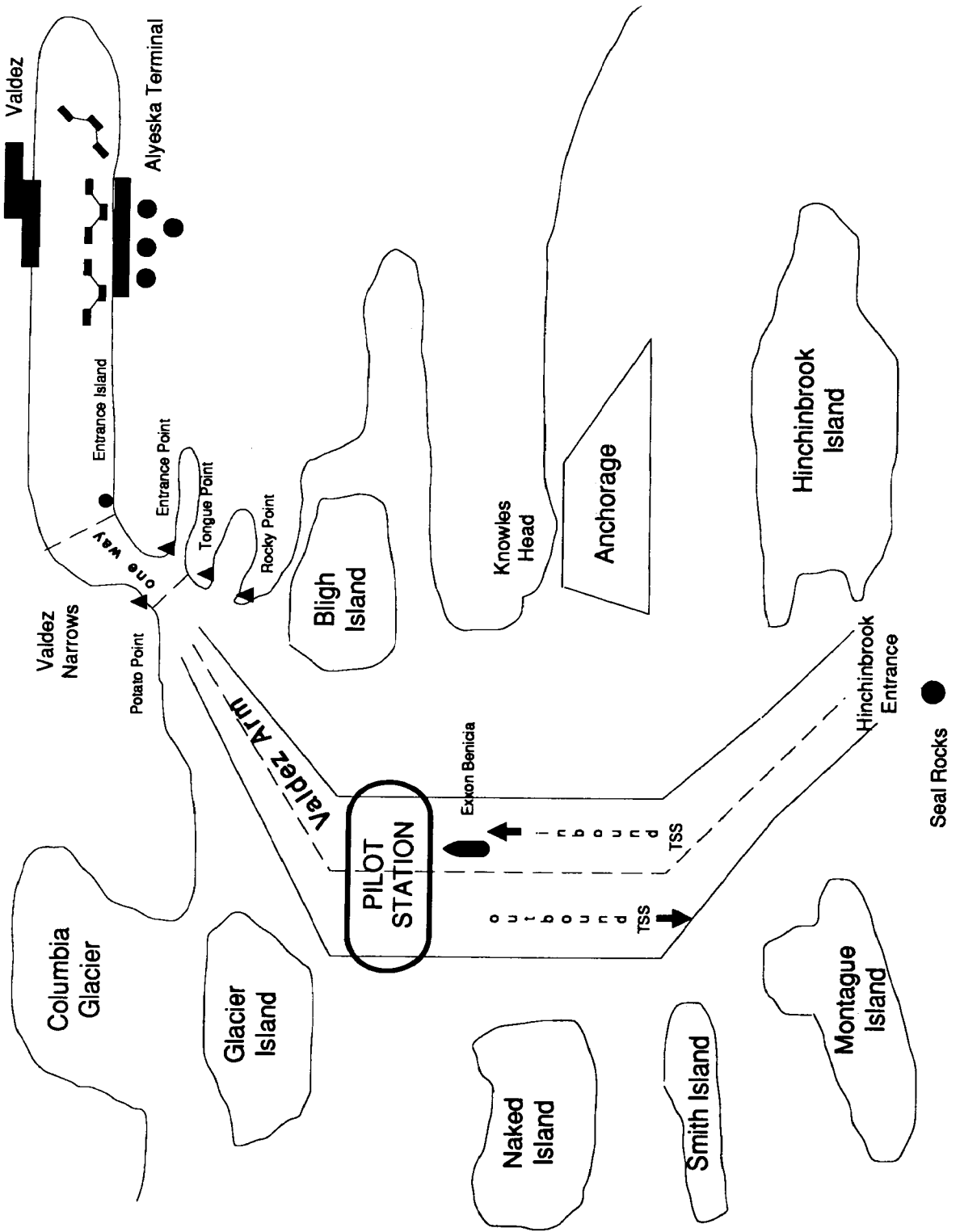


FIG. 2 - General piloting scheme through Prince William Sound and Port Valdez.

since a plan of action had been "accepted" to deal with that potential risk of collision. In the event that deviations from the recommended course of action were experienced, new alarms and alerts would be issued, consistent with SPES' 15 to 24 second update cycle.

In this context, we have seen how the SPES capabilities augment the ExxBridge information display capabilities with reasoning and reactions to unplanned situations, as well as monitoring and tracking vessels in the waterway and by applying local waterways knowledge so as to avoid raising an unwarranted alarm. The combination of this maneuvering, collision avoidance, and practice of good seamanship reasoning provides the bridge watch team with real-time decision support for planned and unplanned navigational situations.

4. SHIPBOARD OBSERVATIONS OF THE SPES

Evaluation of systems is essential for determining the usefulness and contributions of a system. Consequently, sponsors and developers evaluate systems in order to keep such systems consistent with user and sponsor expectations, as well as to insure that a "quality" system is developed. As decision aids are increasingly being developed for large, real-time applications, evaluations of these systems become increasingly important. This section describes observations of the SPES made aboard the EXXON BENICIA during its two-year operational evaluation, which focused on the use and usability of the embedded intelligent reasoning system installed in an integrated ship's bridge. The SPES operational evaluation began in August 1992 and concluded in January 1995, and observations resulting from that evaluation are contained in this section.

The shipboard operational evaluation was carried out aboard the EXXON BENICIA, a 970 foot long, 140 000 deadweight ton Exxon tankship in service between Valdez, Alaska and the West Coast of the U.S. Since the ExxBridge IBS integrates most of the shiphandling and navigation equipment of the conventional bridge into a consolidated workstation, the SPES operational evaluation focused on assessing SPES system use (i.e., who was using the system) and system usability (i.e., how was the system being used). In addition, the SPES' 15-24 second response time was assessed for operational adequacy during this period.

4.1 System Use

Crew input to the SPES and the ExxBridge is effected via a touch sensitive screen. The ExxBridge IBS is comprised of two consoles: a maneuvering display, which consolidates display and control of shiphandling and maneuvering data, and a navigation display, which provides a chart-oriented display consolidating a plan view of the harbour, with overlaid nautical chart and radar target data.

During the vessel transits, the primary task is to follow a pre-planned voyage plan (depicted on the ExxBridge navigation display) safely. In addition,

bridge watch teams are responsible for attending to vessel navigation, maneuvering, collision avoidance, and bridge maintenance activities, as required by the transit.

In the operational evaluation, bridge watch teams aboard the EXXON BENICIA were observed in a variety of situations over a 24-month shipboard observation period. Different conditions such as reduced visibility, wind, traffic, water currents, and floating ice were observed, and crew use of the ExxBridge and the SPES during those situations was noted. In addition to the operational observations, crews provided informal feedback about use of the SPES under varying conditions, and requested information about different uses of the SPES under these varying conditions over the 24 month shipboard observation period.

Major findings regarding system use included the following:

- system use was crew-dependent, e.g., some crews used the SPES more than others;
- the captain's attitude toward ExxBridge use influenced SPES use;
- system use was concentrated in the middle parts of the piloting transit (i.e., the SPES was little used, and of little use, in docking and undocking evolutions);
- the system was used by all members of the ship's navigation team more frequently than was expected; and
- pilots were observed to be conferring with masters over the system's reasoning and recommendations.

Frequency of SPES use varied with different crews aboard the BENICIA. Some crews were observed to be using the system constantly, as a integral part of the ship's electronic navigation complement; other crews used the system, but less frequently. System use appeared to be correlated with master attitude toward the system: if the captain was highly enthusiastic about the SPES and explored its capabilities in a highly visible manner, crews were more likely to frequently use the SPES. On the other hand, if the ship's captain was moderately enthusiastic about the system, and less obvious in his exploration of system capabilities, the ship's crew was observed to use the SPES less often than other crews.

Not surprisingly, the SPES provided little support for near-dock evolutions. Little docking and undocking information had been codified in the SPES, and for those evolutions, masters, mates and pilots were unlikely to refer to electronic display information for advice, preferring instead to rely on visual information.

Overall, the SPES was used more frequently than expected: it was anticipated that navigation officers and masters would refer to the SPES occasionally for piloting advice. However, all crews referred to the SPES often, and pilots were also observed using the system's information and checking its recommendations. All members of the navigation watch team were observed during transits conferring about the system's reasoning and recommendations, and were generally complimentary about the system's capabilities.

4.2 System Usability

Ease of use is a primary concern for system developers. Consequently, a major issue of the SPES shipboard evaluation was an assessment of the system's usability: how was the system used, and which features of the system were found to be most useful?

The SPES features provide information on the current track; next track; waypoints, visibility, weather and VTS information; as well as maneuvering, collision avoidance and "good seamanship" reasoning and recommendations. During the operational evaluation, it was found that masters and pilots were more often seen to be conferring about the system's reasoning and recommendations than they were discussing the current track/next track information provided. In contrast, navigation officers (third and second mates), who were less familiar with the current and next track information and with the transit, were often observed to refer to the current/next track and weather/visibility/VTS information. Thus, it was observed that captains and pilots were using different (higher cognitive order) SPES information than were the navigation officers on watch.

Differences in feature complexity and use observed during the operational evaluation provided interesting insights into SPES usability. For instances, SPES provides simple navigational and piloting features such as electronic checklists, electronic text versions of preplanned voyage plans, and simple collision avoidance capabilities. SPES also provides more complex features including graphical and heuristic reasoning and recommendations about voyage plans, complex collision avoidance and maneuvering reasoning, and the inclusion of heuristic reasoning about "good seamanship" practices and local knowledge in the port of Valdez. Navigation officers (third and second mates) were more often observed accessing the simple SPES features, while masters and pilots were more often seen to be conferring about and discussing the more complex SPES features. Thus, not only were differences in information accessed noted, but the nature of the access [retrieval (navigation officers) vs. retrieval, review, and discussion (masters, pilots)] were also noted.

Neither group was observed to be reluctant to utilize the system's capabilities, to access the reasoning and recommendations provided by the system, or to consider the system's information in effecting a safe voyage plan. Thus, the operational evaluation observations provided anecdotal validation of the system's usefulness to the different members of the ship's navigation team and the pilot.

4.3 System Responsiveness

A third issue of interest during the operational evaluation was the adequacy of the SPES' reasoning and recommendation cycles, which varied between 15-24 seconds. Further, questions about whether the system's LISP garbage collection would impede system reasoning were also of interest. Major findings regarding system responsiveness included:

- SPES 15-24 second response time was found to be more than adequate (in many cases, faster than required);
- garbage collection (i.e., LISP software processing) was not an impediment to system reasoning; and
- the Sun workstation provided a sufficient platform for required SPES reasoning and processing. The Sun was found to provide reliable, robust processing support without any additional environmental safeguards (i.e., without "shake and bake" protections or tests).

Thus, two primary design issues (system responsiveness and adequacy of the Sun workstation processing platform) were examined during the 24-month shipboard observation and evaluation period, and the solutions chosen during design were found to be more than adequate.

4.4 Summary

The SPES operational evaluation focused on assessing the operational usefulness of the intelligent piloting system embedded in an operational integrated bridge system. In summary, the system was found to be helpful to different members of the bridge watch team for different reasons: sufficiently robust and responsive to be of assistance in the piloting and navigation task; and a useful value-added enhancement to the integrated bridge system. Interestingly, the operational evaluation provided insight to design requirements for the next steps for the SPES: since the simple SPES features are relatively straightforward enhancements to an integrated ship's bridge system, their incorporation into an IBS is a natural evolution. In contrast, the more complex SPES features delineated above may take longer to develop, and should be seen as longer term enhancements to integrated ship's bridge systems of the future.

5. NEXT STEPS

Our experience in developing, installing, and evaluating marine piloting expert systems tell us several things:

- as of yet, no intelligent piloting systems have been developed which provide expert decision support for all types of piloting knowledge--trackkeeping, maneuvering and collision avoidance, and the "practice of good seamanship" [23] for all ports in the world,
- substantial advances in reasoning, reliability and decision enhancement can be produced by integrating shipboard navigation systems (including piloting expert systems) with vessel traffic services (VTS) and real-time environmental port data (i.e., the PORTS and/or VIPS systems) [19], and

- a tremendous amount of work in shipboard interface and integration for integrated navigation systems remains to be done.

Next steps for the SPES include development of a fully commercialized version of the SPES, a value added software enhancement to an integrated bridge system or an Electronic Chart Display and Information System (ECDIS). In order to take these next steps, two perspectives are fundamental:

- First, full commercial availability of the embedded SPES presumes the presence of a host integrated bridge system or an ECDIS, and
- Second, since the SPES is an embedded system, a value-added enhancement to an integrated bridge or an ECDIS, standalone, deployment of the SPES (i.e., absent an ECDIS or an integrated bridge) is not envisioned.

Standalone deployment of the SPES (i.e., without a host ECDIS or integrated bridge) is not envisioned, nor is it particularly desirable, since the SPES' primary benefit is its ability to reason about the vast array of electronic and heuristic piloting knowledge currently available aboard the bridges of ships, which is not currently integrated, and since it exists in disparate places aboard the bridge and is resident in several "black boxes" on the bridge, is difficult to assimilate. Thus, providing another "black box" aboard the bridge which contains the SPES defeats the purpose of the SPES (i.e., cognitive integration of the vast array of piloting and navigation information, thus reducing information overload), as well as the motivation behind well-designed integrated bridge systems and ECDIS.

The SPES is currently undergoing a formal shipboard test period, focused on providing an empirical assessment of the SPES' usefulness and contribution to safe shipboard navigation and piloting. A report of this formal shipboard test period will be prepared for the U.S. Department of Transportation, Maritime Administration, and the U.S. Coast Guard, in 1995.

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EXXON LONG BEACH
EXXON NEW ORLEANS
EXXON PHILADELPHIA

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