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MODELS OF MARITIME SAFETY FOR DEVELOPMENT OF NAVIGATION SUPPORT SYSTEMS

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Abstract: *Navigation support systems are part of modern maritime transportation chain where larger and larger vessels are handled in ports. Support systems for sea navigation must meet certain criteria for access, integrity, accuracy and other factors. Modelling of safety criteria for technical creation of support systems like PNS (Pilot Navigation System) or LDS (Laser Docking System) consists of several stages both conceptual, and real time experimental. Even basic systems must be designed and developed in manner where assumed safety factors are met.*

Key words: *navigation support system, pilot navigation, sea transport support*

1. Introduction

Navigation support systems (NSS) for enhancement of safety on sea are systems based on several technical devices for presentation of certain data to the operator of vessel, usually captain, officer or pilot. This systems are built of following blocks:

1) subsystem for positioning, usually GNSS (Global Navigation Sattelite System),
2) computing subsystem,
3) presentation subsystem – Graphical User Interface (GUI).

Additionally these systems can work with several external sensors to mention:

1) laser distance measurement devices (computing distance from berth),
2) radar systems (for long range measurement),
3) external data sources (like meteorological data),
4) other.

System designed as Pilot Navigation System (PNS) with optional docking module (called PNDS (Pilot Navigation Docking System) is presented at fig. 1. That kind of complex system can be treated as a tool for navigators on congested and restricted waters i.e.

- ports/harbours,
- locks,
- channels and under bridges passages.

IMO (International Maritime Organization) has issued recommendations for minimal performance parameters for multiple operational conditions in GNSS (and combined with it systems) i.e. accuracy, integrity, continuity and availability. For miscellaneous types of navigation data are presented in table 1.

Table 1. Minimal user requirements for GNSS type systems in marine environment

IMO navigation requirements	Accuracy	Integrity		Continuity	Availability	
		Alert limit	Time to alert	Integrity risk	over 3 hours	per 30 days
	[m]	[m]	[s]	[$^{-5}$]	[%]	[%]
Ocean and coastal	10	25	10	10	N/A	99.8
Port approach	10	25	10	10	99.97	99.8
Port navigation	1	2.5	10	10	99.97	99.8
Automatic docking	0.1	0.25	10	10	99.97	99.8

Source: IMO (2001).

It can be noted that port navigation along with docking must be accomplished with system of high accuracy and availability, The accuracy of 0.1 m for docking can be obtained by GNSS receivers combined with an external differential source. Detailed parameters can be found in IMO Recommendations A.915 with distinction of service level and system level parameters that are described in table 2.

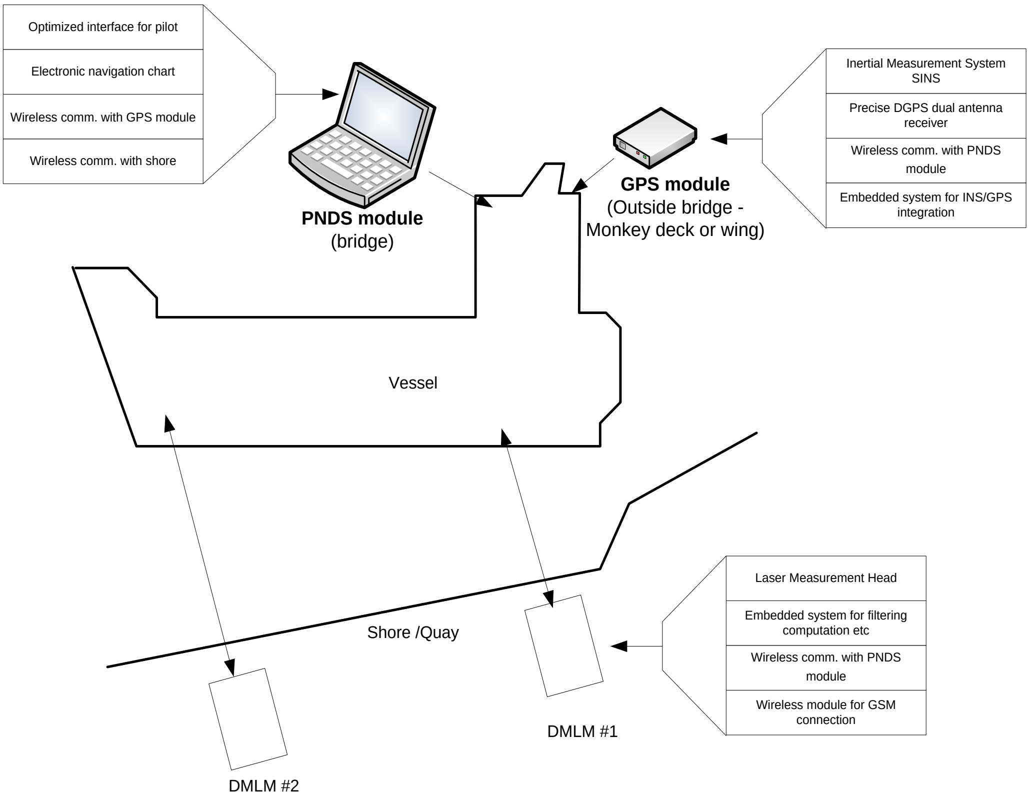

Fig. 1. PNS system with docking modules (DMLM – Distance Measurement Laser Module, DGPS – Differential Global Positioning System, INS – Inertial Navigation System)
Source: Bąk et al. (2010).

Highest values of accuracy i.e. 0.1 m and integrity (alert limit) as 0.25 m are in cargo handling port operations group, which means that such operations requires high level system for support. It is not possible to obtain such values without PNS/PNDS support system.

Modelling of NSS has crucial meaning to its further functioning, and as such development must be done with regard to highest standards. To obtain this features several, both mathematical and computer models must be designed, tested and implemented in the overall system. Basic schematic of the NSS is presented at fig 2. with determination of the modelling points (in circle) for further description.

According to above schematic user inputs some data (like vessel dimensions, area variables, or type of ship) where system presents on graphical interface data from static hydrographic database with dynamic overlay (ship position, distances to berth etc.). On such presentation optimized to the task (like berthing, passage etc.) user can made decision on the output. Modelling of the following points has been determined for the grouping functionality (numbers represents circled values at fig. 2):

1) Modelling of complex systems mainly electronics and mechatronics issues related to reliability of singular and connected devices.
2) Models of HMI (Human – Machine – Interaction) with means of basic input and output interfaces.
3) Models of the core functionality and features of NSS with aspects of navigation safety, reliability and desired parameters of performance.

Table 2. Detailed parameters of the GNSS based systems for certain maritime operations; fix interval is 1 s everywhere

	System level parameters					Service level parameters		
	Accuracy		Integrity			Availability **% per 30** days	Continuity **% over 3 h**	Coverage
	Horizontal [m]	Vertical [m]	Alert limit [m]	Time to alarm **[s]**	Integrity risk **(per 3 hours)**			
Operations	Relative accuracy							
tugs and pushers	1		2.5	10	10^{-5}	99.8	99.97	Local
icebreakers	1		2.5	10	10^{-5}	99.8	99.97	Local
automatic collision avoidance	10		25	10	10^{-5}	99.8	99.97	Global
	Absolute accuracy							
track control	10	N/A	25	10	10^{-5}	99.8	99.97	Global
automatic docking	0.1		0.25	10	10^{-5}	99.8	99.97	Local
Traffic management	Absolute accuracy							
ship-to-ship co-ordination	10		25	10	10^{-5}	99.8	99.97	Global
ship-to-shore co-ordination	10		25	10	10^{-5}	99.8	99.97	Regional
shore -to -ship traffic management	10		25	10	10^{-5}	99.8	99.97	Regional
Port operations	Absolute accuracy							
local VTS	1	N/A	2.5	10	10^{-5}	99.8	N/A	Local
container/cargo management	1	1	2.5	10	10^{-5}	99.8	N/A	Local
law enforcement	1	1	2.5	10	10^{-5}	99.8	N/A	Local
cargo handling	0.1	0.1	0.25	1	10^{-5}	99.8	N/A	Local
Casualty analysis	Predictable accuracy							
ocean	10	N/A	25	10	10^{-5}	99.8	N/A	Global
coastal	10	N/A	25	10	10^{-5}	99.8	N/A	Global
port approach and restricted waters	1	N/A	2.5	10	10^{-5}	99.8	N/A	Regional

Source: IMO (2001).

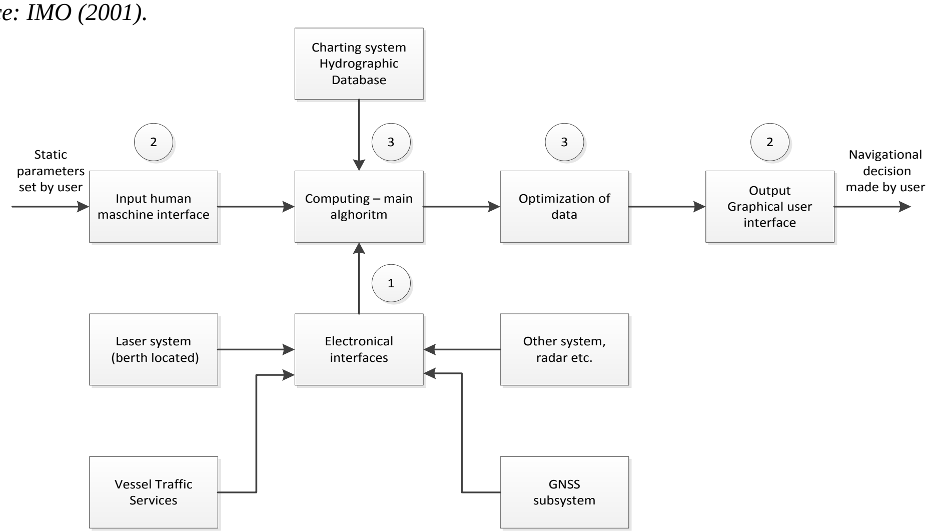

Fig. 2. Basic schematic of the NSS with distinction of modeling points

2. Literature review

Problems with the proper modelling of aspects in modelling firstly has been recognized with mostly technologically developed transport branch i.e. air transportation. Apart from early studies, investigated by many groups to mention (Leiden et al., 2001) (Ianni, 2000) recent work is based in field of models where failure free time is modelled as a set of stochastically system output (Zieja et al., 2015), authors here treated system in far more complex way. Large scale modelling is also present in the macro problems of transport to mention (Jacyna et al., 2014). Especially it can be observed as a new look with scientific perspective, in branches totally neglected so far (nonprofessional personal car transport) to mention (Guzek, 2010).

Several studies has been conducted in the field of modelling in maritime support systems. Practically since the first implementation of early computer aided radar anti-collision warning systems (ARPA) problem with proper interpreting and displaying of navigational data (Gucma, 1977). Problem has risen, when computer systems was implemented widely to the maritime world in 90-ties of XX century. Later there has been singular approaches to the subject to mention: (Sanquist et al., 1996). No common standards has appeared and several manufacturers tried to set own standards unsuccessfully. In Poland from mid 70ties of XX century school of marine traffic engineering has risen in Maritime University Szczecin. First works dedicated to models of interaction between human and interface has been presented in works: (Gucma, 1981), (Gucma, 1988), and complete overview of modeling methods has been published in: (Gucma, 2001). Other conception of risk based modelling has been initiated and presented in several works to mention: (Fuji and Mizuki, 1998).

Modelling of reliability and operability of complex electromechanical systems has been addressed in several studies where overall conception, for instance, has been presented in (Czajgucki and Ziemba, 1991) and ((red) Migdalski, 1992). Safety issues identified as a system in whole complex environment on basis of nuclear plant researches presented in (Fullwood, 2000), were briefly described in: (Kołowrocki and Soszyńska-Budny, 2011).

Another problem that must be addressed at some point of system design is modelling of the human behavior in loop of steering and decision making. This issue has found several scientific attempts where beginning for maritime world has been addressed in: (Smith and Mosier, 1986), (Rothblum and Carvalhais, 1996). Contrary, novel risk analysis methods has been studied with means of cognitive simulation awareness situation displays by group of researcher, has been presented in: (Itoh et al., 2001). Consideration over the display and parametric optimization of information has been addressed in (Gucma and Pietrzykowski, 2009). New approach to the subject basing on mathematic brittle theory has been presented in: (Wang et al., 2013) where, a human error brittle model of complex system based on cellular automaton is built to analyze the internal brittle link of the maritime relation system.

3. Mathematical models of maritime safety

3.1. General assumption

Generally idea of maritime safety (referred to sea transportation) is based on assumption where all issues connected with conduct of a ship from point A to point B without an singular accident. Accident itself here is understood herein as a navigational or maneuvering occurrence of phenomena, such as (Gucma, 2009):

- grounding (understood as unintended contact of the ship’s hull, rudder or propeller with the bottom of sea);
- damage to the hull due to ship’s contact with the shore;
- damage to a marine structure due to ship’s direct or undirect contact;
- damage to a tug assisting in maneuvers;
- damage to a seamark;
- collision with another ship in the area.

The navigation safety in restricted areas can be presented as a mathematical function (Gucma, 2001):

$$P_i = f(A_i, S_i, N_i, H_i, M_i, I_i, R_i) \qquad (1)$$

where:

P_i – navigation safety assessment indicator,
A_i – area parameters,
S_i – vessel parameters,
N_i – parameters of position determination systems,
H_i – hydro-meteorological parameters,
M_i – parameters of a manoeuvre performed,

I_i – parameters of traffic intensity,
R_i – parameters of traffic control system.

Parameters in function represent independently general system as a man – machine steering loop with environment influence assumption.

3.2. Modelling of the functionality of NSS

Modeling of NSS is based on a number of methods, such as empirical methods, physical modeling and mathematical modeling, and on simulation methods. Computer simulation methods previously used at the stage of detailed design of waterways were also first used to optimize NSS systems. The application of these methods allows for a detailed determination of safe maneuvering areas (also designed – non existing) but also as a changes such as the introduction of new NSS for area.

The condition for safe transit of the vessel, is to determine the width of the safe maneuvering areas intended for the exploitation of the vessel in each section of the waterway, in the limits of operating conditions for such vessels at a given confidence level $\mathbf{d}_{\mathrm{ijk}}(1-\alpha)$. Substituting the condition of safe navigation (Gucma, 2001):

$$\left.\begin{aligned} &\bigwedge_{p(x,y)\in\mathbf{D}(t)} \subset \mathbf{Di}(t) \\ &h(x,y,t) \geq T(x,y,t) + \Delta(x,y,t) \end{aligned}\right\} \quad (2)$$

Available navigable waterway area $\mathbf{D_i}(t)$ is characterized as a set of maximum available types of width on the individual (i) lanes of the waterway. In the computer simulation methods for determining the width of the safe areas maneuvering ships the results from the preliminary design stage are used. The simulation research procedure used in the design of NSS on marine waterways is carried out in the following order (Gucma, 2015):

1) formulation of the research problem, including identification of the designing aim, simulation methods used and the type of simulators;
2) construction or selection of vessels' traffic models on the chosen simulator and their verification;
3) design of the experimental system and the conduction of the experiment;
4) elaboration and statistical analysis of the research results.

This procedure was adopted for the research on new waterways cannot be used directly in the context of the use (enter or change) of NSS data for given vessels. It is necessary to take into account the target parameters of the area and the systems of waterways where safety is a key condition to ensure a safe depth (h) at the momentary draft of the vessel (T) in the form (Gucma, 2001):

$$h(x,y,t) \geq T(x,y,t) + \Delta(x,y,t) \quad (3)$$

The size of the water reserve – Δ under the keel at the point x,y in t moment of time determines the safety of the reversing maneuver. Safe water reserve under the keel depends on many factors, and can be written them as a function (Gucma, 2001):

$$\Delta(x,y,t) = f\begin{pmatrix} A(x,y,t), N(x,y,t), S(x,y,t), \\ H(x,y,t), M(x,y,t) \end{pmatrix} \quad (4)$$

where:

$A(x, y, t)$ – parameters of the area at the point (x, y) in the t moment;
$S(x, y, t)$ – parameters of the vessel at the area point (x, y) in the t moment;
$N(x, y, t)$ – system parameters determining the position;
$H(x, y, t)$ – parameters of hydro-meteorological conditions at the point of the area (x, y) in the t moment;
$M(x, y, t)$ – parameters of the performed maneuver at the point of the area (x, y) in the t moment.

Besides the parameters A and H which are independent of the operator as a quasi-stochastic parameters, and S and M, which in turn are the result navigator's work, parameter N is subjected to modeling from the author's point of view. The basic parameters determining the system components that affect the variable N are associated with accuracy, availability and reliability of individual technical systems included in the NSS.

Precision requirements for NSS designed for the waterway describes the condition (Gucma, 2001):

$$D(t)_{ijk} \geq d_{ijk}(1-\alpha) \quad (5)$$

assuming that the accuracy of the position determination and the given confidence level is determined by the width of a safe maneuvering area. That is:

$$d = f(d_n) \tag{6}$$

thus:

$$d = f(N_i) \tag{7}$$

where:

d – the width of safe maneuvering area,
d_n – the navigation component of the width for safe maneuvering area,
N_i – parameters of the *i*-system for determining the position.

The resulting relation directly submits the width of the safe maneuvering area to the parameters of the designed NSS.

Another issue crucial for modeling of the NSS is traffic estimation. Other vessels do interact with own vessel and spatial distribution is one of the main parameters of traffic flow. To estimate distribution of own position i.e. vessels hull position relative to the axis of the route NSS estimates information about the position of the vessel's center of gravity, shape of the waterline and the course. Different types of distributions are used depending on the type and shape of the waterway like: normal, logarithmic or triangle distribution. For NSS modelling normal distribution with PDF (probability density function) was used (Perkovic et al., 2012):

$$d_l(y) = \frac{1}{\sigma_l \sqrt{2\pi}} e^{-\frac{(y-m_l)^2}{2\sigma_l^2}} \tag{8}$$

where:

y - is distance to the axis,
m - average of ship's distance to the waterway axis,
σ - standard deviation of ship's distance to the waterway axis.

Such defined function can bring answers for design of NSS like type of presentation or maximal error of positioning of waterline. Modern NSS can present even 32 points of waterline on the digital chart i.e. simultaneous computation for 32 points are done every second.

3.3. Human – Machine Interaction modeling

Man inside the steering loop phenomena's is crucial for understanding the navigator's cognitive process. Models of interaction are indispensable for the NSS design and in work (Itoh et al., 2001) task of modelling was done by eye tracking observation with verbal expression of the orders to follow. Generic Rasmussen's model has been adopted – SL model (Step Ladder) along with the SRK (skill-rule-knowledge) paradigms (Rasmussen, 1986). Model of navigator has been presented on fig. 3.

Models presented by Rasmussen and other researchers as above described, has generally non implementable quality based criteria of acceptance for given type of interactions. In general all data coming to the system are evaluated somehow and afterwards some chosen metrics are granted to model. Rasmussens MMI model (Man – Machine - Interaction) is based on elements :

- The system,
- The environment,
- The user(s) and,
- The task(s) to be undertaken.

This paradigm will not let to have fully measurable means, and such attempt has been done in (Gucma, 2008). Model obtained in this thesis has been tested also in NSS optimization and some of outputs has been presented during largest worldwide eye tracking conferences ECEM in 2013 (Gucma and Muczyński, 2013). Decision model for presenting or neglecting information can have a form of matrix. For the *a*-th type of sea area we observe a matrix χ_a with dimensions $\boldsymbol{I} \times \boldsymbol{J} \times \boldsymbol{L} \times \boldsymbol{K} \times \boldsymbol{N}$, where sets has following meanings: ***I***- reflects type of vessel, ***J***-type of maneuver, ***L*** – type of navigation information, ***K*** – its form, ***N*** represents external conditions. Optimization task for obtaining minimal information for performance of safe maneuver can be stated as a finding the matrix $\boldsymbol{X}_a \in \chi_a$ with elements $x^a_{i,j,l,k,n}$ with values 0 or 1 set that states if information will be skipped or presented on display for which matrix the sum of its elements will become minimal:

$$F_0(\boldsymbol{X}_a) = \sum_{i=1}^{\mathrm{I}} \sum_{j=1}^{\mathrm{J}} \sum_{l=1}^{\mathrm{L}} \sum_{k=1}^{\mathrm{K}} \sum_{n=1}^{\mathrm{N}} x^a_{i,j,l,k,n} \rightarrow \min \tag{9}$$

with restrictions:

$$R(\boldsymbol{X}_a) \le R^{dop}_{a,i,j,l,k,n} \quad (10)$$

$$Q(\boldsymbol{X}_a) \le Q^{dop}_{a,i,j,l,k,n} \quad (11)$$

$$Z(\boldsymbol{X}_a) \le Z^{dop}_{a} \quad (12)$$

for:

$$a \in \boldsymbol{A},\ i \in \boldsymbol{I},\ j \in \boldsymbol{J},\ l \in \boldsymbol{L},\ k \in \boldsymbol{K},\ n \in \boldsymbol{N},$$

where:

$\boldsymbol{X}_a$ –matrix of navigational information used for performance of maneuver at given sea area a

$R(\boldsymbol{X}_a)$ –navigation risk for performance of *j*-th maneuver by *i*-th vessel with *l*-th navigation information of *k*-th information visualization on *a*-th sea area

$R^{dop}_{a,i,j,l,k,n}$ –accptable navigation risk for performance of *j*-th maneuver by *i*-th vessel with *l*-th navigation information of *k*-th information visualization on *a*-th sea area

$Q(\boldsymbol{X}_a)$ –information of for performance of *j*-th maneuver by *i*-th vessel with *l*-th navigation information of *k*-th information visualization on *a*-th sea area

$Q^{dop}_{a,i,j,l,k,n}$ –acceptable amount of information of for performance of *j*-th maneuver by *i*-th vessel with *l*-th navigation information of *k*-th information visualization on *a*-th sea area

$Z(\boldsymbol{X}_a)$ –cost of development of NSS on given *a*-th area

Z^{dop}_{a} –acceptable cost of development of NSS on given *a*-th area

That stated optimization form (8) allows to model the minimal required information set for performance of safe maneuvers at are with the support of NSS. That model of information minimization is used on design stage of NSS build up, whilst for latter optimization researches must be carried on with use of sophisticated simulators connected with eye and head of navigator tracking.

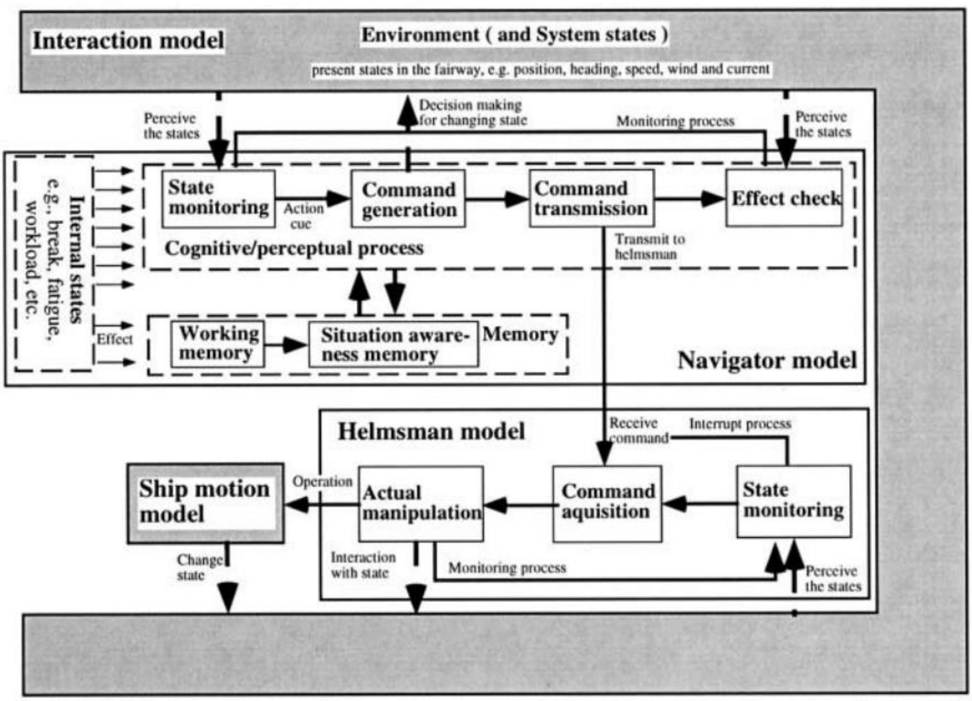

Fig. 3. Architecture for the cognitive model for ship navigation
Source: Itoh et al. (2001).

3.4. Reliability of components models for NSS

NSS (navigation Support System) operational reliability can be defined as a component of technical reliability of individual components and subsystems R_1, .., R_{n-1},R_n, it takes the form:

$$R_s(t)=R_1(t)\cdot R_2(t)\cdot R_3(t)\cdot\ldots\cdot R_n(t)=\prod_{i=1}^{n}R_i(t) \quad (13)$$

Assuming an exponential distribution of the reliability function, coefficient λ which is the failure rate which is constant in time (assuming correct operation of the system at time *t*), so:

$$R_s(t)=e^{-\lambda_1 t}\cdot e^{-\lambda_2 t}\cdot e^{-\lambda_3 t}\cdot\ldots\cdot e^{-\lambda_n t}= =exp\left[-\sum_{i=1}^{n}\lambda_i t\right]=exp\left[-\lambda t\right] \quad (14)$$

The failure rate to the whole NSS system is the sum of individual failure rates of the subsystems (i=1,2,3…n) included in the NSS. The disadvantage of this type of solutions is the full impact of the various subsystems on the survival of the system as a whole. The elimination of this phenomenon by the introduction of redundancy is possible in NSS eg. by:

- introducing additional sensors which are not based on the same principals of the measurement (eg. laser rangefinders, or FMCW radar),
- doubling systems such as GNSS or cellular modems included in the NSS.

For the structure of SWNM redundant subsystem the following is true:

$$Q_i=1-R_i=1-e^{-\lambda_i t} \quad (15)$$

where:
Q_i is a measure of unreliability (probability) of the damage of each component of the system, so the unreliability of the whole NSS can be written as:

$$Q_s=Q_1\cdot Q_2\cdot Q_2\cdot\ldots\cdot Q_n=\prod_{i=1}^{n}Q(t) \quad (16)$$

wanted NSS reliability is then given as:

$$R_s=1-Q_s \quad (17)$$

Another measure of reliability for maneuvering assistance systems and navigation reliability determining the ship's position using NSS at a given level of accuracy. Another measure of reliability for NSS is reliability of the position determination at certain level of accuracy and integrity (as presented in table 1), in general it can be modeled using formula 17.
Presented model allows in pretty fast way to asses subcomponents of NSS in accordance of its usability.

4. Case study

Within the frame of project entitled *The Construction of the Pilot-Docking system (PNDs) for LNG tankers and sea ferries*, NSS system was developed that allows quick and safe measuring the distance of the ship from the quay or berth. System utilizes laser modules presented on fig. 4 These heads can be incorporated in network (this feature has been patented by author) as it is presented on fig. 5. System can work in mesh mode or in standard transmission mode. In the research phase of this NSS, several features has been developed to mention:

- integration of cartometric functions of maneuvering and navigation support systems with the sensors reading distances with high accuracy (laser pulse sensors)
- the introduction of high distribution of radar and laser techniques and methodology for the development of these results
- development of the first Polish modular PNDs equipment to determine the position of the LNG tankers and sea ferries
- development of communication methods of short-range redundant mesh networks for rapid data exchange with sensors

System has been implanted according to demands of user where every system is bit different. Apart from modelling of core features like range of laser, most of such systems demands accuracy of 0.01m and integrity risk not worse than 10-5 in 3 hours period.
System PNDS has been installed in Slovenian port Koper on berth where containers vessels are handled of size up to 10.000 TEU (Twenty foot container equivalent). On fig. 6 working system is presented.

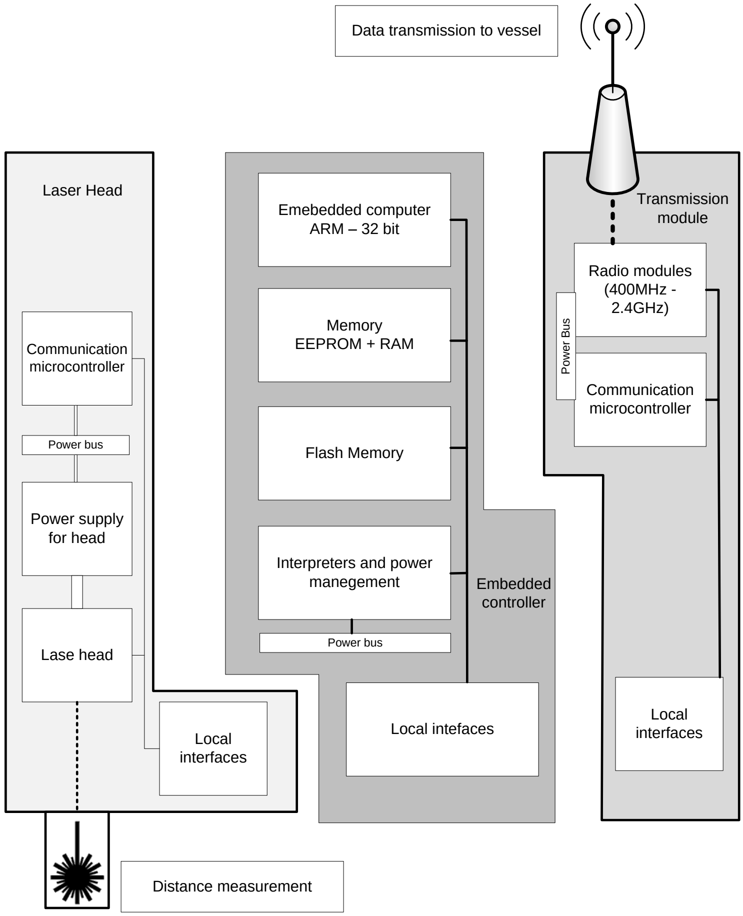

Fig. 4. Single laser head of PNDS system
Source: Bąk et al. (2010).

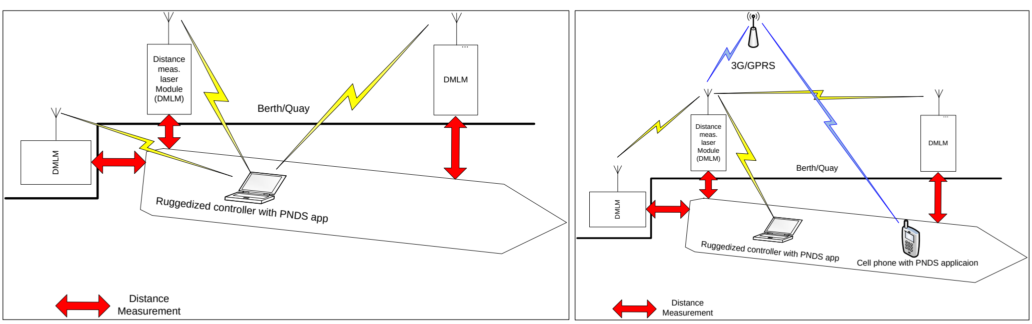

Fig. 5. Measurement modes with 3 laser heads in standard mode (left) and mesh mode (right)

Fig. 6. View of the terminal in the port of Koper (on the left) and installed PNDs sensor system, on 09/10/2015; in the background, a container ship with a capacity of about 6 thousand TEU

5. Conclusions

In article several methods and aspects of modelling Navigational Support Systems (NSS) has been presented. Key issues that has been touched during the design of complete methodological process are:

1) Core functionality modelling of NSS with aspects of navigation safety, reliability and desired parameters of performance.
2) Technical system reliability in form of complex reliability
3) Modeling of HMI (Human – Machine – Interaction) with means of basic input and output interfaces.

It is important to keep in mind that no complex method has been developed yet, and whilst some of methods can apply to the functioning of NSS like determination of maximum traffic on area or reliability of subcomponents, it must be furtherly researched. Especially some parts of optimization algorithms where different methods are applied or interconnections between the described methods and its impact to whole system shall be investigated.

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