Scientific Journals
Maritime University of Szczecin

Zeszyty Naukowe
Akademia Morska w Szczecinie

2011, 25(97) pp. 41–47

2011, 25(97) s. 41–47

Navigational decision support system as an element of intelligent transport systems

Nawigacyjny system wspomagania decyzji jako element inteligentnych systemów transportowych

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Key words: navigation safety, intelligent transport systems, navigational decision support system

Abstract

A rapid development of information technologies opens increasingly wider opportunities for enhanced performance of all modes of transport, including carriage by sea. Such chances are offered by new and existing intelligent transport systems. The idea of creating a maritime intelligent transport system is convergent with the conception of e-navigation developed in recent years on the IMO forum. Navigational information systems, one component of the maritime intelligent transport system, support the process of ship conduct. We should expect that developments of these systems will be going towards decision support systems – intelligent navigational advisory systems. Apart from information functions, the tasks of these systems include hazard identification in ship movement (e.g. collision situations), warning against hazards and automatic generation of solutions (recommended manoeuvres). This article characterizes tasks of the maritime intelligent transport system and the place and functions of navigational decision support systems.

Słowa kluczowe: bezpieczeństwo żeglugi, inteligentne systemy transportowe, nawigacyjny system wspomagania decyzji

Abstrakt

Szybki rozwój technologii informacyjnych stwarza coraz większe możliwości poprawy funkcjonowania wszystkich rodzajów transportu, w tym transportu morskiego. Takie możliwości postrzega się w budowie i rozwijaniu inteligentnych systemów transportowych. Koncepcja budowy morskiego inteligentnego systemu transportowego jest zbieżna z rozwijaną w ostatnich latach na forum IMO koncepcją e-nawigacji. Jednym z elementów morskiego inteligentnego systemu transportowego są nawigacyjne systemy informacyjne, wspomagające proces prowadzenia statku. Należy spodziewać się rozwoju tych systemów w kierunku systemów wspomagania decyzji – inteligentnych nawigacyjnych systemów doradczych. Zadaniem tych systemów jest, obok funkcji informacyjnych, identyfikacja zagrożeń w ruchu statku (np. sytuacji kolizyjnych), ostrzeganie o zagrożeniach oraz automatyczne generowanie rozwiązań (propozycje manewrów). W artykule scharakteryzowano zadania morskiego inteligentnego systemu transportowego oraz miejsce i funkcje nawigacyjnych systemów wspomagania decyzji, stanowiących jeden z jego elementów.

Maritime transport

Being one of the links of the transport chain, maritime transport operates in combination with other modes of transport. Like these other modes of transport, its primary aim is to transfer cargo and people by sea.

Maritime transport system

The carriage of cargoes and people by sea is a service offered as a product on the transport service market. The players on this market (companies) offer maritime transport services. According to the definition [1], transport system is a system aimed at carrying people and (or) cargoes. In this approach, similarly to other modes of transport [2], maritime transport services are provided by a maritime transport system $\mathbf{S_{MT}}$. The system is described by a set of elements $\boldsymbol{A}$ characteristic of relations $\boldsymbol{R}$ between each other and the environment [3]:

$$\mathbf{S_{MT}} = \langle \boldsymbol{A}, \boldsymbol{R} \rangle \tag{1}$$

where:

- $\boldsymbol{A}$ – set of elements: $\boldsymbol{A} = \{a_i: i = 1, 2, ..., n\}$
- $\boldsymbol{R}$ – set of relations that exist between system elements and between the system and environment elements: $\boldsymbol{R} = \{\boldsymbol{R}_j: j = 1, 2, ..., m\}$).

System elements are objects taking part in the process of moving cargoes and people and objects related with the movement process. These include: seaports, sea-going ships as cargo carrying vehicles, waterways, equipment and traffic arrangements including regulations for traffic safety and control. People participating in the execution of transport services are major elements of the system.

Elements of the system have certain characteristics, described by values of attributes. Each element is characterized by a vector of characteristics with the components w_i^k; $k = 1, 2, ..., p_i$:

$$\boldsymbol{w}_i = \langle w_i^1, w_i^2, ..., w_i^{p_i} \rangle \tag{2}$$

where p_i is a number of characteristics of an i-th element of the system.

The size of the set of relations $\boldsymbol{R}$ depends on an objective or objectives that the system attempts to achieve. Each relation $\boldsymbol{R_j}$ is a subset of a Cartesian product.

One such subsystem in the maritime transport system is a subsystem of marine traffic $\mathbf{S_{MTr}}$. Its aim of operations is to conduct sea-going vessels according to their objectives, with parameters of the process properly maintained. The system elements represented in the $\mathbf{S_{TMr}}$ model are as follows:

- technical infrastructure $\mathbf{I_T} = \{\langle \boldsymbol{o}^i, \boldsymbol{w_o}^i \rangle\}$, where $\boldsymbol{o}^i$ – i-th technical object, $\mathbf{S_{TMr}}$ – waterway areas (open sea, restricted areas, berthing areas and anchorages, turning basins), sea-going vessels, aids to navigation, facilities and systems of vessel traffic management, communications equipment, regulations (international, national, local); $\boldsymbol{w_o}^i$ – vector of attributes describing an i-th object;
- decision-making infrastructure $\mathbf{S_{MTr}}\ \mathbf{I_D} = \{\langle \boldsymbol{d}^j, \boldsymbol{w_d}^i \rangle\}$, where $\boldsymbol{d}^j$ – j-th decision maker – harbour master, VTS operator, operator at a weather navigation centre, pilot, ship's captain, watch officer (navigator), operator at a marine rescue centre; $\boldsymbol{w_d}^i$ – vector of attributes describing a j-th decision maker,

Transport process

The transport system approached dynamically corresponds to the dynamic transport process $\mathbf{P}$. The process $\mathbf{P}$, in turn, can be divided into three sub-processes:

- $\mathbf{P_I}$: taking place inside $\mathbf{S_{MTr}}$,
- $\mathbf{P_O}$: taking place outside $\mathbf{S_{TM}}$ and forcing action in $\mathbf{S_{TM}}$, and taking place in $\mathbf{S_{TM}}$ while affecting the environment.

Among the processes taking place inside the system two can be distinguished: decision processes $\mathbf{P_{Id}}$ and technological processes $\mathbf{P_{It}}$: $\mathbf{P} = \{\mathbf{P_{Id}}, \mathbf{P_{It}}\}$. These processes are determined by technical, economic and organizational constraints as well as those imposed by the environment.

Similarly to the maritime transport system, among the processes taking place inside the subsystem $\mathbf{S_{MTr}}$ decision processes $\mathbf{P_{IMTr\,d}}$ and technological processes $\mathbf{P_{IMTr\,t}}$ can be distinguished:

- $\mathbf{P_{IMTr}} = \{\mathbf{P_{IMTr\,d}}, \mathbf{P_{IMTr\,t}}\}$, where $\mathbf{P_{IMTr}}$ – transport processes taking place inside $\mathbf{S_{RM}}$,
- $\mathbf{P_{IMTr\,d}} = \{\mathbf{P^{of}_{IMTr\,d}}, \mathbf{P^{cf}_{IMTr\,d}}, \mathbf{P^{mc}_{IMTr\,d}}\}$, where $\mathbf{P^{of}_{IMTr\,d}}$ – a set of decision processes connected with the organization of vessel traffic flow, $\mathbf{P^{cf}_{IMTr\,d}}$ – a set of decision processes connected with the control of vessel traffic flow, $\mathbf{P^{mc}_{IMTr\,d}}$ – a set of decision processes connected with the control of single vessel movement,
- $\mathbf{P_{IMTr\,t}} = \{\mathbf{P^{of}_{IMTr\,t}}, \mathbf{P^{cf}_{IMTr\,t}}, \mathbf{Pmc^{mc}_{IMTr\,t}}\}$, where $\mathbf{P^{of}_{IMTr\,t}}$ – a set of technological processes of the organization and management of information and technical facilities in connection with planning and controlling vessel traffic flow, $\mathbf{P^{cf}_{IMTr\,t}}$ – a set of technological processes of the organization and management of information and technical facilities in connection with planning and controlling one vessel movement, $\mathbf{P^{mc}_{IMTr\,t}}$ – a set of operational processes connected with a sea voyage of a vessel.

The distinguished decision processes $\mathbf{P_{IMTr\,d}}$ taking place within the marine traffic subsystem $\mathbf{S_{MTr}}$ are strictly related to areas of decisions made by participants of the transport process. The major decision makers include:

- shipowners: their objective is to optimize the operation of their fleet while providing transport services ordered to them;
- operators responsible for the organization and supervision of vessel traffic within port approaches and basins (VTS): their objectives are to efficiently handle vessels – assist in collision

avoidance, control movements of each ship, minimize their waiting times before arrival and departure;
- navigators on watch: their main objective is to handle a ship on a sea voyage according to shipowner's guidelines and, at the same time, observe the principles of safe navigation, regulations in force and instructions of VTS operators.

Maritime intelligent transport system

Intelligent systems

Intelligent systems are commonly referred to as systems that have characteristics attributed to human intelligence. These characteristics include, *inter alia*, a capability to adapt to changing conditions (adaptation), autonomy in performing tasks, ability to act in complex conditions (complexity) and the capability of learning. Adaptation is understood as system's ability to adapt to changes within the system and in its environment. The autonomy of the system means it is capable of solving problems with no need of outside intervention (including action of people). Complexity may refer to multidimensional nature of decision space, many modes of operation as well as non-linearity of system dynamics. Learning consists in the ability to modify the system behaviour when conditions of system operation change. Each of the mentioned properties should allow for possible disturbances in the system, incompleteness or uncertainty of data, including their indeterminacy or inaccuracy (imprecision).

The development of intelligent systems is spurred by the human expectations and need of getting support, or, increasingly, of being replaced in solving difficult and complex problems requiring knowledge and intelligence [4]. This goes in line with the development of artificial intelligence methods and tools. Among other things, the research in this area concerns:

– problems of knowledge acquisition and representation;
– inference processes;
– formulation and solving of problems in conditions of differently formalized uncertainty, e.g. using the theories of fuzzy sets or approximate sets;
– applications of artificial neural networks as a universal tool approximating multi-dimensional sets of data, which has the learning capability;
– use of genetic and evolutionary algorithms for solving optimization problems;
– latest computation techniques, e.g. soft computing, computing with words.

The presently used systems termed intelligent differ from each other in that they have a various range of properties recognized as typical of intelligent systems.

Intelligent transport systems

The term intelligent transport systems (ITS) was coined in the second half of the 20th century. The aim of implementing these systems was to improve the functioning of transport, inter alia, by the implementation of information technologies. The research in this area, which originated in Japan and the USA, was mainly concerned with the enhancement of road traffic safety. An official document of the Japanese government [5] of 1999 defined nine areas of developing and implementing ITS:

1. Advances in navigation systems,
2. Electronic toll collection systems,
3. Assistance for safe driving,
4. Optimization of traffic management,
5. Increasing efficiency in road management,
6. Support for public transport,
7. Increasing efficiency in commercial vehicle operations,
8. Support for pedestrians,
9. Support for emergency vehicle operations.

Actions undertaken at present, taking into account the integration of all modes of transport, aim at:

– rationalization of transport system/s operation,
– counteracting accidents,
– counteracting traffic **congestion**,
– counteracting environment pollution.

The so called ITS architecture [6] is adopted as a basis for building ITS systems in particular countries. This architecture is made up of general principles, accounting for specifics of a country and its transport system, outlining a framework for designing such systems. It defines the system functions and physical subsystems and interfaces performing these functions, communication requirements for efficient transmission of information. The architecture also identifies standards for interoperability within a given country or region.

For instance, the main components of ITS architecture in Japan and the USA are: 1) units providing user services; 2) logical architecture; 3) physical architecture.

Additionally, the Japanese ITS comprises standardization candidate areas, while the ITS USA includes a set of tools and technologies enabling ITS users to achieve desired objectives (market packages) and to navigate the architecture documentation. An analysis of ITS architectures in other countries shows that they reflect a similar philosophy and differences are slight.

Maritime intelligent transport systems tasks

Each mode of transport (land, air, sea, other) has its own specifics. As for maritime transport, it can be represented as the ITS subsystem: maritime intelligent transport systems (MITS).

Similarly to other modes of transport, particularly the leading road transport, several tasks (services) can be distinguished that are performed by MITS [3]. These are:

- traffic management (processes $\mathbf{P}^{of}_{\mathbf{IMTr\ d}}$, $\mathbf{P}^{cf}_{\mathbf{IMTr\ d}}$):
  - access control,
  - dynamic speed adjustment,
  - managing the traffic environment and its requests,
  - accident management,
  - alteration of routes,
  - traffic monitoring;
- information for travellers, vessel commanders, shipowners, marine agents (processes $\mathbf{P}^{mc}_{\mathbf{IMTr\ d}}$):
  - information before and during a voyage,
  - navigational advice and assistance;
- payment systems:
  - port dues,
  - pilot service dues,
  - freight, charter and other charges;
- safety management and damage control (processes $\mathbf{P}^{of}_{\mathbf{IMTr\ d}}$, $\mathbf{P}^{cf}_{\mathbf{IMTr\ d}}$, $\mathbf{P}^{mc}_{\mathbf{IMTr\ d}}$):
  - alarms in failure and emergency situations,
  - collision avoidance,
  - rescue services management;
- freight and fleet management:
  - coordinated port logistics,
  - fleet and resources management,
  - freight management,
  - dangerous goods management,
  - operational planning management.

The performance of these services will enable the achievement of aims defined for ITS in reference to maritime transport.

E-navigation

The idea of maritime intelligent transport systems is convergent with current directions of marine navigation developments, including e-navigation promoted at the IMO forum over the past years. According to the definition in [7] "E-navigation is the harmonized collection, integration, exchange, presentation and analysis of maritime information onboard and ashore by electronic means to enhance berth to berth navigation and related services, for safety and security at sea and protection of the marine environment".

The aim is to develop an accurate, safe, secure and cost-effective system with the potential to provide global coverage for vessels of all sizes. In particular, such system should be able to [8]:

- minimise navigational errors, incidents and accidents;
- to protect people, vessels, cargoes, marine environment and its resources;
- to improve safety and security;
- to reduce costs of transport and infrastructure maintenance;
- bring profits to shipowners.

E-navigation will be composed of:

- electronic navigation charts,
- positioning systems – combined use satellite and terrestrial radionavigation services,
- vessel information systems – route, heading, manoeuvring parameters and other status items,
- communication systems – ship-to-shore, shore-to-ship and ship-to-ship,
- integrated displays – on board ship and ashore, information prioritization and alert capability.

Navigational decision support systems will be gaining importance – intelligent navigational advisory systems, navigational information systems supporting the ship conduct process, with greater capabilities than navigational information systems used to date. Apart from information functions, these systems will perform tasks such as the identification of hazards in vessel movement (e.g. collision situations), warning against hazards and automatically generating solutions (proposing manoeuvres).

Navigational decision support systems

Navigational decision processes

The starting point for determining tasks and functions of navigational decision support systems is an analysis of navigational decision processes on board a vessel and on land (at shore-based centres).

Navigational decisions made on board can be assigned to decision processes taking place within the marine traffic subsystem $\mathbf{P}_{\mathbf{IMTr\ d}}$, particularly the processes of vessel movement control $\mathbf{P}^{mc}_{\mathbf{IMTr\ d}}$.

These decisions covering various time ranges, from voyage planning and its modifications to safe ship movement control, require that the specific character of the marine area, especially a restricted area, be taken into account. Decisions made relate to standard or emergency situations.

On this basis, the following areas of decision making can be distinguished and the corresponding navigational decision processes $\mathbf{P}^{mc}_{\mathbf{IMTr\,d}}$:

- $\mathbf{P}^{mc,wr}_{\mathbf{IMTr\,d}}$: weather routing, where changes of weather conditions during the voyage are taken into account – strategic decisions,
- $\mathbf{P}^{mc,od}_{\mathbf{IMTr\,d}}$: ship movement control (collision prevention and avoidance) – operational decisions,
- $\mathbf{P}^{mc,ra}_{\mathbf{IMTr\,d}}$: ship movement control in restricted areas, including port basins – operational decisions,
- $\mathbf{P}^{mc,es}_{\mathbf{IMTr\,d}}$: ship movement control in emergency situations (rudder or propulsion damage, rescue operation, etc.) – operational decisions,

where $\mathbf{P}^{mc}_{\mathbf{IMTr\,d}} = \{\mathbf{P}^{mc,wr}_{\mathbf{WSd}}, \mathbf{P}^{mc,od}_{\mathbf{IMTr\,d}}, \mathbf{P}^{mc,ra}_{\mathbf{IMTr\,d}}, \mathbf{P}^{mc,es}_{\mathbf{IMTr\,d}}\}$.

Navigational decisions made at shore-based centres are mainly related to tasks of vessel traffic flow organization and control – $\mathbf{P}^{of}_{\mathbf{IMTr\,d}}$, $\mathbf{P}^{cf}_{\mathbf{IMTr\,d}}$. These tasks are performed by VTS systems in order to provide for the safety of navigation, traffic efficiency and the environment protection [9]. The basic tasks (functions) of a VTS system are as follows:

- organization of traffic in a fairway,
- traffic supervision and control,
- navigational assistance (information function),
- coordination of rescue operations in case of accidents and disasters,
- management and control of navigational systems operation,
- delivery of data for port and regional services and data storage for administrative, research and planning purposes.

Having considered the above functions (tasks) of the VTS system, we can identify areas of decision making and corresponding decision processes $\mathbf{P}^{of}_{\mathbf{IMTr\,d}}$ and $\mathbf{P}^{cf}_{\mathbf{IMTr\,d}}$, which are as follows:

- $\mathbf{P}^{of,ss}_{\mathbf{IMTr\,d}}$: planning – organization of vessel traffic flow in standard situations,
- $\mathbf{P}^{of,es}_{\mathbf{IMTr\,d}}$: organization procedures in emergency situations,
- $\mathbf{P}^{cf,cs}_{\mathbf{IMTr\,d}}$: solving collision situations (collision avoidance),
- $\mathbf{P}^{cf,es}_{\mathbf{IMTr\,d}}$: procedures in emergency situations,

where $\mathbf{P}^{of}_{\mathbf{IMTr\,d}} = \{\mathbf{P}^{of,ss}_{\mathbf{IMTr\,d}}, \mathbf{P}^{of,es}_{\mathbf{IMTr\,d}}\}$, $\mathbf{P}^{cf}_{\mathbf{IMTr\,d}} = \{\mathbf{P}^{cf,cs}_{\mathbf{IMTr\,d}}, \mathbf{P}^{cf,es}_{\mathbf{IMTr\,d}}\}$.

Decisions made by VTS operators aim at ensuring the safety of vessel traffic and support the navigator steering a vessel.

Navigational systems in decision support processes

The primary tasks of navigational systems installed on board ships and at shore-based centres is to assist the navigator in decision making to ensure safe and efficient navigation through automation of data acquisition, processing and presentation processes. This facilitates and improves solutions of complex navigational situations as well as the control of their execution. These systems are supplemented with modules for analysis and assessment of decision variants before decisions are made, and for automatic solution generation. In this connection, navigation systems can be divided into:

- information systems,
- decision support systems.

Information systems mainly operated on the basis of methods and tools of:

- data acquisition,
- data integration,
- computing, including functions for determining target approach parameters and identification of dangerous situations,
- communication with the user.

Examples of such systems, used on board ships and ashore, are Automatic Radar Plotting Aid (ARPA), Automatic Identification System (AIS), Electronic Chart Display and Information System (ECDIS), Global Navigational Satellite System (GNSS) – e.g. GPS (Global Positioning System), Global Maritime Distress and Safety System (GMDSS). For navigation support, land-based centres have such systems as Vessel Traffic Services (VTS), Vessel Traffic Management Systems (VTMS) and Vessel Traffic Management and Information Systems (VTMIS). There are many VTS systems operating throughout the world, covering areas of heavy traffic and / or areas difficult for navigation. To increase the effectiveness of these information systems, management modules are added to support the operator in decision making (VTMS systems). Attempts are made to merge individual VTS (VTMS) systems into co-operating units so that larger traffic areas will be supervised and controlled (VTMIS).

Navigational decision support systems

Decision support systems make up another step forward in the development of computer-based systems. They use model bases and knowledge bases for solving decision problems. Apart from tasks already implemented by information systems, support of navigational decision processes ($\mathbf{P}_{\mathbf{WSd}}$) should comprise:

- monitoring, analysis and assessment of a navigational situation, including alarming in dangerous situations and informing on a current navigational safety level;
- prediction of a navigational situation;
- solving collision and emergency situations using adequate computing models;
- planning, coordination and surveillance of ship movement processes, and the same functions relating to vessel traffic performed by shore-based centres;
- explanation (justification) of situation assessment results and of solutions generated by the system;
- interaction with the navigator via a user interface;
- automatic (in some situations, after approval by the operator / navigator) performance of a manoeuvre.

Various types of such systems are as follows:

- weather routing systems (processes $\mathbf{P}^{\mathbf{mc,wr}}_{\mathbf{IMTr\ d}}$); their function is to determine an optimal route of an ocean-going vessel based on the present and predicted weather data, taking into account ship's speed and manoeuvring characteristics; examples are SPOS (Meteo Consult), Bon Voyage (Applied Weather Technologies) or Bridge (Weather News),
- pilot navigation systems (processes $\mathbf{P}^{\mathbf{mc,ra}}_{\mathbf{IMTr\ d}}$), intended for navigation in restricted areas, often referred to as pilot navigation; examples of such systems are E-Sea Fix system (Aachus based Danish Marimatech) and the Pilot Navigation System (PNS) developed at the Maritime University of Szczecin (MUS) [10],
- docking systems (processes $\mathbf{P}^{\mathbf{mc,ra}}_{\mathbf{IMTr\ d}}$), used to assure the safety of the vessel, cargo and the marine environment during berthing and unberthing manoeuvres, particularly by ships carrying dangerous cargo; examples of this type of systems are SmartDock (Trelleborg Harbour Marine) and Maritech-made BAS (Berthing Aid System) [11];
- dynamic positioning systems (processes $\mathbf{P}^{\mathbf{mc,od}}_{\mathbf{IMTr\ d}}$, $\mathbf{P}^{\mathbf{mc,ra}}_{\mathbf{IMTr\ d}}$); used for precise ship manoeuvring: maintaining ship's operating position; moving a ship to another position maintaining a specific low speed; controlling the position, speed and course during ship's operations; Examples of DP systems include K-POS (Kongsberg Shipmedics), Mate DP (Marine Technologies) and NavDP (Navis in Control).

A prototype NDSS system (Navigational Decision Support System), created and developed at the Maritime University of Szczecin, fully performs the seven functions on board a ship listed above in this section (processes $\mathbf{P}^{\mathbf{mc,od}}_{\mathbf{IMTr\ d}}$) [12]. The system is intended for navigation in open sea areas.

The foregoing navigation systems – both information systems assisting in decision processes and decision support systems – perform some of the functions expected from maritime intelligent transport systems. As an essential component of MITS, they will create opportunities for providing such services as:

- traffic management,
- supplying information to vessel operators,
- safety and accident management.

Summary

As advances in information technologies are impressively fast, new wider opportunities arise for improving all modes of transport operations, including maritime transport. Maritime intelligent transport systems (MITS) can make up one of subsystems of intelligent transport systems.

In effect, navigational information systems tend to be developed towards decision support systems. A variety of user requirements calls for designs of specialized decision support systems.

Navigational decision support systems will constitute an important element of maritime intelligent transport systems.

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