THE JOURNAL OF NAVIGATION (2003), **56**, 153–175. © The Royal Institute of Navigation
DOI: 10.1017/S0373463302002175 Printed in the United Kingdom

Functional Scope and Generic Model of Integrated Navigation Systems

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The increasing degree of integration of navigation systems and of complexity of these systems place new requirements on their use, test methods and specifications. These systems (Integrated Bridge Systems, Integrated Navigation Systems, Track Control Systems) contain a large number of functionalities, which have hitherto been carried out by equipment and units clearly delimited from one another. The purpose of this study is to develop a framework for Integrated Navigation Systems that enables an equipment-independent description of the requirements in order to take account of the large range of existing systems as well as future developments. In Part A, the functions fundamental to navigation operations are identified. A hierarchical approach is used to identify the global process task, task areas, tasks, functionalities and, finally, elementary functions. In Part B, a model of the 'integrated navigation' process is derived from the functional analysis. With the aid of the model it is possible to identify functional dependencies and resultant error chains. A 'three-dimensional network' is developed that represents the information flows between the functional units. In Part C, requirements on the testing of Integrated Navigation Systems are derived from the functional model. Independent of specific technical implementations, the starting points are information flows. The requirements the functions place on their respective input information are identified. Furthermore, categorisation of the test requirements is undertaken. This paper is a shortened version of the 'Integrated Navigation Systems scope and model'. The complete paper (183 pages) may be obtained from the authors.

KEY WORDS

1. Integration. 2. Modelling. 3. Marine.

PART A – FUNCTIONAL ANALYSIS OF NAVIGATION OPERATIONS.

1. THE APPROACH. The aim of the analysis of navigation operations is to identify the functions fundamental for integrated navigation systems (Kuternoga and Mathes, 1997; Laux, 1991; Gebhardt, 1994; Bürcks and Peters, 1996). 'Fundamental' means considering only those functions that have to be available in an integrated navigation system (INS), irrespective of the technical implementation, in order to fulfil the tasks of the operation. Identification of these functions starts from the global process task. From this, the individual task areas and tasks, functionalities and functions are deduced.

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The functional analysis of the navigational process can be broken down into the following levels:

(a) Definition of the 'global process task'.
(b) Task areas, i.e. groups of tasks clearly de-limitable in relation to one another in terms of contents and time.
(c) For each task area: identification of 'tasks'. Tasks are defined by a purpose that is achieved by carrying out a sequence of functions.
(d) For each task: identification of the 'functionalities'. A hierarchical classification of functionalities in levels is produced, the degree of abstraction decreasing with increasing number of levels, and the degree of detail conversely increasing.
(e) For each functionality: identification of the 'elementary functions', which are defined by virtue of their 'effects': they generate one or more output variables from a defined set of input variables.

The result of the analysis is a catalogue of functions. The structure of this catalogue follows the breakdown of the navigation process into tasks and functionalities. For each function the necessary input data and the supplied output data are listed in detailed form. This catalogue serves as an information source for development of the functional model of navigation operations.

2. FROM THE GLOBAL PROCESS TO INDIVIDUAL FUNCTIONS.

2.1. *Global process task*. Definition of the *global process task* forms the basis for identification of functions. Ship operation is considered from the aspect of 'integrated navigation'. This process comprises the following aspects:

2.1.1. *Voyage planning*. Requires completion of the planning tasks necessary for subsequent execution of a voyage. Within INS, planning tasks primarily serve the purpose of creating and providing set data which serve as input information for subsequent execution of the voyage plan. The necessary input data for developing the voyage plan must be compiled and evaluated.

2.1.2. *Voyage execution and monitoring*. Requires undertaking the voyage on the basis of the set data developed within voyage planning. Essentially, this task breaks down into determining set/actual deviations and determining set values for influencing the ship's movement parameters.

2.1.3. *Management of data and reference parameters*. Requires recording and administering data that are required to execute the process task. This involves maintenance of the geographical database, and recording and administering 'static' ship data and parameters as well as further local and global reference parameters. These data are necessary to describe and monitor the movement of the vessel, e.g. manoeuvring characteristics, sensor locations and geographical reference systems.

2.1.4. *Dealing with unplanned incidents*. Requires planning and executing deviations from the original voyage plan as a reaction to unplanned incidents. These may include collision avoidance, grounding avoidance, evasion of bad weather regions or man-overboard manoeuvres.

2.1.5. *Recording the current situation*. This area comprises all functionalities that serve the purpose of observation of the current situation of own ship, monitoring of

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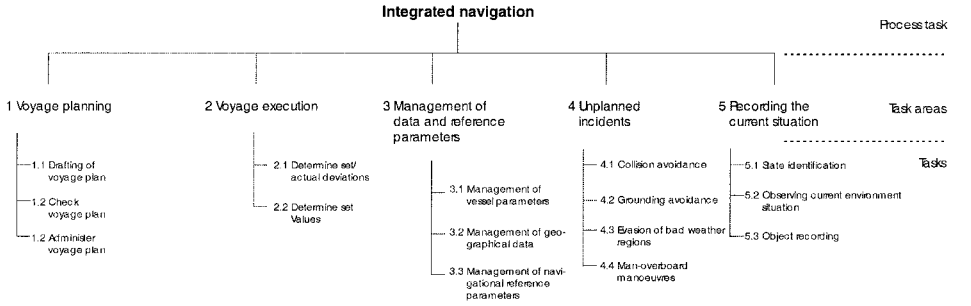


Figure 1. Global process tasks, task areas and tasks of navigation operations.

actual values used within the control system and of the environment (e.g. weather, sea, traffic).

From these aspects, the following definition for the process task of integrated navigation is produced:

> Integrated navigation is the planning and execution of the voyage of a ship from a departure point to a destination point. When executing the voyage, the reference data created as part of planning as well as the influencing environmental parameters must be taken into account. To ensure the safety and economic efficiency of the voyage, changes in the voyage plan should be undertaken if necessary.

2.2. *Task areas.* The identification of task areas serves the purpose of structuring the process of integrated navigation. By introducing the task area level, the complex process can be divided into comprehensible units, which can be considered separately in the further course of the analysis. The task areas of the 'integrated navigation' process can be derived directly from the definition of the global process task given above: voyage planning, voyage execution, management of data and reference parameters, dealing with unplanned incidents, and recording the current situation.

2.3. *Tasks.* Below the five above-mentioned task areas, the tasks of integrated navigation can be classified as shown in Figure 1. The three upper levels of the analysis of integrated navigation are illustrated. Task areas are broken-down to tasks. The global process task is thus fulfilled by the execution of tasks. The function catalogue is structured according to the tasks represented here.

2.4. *Functionalities.* Functionalities represent closed functional units that have to be executed to fulfil a task. They process a set of input data and supply a defined set of output information. Functionalities may be structured in several levels, i.e. a complete functionality with a high degree of abstraction can be described by a quantity of functionalities with a lower degree of abstraction. This process of subdivision is carried out recursively until the level of functions is reached. Figure 2 shows the task areas with related tasks and functionalities in summary form.

2.5. *Functions.* Finally, the elementary, lowest level 'functions' for each functionality are identified. Moreover, the respective functionality is implemented by the combination of several elementary individual functions.

2.6. *Identification of functionalities and their respective functions.* Various types of functionality were identified that can be implemented by a certain set of functions. The following types may be distinguished:

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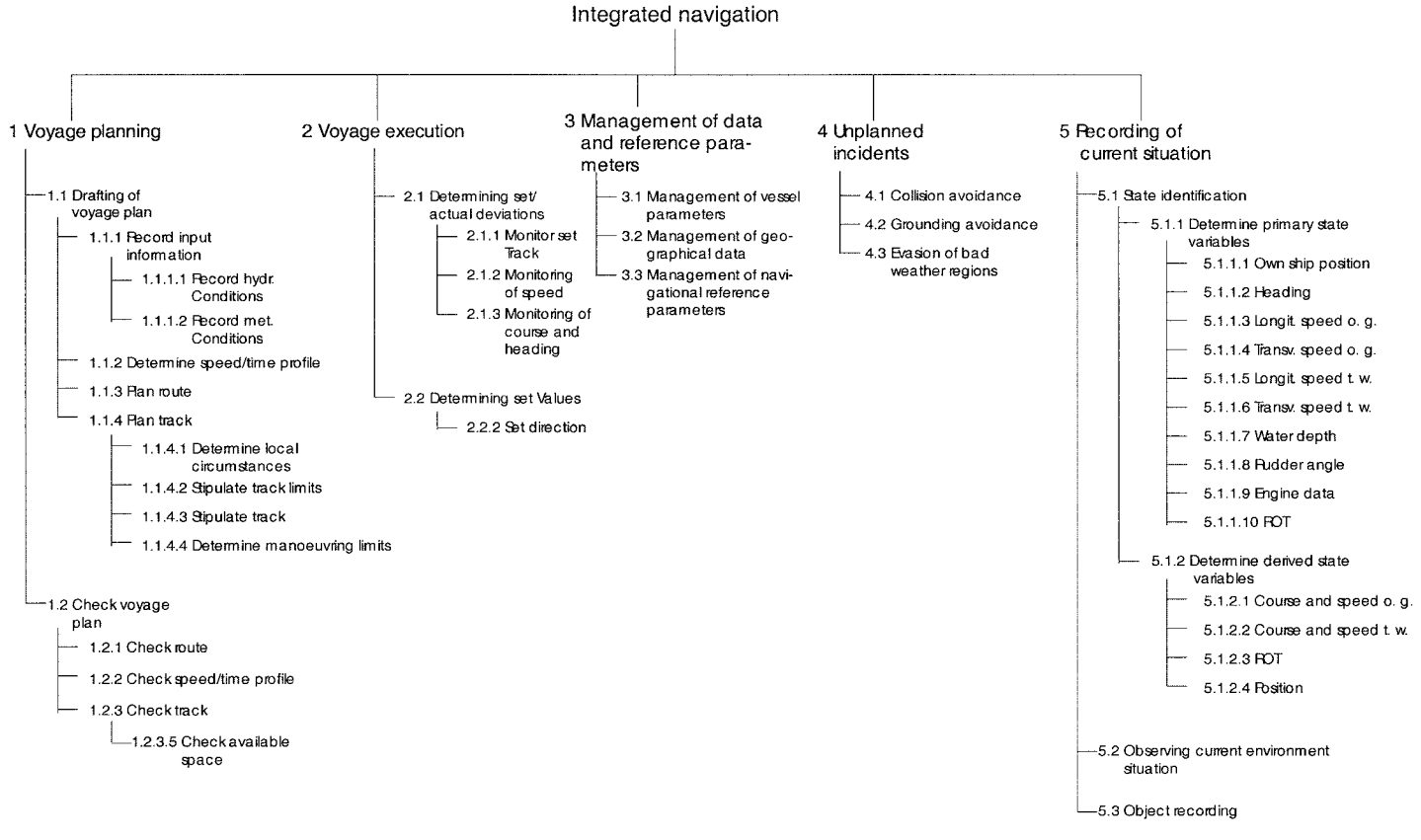


Figure 2. Functionalities of integrated navigation.

2.6.1. *Functionalities for data recording*. Functionalities of this type are used to determine and provide information that is required by other functionalities. They consist of the following elementary functions:

(a) Record input data,
(b) Evaluate data,
(c) Provide set values/information.

2.6.2. *Functionalities for selection of system data*. Functionalities of this type are necessary for executing the task 'State identification'. These functionalities determine, from a set of input data, which may be available from several sources, a 'system datum' for the respective state variable. The system datum is a state variable of a given type which must be used by all functionalities or functions concerned. Functionalities for selection of system data are composed of the following functions:

(a) Record data,
(b) Evaluate data,
(c) Compare data,
(d) Assess result of comparison,
(e) Select information to be provided,
(f) Provide information.

2.6.3. *Functionalities for the set/actual comparison*. Functionalities of this type compare a set value for a certain datum with a current actual value. The deviation serves as input information for adjustment/control. These functionalities are implemented by the following functions:

(a) Record set value,
(b) Record actual value,
(c) Record assessment criteria,
(d) Compare set value and actual value,
(e) Assess comparison,
(f) Provide result of comparison.

The function 'Record assessment criteria' reads the information necessary for assessment of the comparison. For example, it may be examined whether the difference between set and actual lies within a given limit. The functions 'Record assessment criteria' and 'Assess comparison' are optional.

2.6.4. *Functionalities for influencing state variables*. It is characteristic of functionalities of this type that they contain an elementary individual function 'Act'. In general, such functionalities consist of the following functions:

(a) Record information,
(b) Assess information,
(c) Act.

The function 'Record information' may be implemented several times for one functionality.

3. EXAMPLES: TASK AREA 'VOYAGE MONITORING AND EXECUTION'.

3.1. *Task:* '*Determining set/actual deviations*'. The purpose of the task is to determine and provide differences between set values (from voyage planning) and actual

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values (from the task 'State identification'). The result of this set/actual comparison is used as input information within the task 'Determining set values' (see Section 3.2.). The functionalities necessary for fulfilling this task are derived from the resultant information provided within this task:

(a) Monitoring track parameters: observance of track sections, track limits (maximum deviations), manoeuvring limits, of the set values for ROT/turning radii and of the rudder setting points at course changing points, given passage and arrival times;
(b) Monitoring the course: comparison of set course and actual course;
(c) Monitoring the speed: comparison of set speed (any desired source) and actual speed.

3.1.1. *Functionalities of task:* '*Determining set/actual deviations*'. The following functionalities are produced for the task 'Determining set/actual deviations':

(a) Monitoring observance of the set track:
  (i) Monitoring transverse deviation, i.e. comparison of present position/track limits ('off-track limits');
  (ii) Monitoring the time profile: fixed passage and arrival times;
  (iii) Monitoring planned course changes: observance of rudder setting points, turning radii/ROT/rudder angles at course changing positions, observance of manoeuvring limits;
(b) Monitoring of course and heading: comparison of set and actual course, consideration of permitted deviations for the actual course; monitoring the heading;
(c) Speed monitoring: comparison of a set speed (e.g. from track planning) with measured value.

Along with these functionalities, fundamental for fulfilling the process task, the task contains two further 'administrative functionalities' which serve as interfaces to other processes or to external data receivers and data sources:

(d) Administering the current voyage plan;
(e) Scanning external set values.

3.1.2. *Functions of task* '*Set/actual comparison*'. The fundamental functionalities assigned to this task are of the 'set/actual comparison' type. They thus possess the following elementary individual functions:

(a) Record set values;
(b) Record actual values;
(c) Compare set and actual values;
(d) Assess comparison;
(e) Provide result.

3.2. *Task:* '*Determining set values*'. The purpose of the task is to determine set values for rudder angle and engine control in order to take the ship onto the planned track. As input data, the resultant data from the task 'Determining set/actual deviations' are used, i.e. the difference between the set data (from voyage planning) and the actual data (from the state identification). The process of determining set values may be carried out both manually and automatically. Although establishing the degree

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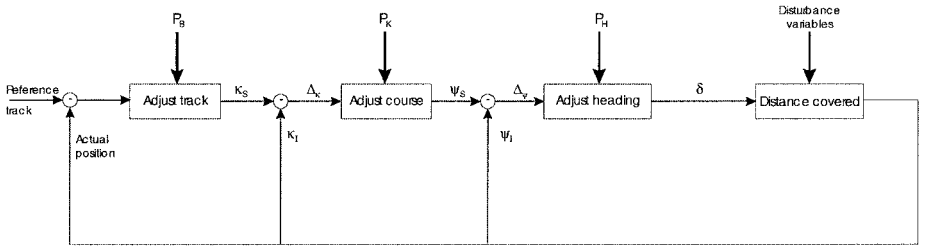


Figure 3. The functionality 'Set direction'.

of automation is not basically the content of functional analysis, distinctions must be made in this task:

(a) Automatic track control is permissible only under certain circumstances. The assessment criteria are the current range of the track, which must lie below a fixed limit, and the necessary course change to steer onto the track, which must not exceed a fixed limit value;
(b) Automatic and manual track control differ considerably in terms of their input data. Course changes in automatic track control are generally arranged by a set value for the ROT. In manual track control, the turning radius as a function of the manoeuvring room available is the deciding variable.

These peculiarities are taken into account by virtue of the fact that some of the input data are optional.

3.2.1. *Functionalities of task 'Determination of set values'*. When determining set data, the direction and speed of the ship are the deciding parameters. For this reason, a distinction is made between two global functionalities: 'Set speed' and 'Set direction'. The functionality 'Set direction' essentially consists of three control functionalities (Figure 3):

(a) 'Adjust heading': the heading is adjusted to a set value. The setting variable is the rudder angle δ.
(b) 'Adjust course made good': the course made good is kept at a set value. From the difference between actual course and set course, a set heading ψ_S is determined.
(c) 'Adjust track': a set course made good κ_S is determined from the current track deviation Δ_b.

The deviations Δ_b, Δ_κ and Δ_ψ are resultant information of the task 'Determining set/actual deviations'. The controller behaviour is governed in each case by means of a set of parameters (P_x). These parameters determine the characteristics of the controller (time constants, proportionality factors, etc.). For automatic track control, certain limit values are stipulated here (e.g. track controller: off-course limits and off-track limits). The functionality 'Set speed' serves to exert influence on the present speed. The following input variables are considered (Figure 4):

(a) Difference between set and actual speed;
(b) Limit values, e.g. manoeuvring limits which are incorporated as parameters in speed control.

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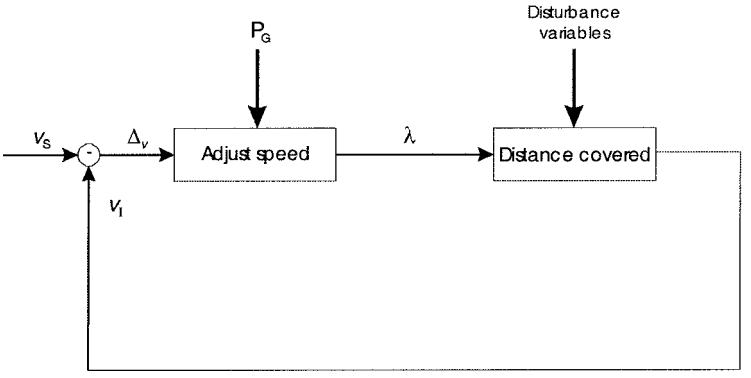


Figure 4. The functionality 'Set speed'.

3.2.2. *Functions of task: 'Determination of set values'*. The functionalities of the task 'Determining set values' are of the 'Influencing state variables' type. Each functionality accordingly contains the following elementary individual functions:

(a) Record information: scan the input data relevant for influencing the respective parameter. This includes the particular set/actual deviation to be adjusted as well as the controller parameters.
(b) Assess information: as to whether adjustment of the set/actual deviation is permissible.
(c) Act: execute the adjustment, i.e. determining the setting variable.

4. CATALOGUE OF FUNCTIONALITIES AND ELEMENTARY FUNCTIONS. The following sections contain the catalogue of functionalities and functions identified for the process of integrated navigation. The structure of the catalogue follows the process tasks defined in Section 1. The format of the tables of functionalities and functions (Table 1) differs according to the depth of classification of the tasks concerned. The table contains the following columns, depending on the depth of classification of the particular functionalities considered:

(a) *Abstract functionalities of level 1*: This level is introduced for complex functionalities. From these functionalities, it is not yet possible to derive elementary individual functions directly.
(b) *Detailed functionalities of level 2*: This is the 'lowest' level of functionalities for the respective task. The analysis of these functionalities leads directly to elementary individual functions.
(c) *Function*: This column contains the elementary individual functions of the particular functionality.
(d) *Input and output information*: For each function, the necessary input information and the supplied output information are listed.

PART B – FUNCTIONAL MODEL OF THE INTEGRATED NAVIGATION PROCESS.

5. INTRODUCTION. Modern INS offer a large number of functions that are necessary to fulfil the tasks of navigation operations. With the increasing degree

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Table 1. Functionalities and Functions for task area 'Voyage Execution and Monitoring' Task: 'Determining set/actual deviations'.

Functionality level 1	Functionality level 2	Function	Input information	Output information
1. Monitor observance of set track	1.1. Monitor transverse deviation	1.1.1. Record set and actual values	Planned track (way point list) Actual position	Necessary input data for monitoring the set track are available
		1.1.2. Compare data	Output information from 1.1.1.	Deviation of actual position from reference track Graphic representation of set track and track limits Representation of actual position of ship
		1.1.3. Assess comparison	Output information from 1.1.2. Track limits	Statement whether actual position is within track limits
		1.1.4. Provide result	Deviation of actual position from the set track, track limits	Output of current deviation from the set track for the user, display whether deviation is within the given limits Alarm if actual position is outside the 'track confinement' (set track and limits)
	1.2. Monitoring the time profile	1.2.1. Record set and actual values	Present position Set position for which passage/arrival time is stipulated Present time Fixed passage or arrival time	Necessary input data for monitoring the time profile are available
		1.2.2. Compare data	Output information from 1.2.1.	Distance between actual position and 'set position' Time difference between reference passage/arrival times and present time for position considered
		1.2.3. Assess comparison	Output information from 1.2.2. Limits for time diff./distance	Statement whether determined time difference or distance is within given limits
		1.2.4. Provide result	Output information from 1.2.2. Output information from 1.2.3.	Statement whether schedule is being observed
	1.3. Monitoring planned course changes	1.3.1. Record set and actual values	Actual position Actual values for ROT, turning radius, rudder angle Reference track (last WP point/course change point/next WP etc.) Reference value for turning radius or ROT at course changing point Manoeuvring limits (maximum rudder position/max. ROT)	Graphic representation of position and movement of ship in track section considered Representation of preset values for manoeuvre at course changing point Representation of manoeuvring limits
		1.3.2. Compare data	Output information from 1.3.1.	Difference between position/movement and given track geometry Deviation actual/set values for turning radius or ROT Difference between actual values for ROT/rudder position and manoeuvring limits
		1.3.3. Assess comparison	Output information from 1.3.2.	Statement whether position/movement of ship is within limits Statement whether set/actual deviation of ROT or turning radius is within given limits Statement whether actual values for ROT/rudder position are within manoeuvring limits
		1.3.4. Provide result	Output information from 1.3.2. Output information from 1.3.3.	Output of set/actual deviations for the user Provision of deviations for use by other functionalities

of integration, the interdependences and interlinking between functions are also increasing. The growing number of interactions between the system components means that the number of possible system states becomes very large. Implementation of different functions – depending on the particular manufacturer or equipment philosophy – may differ widely. An approach was selected that enables an equipment-independent description of the functional properties of INS. In Part A, a catalogue of the functions of navigation operations was presented, which serves as a basis for the functional description of INS. In this catalogue, the functions are classified in a hierarchy using logic and content. For the functions, the input and output information necessary or supplied in each case has been listed. Along with a hierarchical structure of the functionalities and functions, the function catalogue likewise contains a list of the information flows belonging to each function.

The aim of this section is to develop a model of the process of integrated navigation – based on the functional analysis (Part A). With the aid of a model it is possible to identify functional dependences and resultant error chains. On the basis of the functionalities, functions and information flows identified in Part A, a 'three-dimensional network' is developed which on several abstraction levels represents the information flows between the functional units present in the INS. The approach used here for the development of the functional model is based on the 'structured analysis'. This involves a formalised method for the description of existing systems or systems to be developed, which is chiefly used for software development (DeMarco, 1979; McMenamin and Palmer, 1984; Raasch, 1993). The different description forms for differing aspects of the model and their syntax are explained.

6. MODELLING APPROACH.

The modelling method used here must fulfil the following requirements:

(a) Capacity to support a hierarchical view on systems (tasks, functionalities and functions);
(b) High flexibility, e.g. no restrictions with regard to the field of application considered;
(c) Simple notation, i.e. simple for developers and users to learn and use;
(d) Support for a 'functional system view'.

It was found that the method of structured system analysis ensures excellent fulfilment of these requirements. In particular, this method offers the possibility of representing large and complex systems in a readily comprehensible manner. This is achieved by having various aspects of the system represented by different sub-models. For the purpose of modelling the integrated navigation process the following sub-models are used:

(a) The *context diagram* represents the system's reference to its surrounding environment. The interfaces of the system to the 'outside world' are specified.
(b) *Data flow diagrams* represent the input and output information and the functional dependences for each functional unit considered.
(c) The *data dictionary* specifies in detail the data flows represented in the data flow diagrams.

This structured system analysis is based on the concept of recursive breakdown of a complex system into comprehensible sub-systems. For the purpose of modelling the

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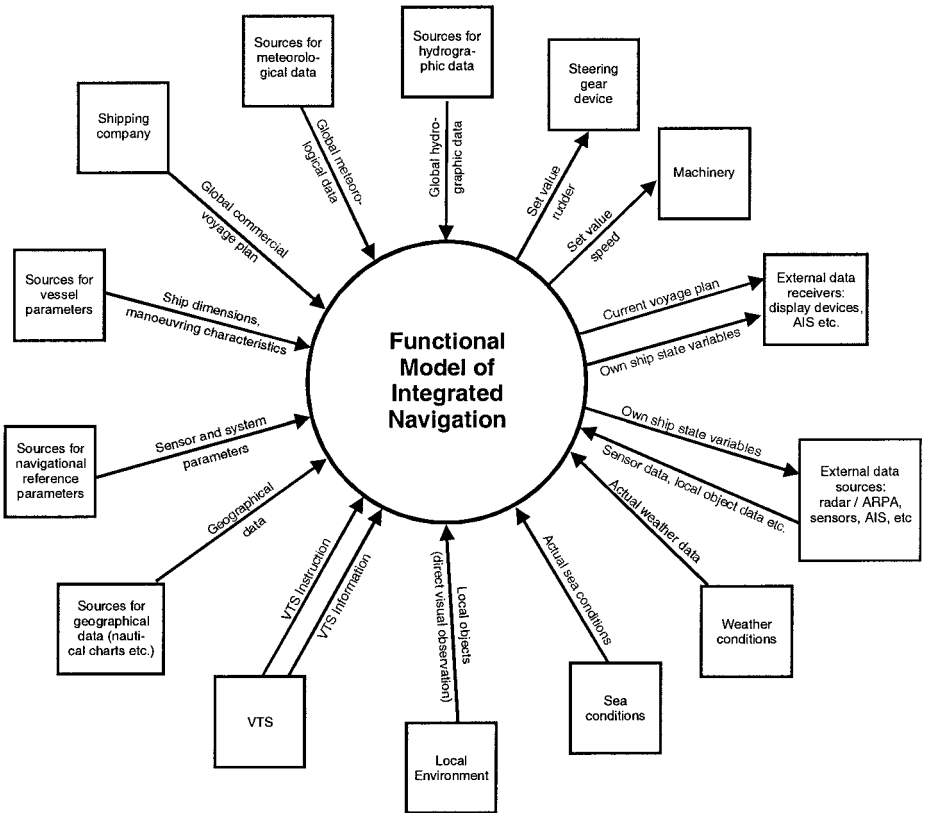


Figure 5. Context diagram for the 'Integrated Navigation System'.

functionality, the function-orientated breakdown already carried out in Part A is used. The starting point used is the system as a whole, in a top-down approach. Taking the system tasks as a basis, the assigned functionalities are refined until the level of elementary individual functions is reached. The result of this progressive refinement is explained in the hierarchical structure of the data flow diagrams (Section 7). This approach is supplemented by an object-orientated breakdown of the information flows within the system.

6.1. *Context diagram* (*CD*). The context diagram forms the starting point of a structured system analysis. The main purpose of this diagram is to define the scope of the analysis clearly and identify the boundary of the system (Figure 5). Furthermore, the external units are represented with which the system communicates. The comparison of the context diagram with the 'top level' data flow diagram (Figure 6) shows that the 'system' delimited in the data flow diagram is represented in the context diagram by one process. The number and type of data flows beyond the system boundary is identical in the two diagrams.

6.2. *Data flow diagrams* (*DFD*). Data flow diagrams represent the functional dependences between processes in the form of exchanged information (data flows). Processes are represented by circles with a name and a number. From this, the manner of classification in the hierarchical structure of the system considered is apparent. The hierarchical structure of data flow diagrams is based on the concept of progressive

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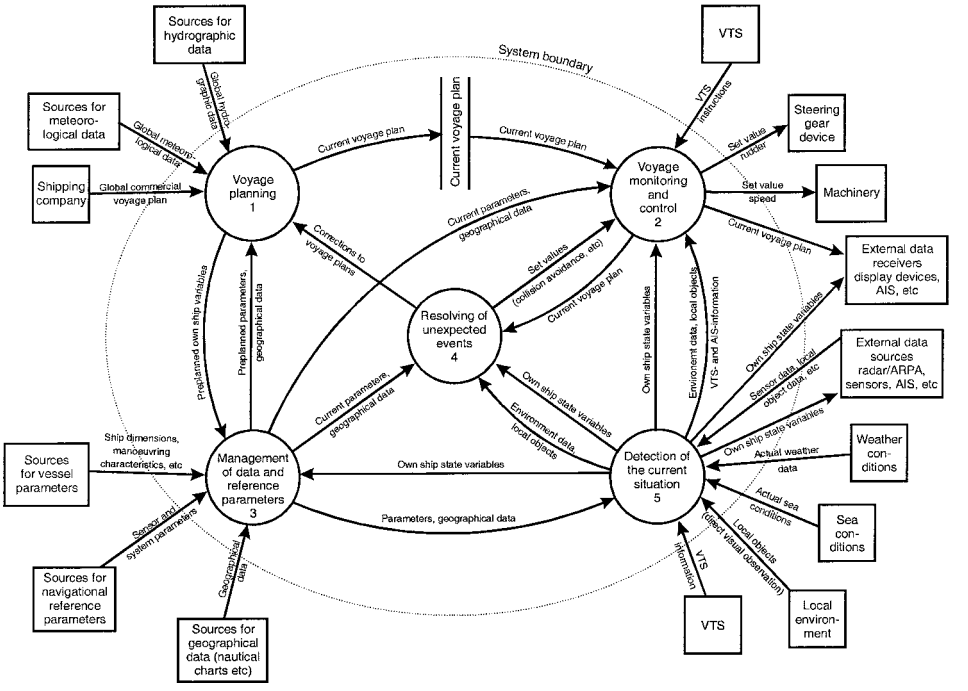


Figure 6. Top-level diagram of the 'integrated navigation' system (DFD 0).

refinement. If the content of a process is describable in simple terms, the refinement is terminated. Otherwise, it is divided ('functionally partitioned') into several sub-processes on the next refinement level (see Part A).

From the numbering of the data flow diagrams, the allocation to the particular overriding process and also the respective classification level are obtained. The 'top-level diagram' (Figure 6) is given the number 'DFD 0'. The processes represented are numbered from 1 to n (here: $n = 5$). The data flow diagrams of the levels below are identified with these numbers. The processes represented in these diagrams are again numbered from 1 to n, the respective number of the diagram being placed before the process number. This number code is continued recursively until the lowest classification level is reached. Figure 7 shows this method in schematic form.

Data memories are represented by two parallel lines. The data types contained in a particular memory are specified in the data dictionary. Data flows are channels for information flows with a known composition. Data packages may be transmitted via these channels and trigger the receiving process, i.e. the data package serves as an 'incident' that 'triggers' the receiving process. Input information may be converted into output information by the process. The composition of the data packages transmitted at any given time characterises the respective channel. The description of the data packages is contained in the data dictionary. External units, i.e. objects of the environment with which the system concerned communicates, are identified in the context diagram and in data flow diagrams by 'terminators'. These are not described in detail and appear in the model only as transmitters and receivers of data. Data flows between terminators and the system represent interfaces of the system with the environment.

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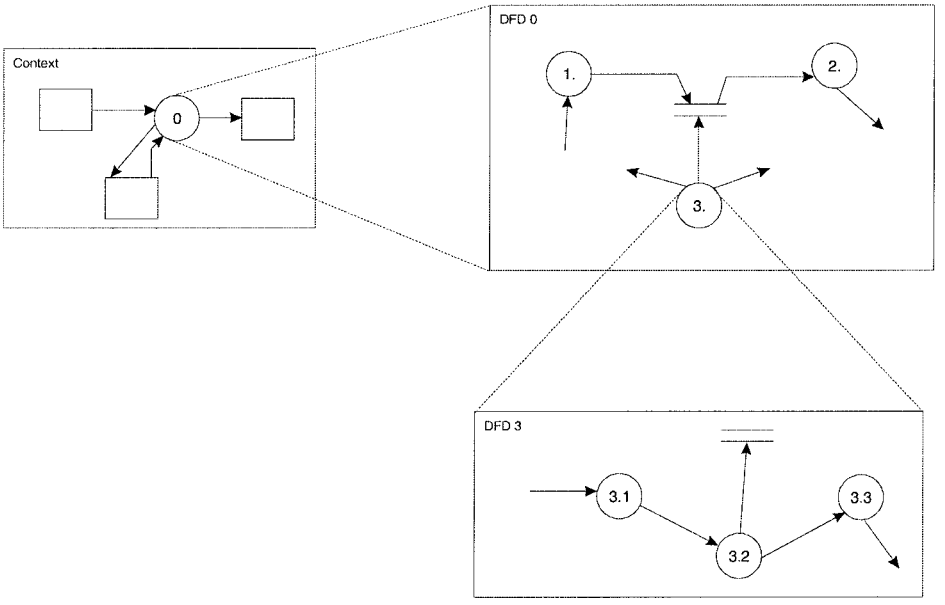


Figure 7. Model hierarchy: top-down from DFD 0 to DFD n.n.

Table 2. Elementary data types.

	Data type	Description
1	3D_VECTOR	3-dim vector (from a reference point in the three spatial directions)
2	ANG_VELOCITY	Angular velocity in [l/s] or [l/min]
3	ANGLE	Any desired angle in [deg]
4	DISTANCE	Distance in [m] or [sm]
5	ID	Any desired but unique identifier for an object
6	NAUT_ANGLE	Nautical angle, unit [deg], value range [0;360]
7	NAUT_SPEED	Speed in [kts]
8	OBJ_TYPE	Description of the type of an object
9	POSITION	Geographical position in degrees longitude and latitude
10	PRESSURE	Pressure in [Pa]
11	RATIO	Relative value, expressed as a % of a maximum value
12	SPEED	Speed in [m/s]
13	TEMPERATURE	Temperature in [°C]
14	TIME	Any desired time

6.3. *Data dictionary*. The data dictionary ('DD') contains the detailed specification of the data types exchanged within the system, i.e. the data flow. Each entry in the data dictionary contains an explanatory note relating to the particular data type and a list of elements (attributes), which are contained in the data type. The data dictionary consists of three parts:

6.3.1. *Elementary data types*. These are the 'basic modules' from which all information exchanged within the INS is composed. They are not used in this form, but as elements of simple and composite data types (Table 2).

6.3.2. *Simple data types*. Simple data types containing precisely one information element. This is defined by an elementary data type (Table 3).

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Table 3. Simple data types.

	Data type	Description	Structure
1	Deviation of CMGx	Set/actual deviation for course made good at measuring point x (in the ship KOS)	NAUT_ANGLE
2	Deviation of CTWx	Set/actual deviation for course through water at measuring point x (ship KOS)	NAUT_ANGLE
3	Deviation turning radius	Set/actual deviation for the turning radius of the ship	DISTANCE
4	Deviation of HDG	Set/actual deviation for heading	NAUT_ANGLE
5	Deviation of ROT	Set/actual deviation for rate of turn	ANG_VELOCITY
6	Deviation of route	Set/actual deviation for a route	DISTANCE
7	Dev rudder setting point	Set/actual deviation for a rudder setting point on the planned track	DISTANCE
8	Deviation of SOGx	Set/actual deviation for speed over ground at measuring point x (ship KOS)	NAUT_SPEED
9	Deviation of STWx	Set/actual deviation for speed through water at measuring point x (ship KOS)	NAUT_SPEED
10	ATEMP	Air temperature	TEMPERATURE
11	BAR	Air pressure	PRESSURE
12	CMGx	Course made good at measuring point x (in the ship KOS)	NAUT_ANGLE
13	CPA	Closest point of approach, passing distance	DISTANCE
14	CTW object	Course through water of an object (i.e. generally a foreign ship)	NAUT_ANGLE
15	CTWx	Course through water at measuring point x (in the ship KOS)	NAUT_ANGLE
16	DEPTHx	Depth under the keel at the point x	DISTANCE
17	Turning radius	Radius of turning circle in manoeuvres	DISTANCE
18	DRIFT	Value of speed of current	NAUT_SPEED
19	Incident position	Geographical position at which the incident took place	POSITION
20	Overall height of ship		DISTANCE
21	HDG	Heading	NAUT_ANGLE
22	KrK	Gyro compass course	NAUT_ANGLE
…	…		
70	Time		TIME

6.3.3. *Composite data types.* Data of this type are produced from the combination of different simple data types and have a defined internal structure (Table 4). Data flows can be broken down recursively into smaller units, until each data flow is described by a unique set of elementary data types.

7. EXAMPLES FOR DATA FLOW DIAGRAMS.

The top-level DFD 0 shows a clear division between 'Voyage planning' (Process 1; DFD 1) and 'Voyage execution or monitoring' (Process 2; DFD 2). The 'current voyage plan' memory represents the connecting link between these two processes. Amongst other things, this memory contains the set track valid in the system, which is usable for automatic track control. Further processes are e.g. used for the procurement and administration of data: Process 3 ('Management of data and reference parameters') models the 'Sea chart management' and the recording and administration of ship data, etc. In turn, the data flow 'State variables' (part of Process 3) primarily models the transmission of the ship's position for selection of the current sea chart. It should be borne in mind that the whole 'integrated navigation' process chiefly supplies two items of output information: 'Set rudder angle' and 'Set engine data'. The information flow via the current values of rudder angle and engine data is affected via the process 'State identification' and is thus encapsulated in the data flow 'Sensor data'.

7.1. *DFD for task area 'Voyage planning' (Task 'Drafting voyage plan').* The data flow 'Voyage plan data' (see DFD 1 in the original paper) has been broken down in DFD 1.1 (Figure 8) into the components route data, track data, set speeds and passage and arrival times. The data flow 'Set speeds' may contain speeds through the water or over ground. The set speed used as a basis in the system at any given time during the voyage must correspond to the sensor technology available. The basic assumption when considering voyage plan data is that the voyage plan may adopt two 'states': 'route' or 'track'. These differ in terms of their reference to the surrounding environment. A track has a unique local reference (with regard to the geographical, meteorological and hydrographic conditions), while a route has more of a global character. Thus a track is automatically 'more detailed' than a route. Since only the track takes local details (e.g. waterway, traffic separation regions) into account, only these may form the basis for automatic track control. Moreover, DFD 1.1 shows that the data flow 'Correction information' consists of three components:

(a) track-related correction information;
(b) route-related correction information;
(c) correction information for the speed/time profile.

7.2. *DFD for task area 'Voyage execution and monitoring'.* The process represented in DFD 2 (Figure 9) models the execution of the voyage. On the abstract level represented here, voyage execution can be modelled by two processes:

(a) '*Determining set/actual deviations*' (Process 2.1): determining the deviations between current state variables (position, courses, speeds) and set values. Set values originate from the following sources:
  (i) the current voyage plan;
  (ii) other processes within INS, particularly Process 4 'Dealing with unplanned incidents';
  (iii) other sources, e.g. instructions from vessel traffic services.

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Table 4. Composite data types.

	Data type	Description	Structure
1	Absolute object data	Data which describe foreign object, movement in absolute system	
2	Deviation of arrival time	Deviation from a planned arrival time for a given position	Arrival position AS POSITION + Time deviation AS TIME
3	Deviation of track	Deviation from a set track	Transverse deviation + longitudinal deviation
4	Deviation of speed/time profile	Set/actual deviations, SOGx for route sections Set/actual deviations, passage and arrival times for selected way points	ARRAY OF [WP ID + deviation SOGx] + ARRAY OF [WP ID + deviation arrival time] + ARRAY OF [WP ID + deviation passage time]
5	Deviation of manoeuvre	Deviation from planned manoeuvre given By turning radius or ROT and rudder setting point	[Deviation turning radius II deviation ROT] + Deviation rudder setting point
6	Deviation of passage time	Deviation from a planned passage time for a selected object	Object AS ID + Time deviation AS TIME
7	Current sea data	Observed current sea data: wave heights, frequency, direction	
8	Current weather data	All data describing the current weather	
9	Current voyage plan	Present voyage plan used by the INS	Voyage plan data
10	Arrival time	Planned arrival time for a given position	Arrival position AS POSITION + Arrival time AS TIME
11	Selected manoeuvre	Selected man-overboard manoeuvre	
12	Evasion track	Evasion track for collision/grounding avoidance	Way point list
13	Evasion route	Route for evasion of bad weather regions	Way point list
14	Track data	Planning data describing a track, result of track planning	Track way point list + ARRAY OF [ref. CMGx] + ARRAY OF [way point distance] + ARRAY OF [manoeuvre at way point]
15	Track limits	Maximum transverse and longitudinal deviations for planned track	ARRAY OF [WP ID + max. transverse deviation max. + longitudinal deviation
…	…		
89	Wind information	Information on wind conditions to be expected, related to route or track	

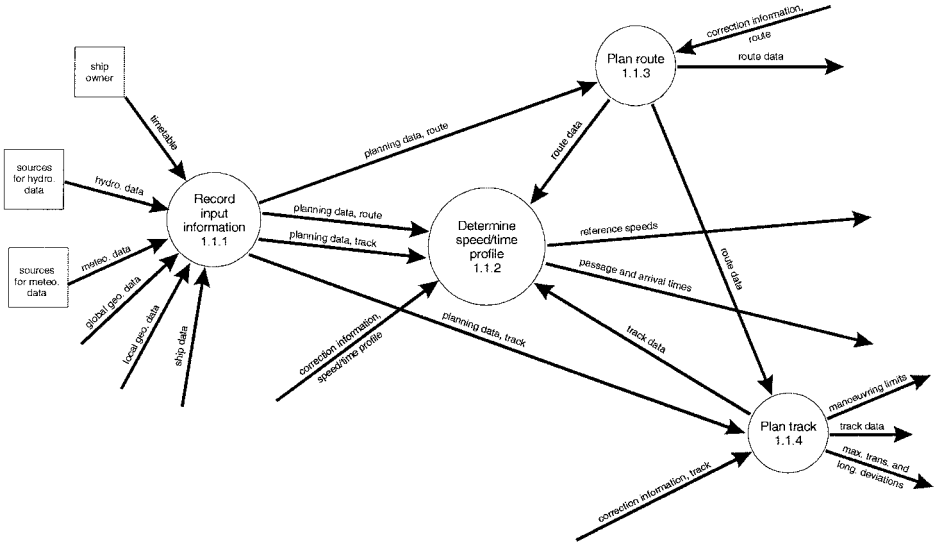


Figure 8. Task 'Drafting voyage plan' (DFD 1.1).

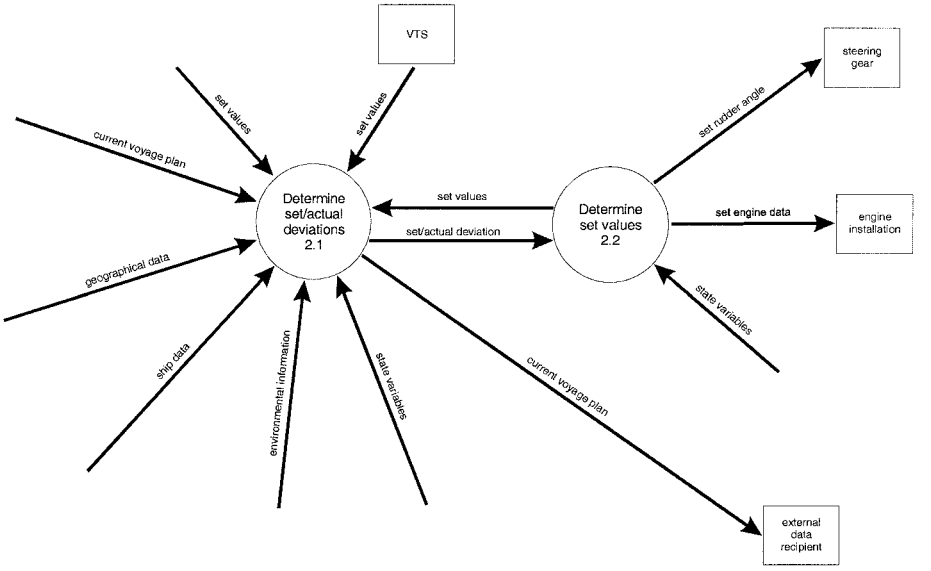


Figure 9. Task area 'Voyage execution and monitoring' (DFD 2).

(b) '*Determining set values*' (Process 2.2): this process models the actual control process (see also Part A). The output information of this process supplies:
  (i) set values for courses and heading ('Course/heading controller'; based on Process 2.1);
  (ii) the central output data flows of the INS, i.e. set values for the rudder angle or set engine data.

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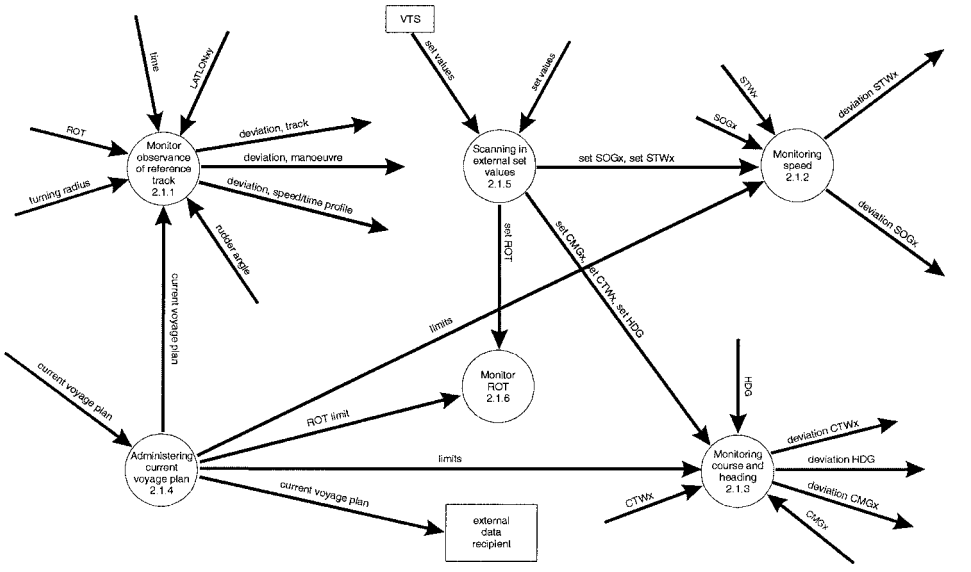


Figure 10. Task 'Determine set/actual deviations' (DFD 2.1).

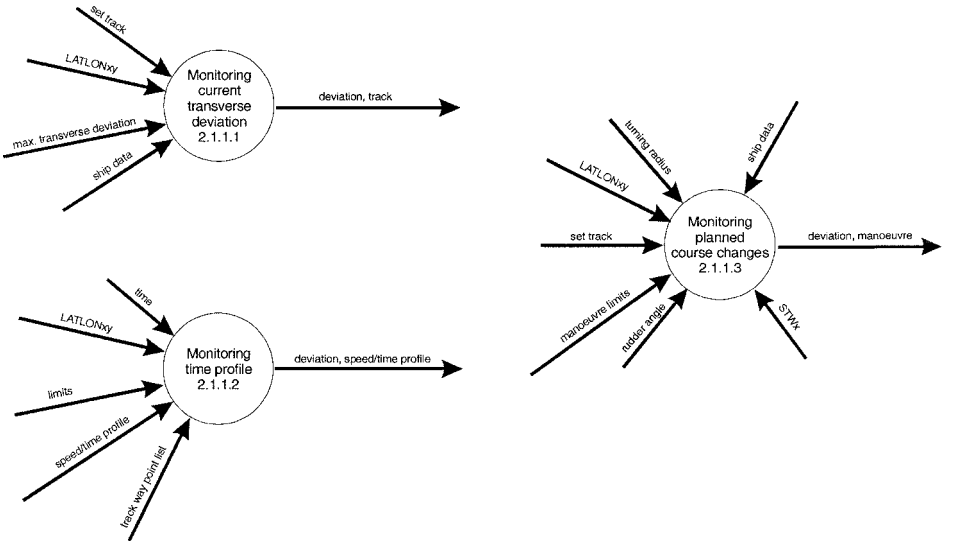


Figure 11. Functionality 'Monitoring of set track' (DFD 2.1.1).

7.2.1. *Task 'Determining set/actual deviations'*. Within Process 2.1, the set values from the current voyage plan are made available by Process 2.1.4. Set values that serve to deal with unplanned incidents or are received from external sources are made available via Process 2.1.5. The limits, too, are processed here, along with the set and actual values. Limits for task 'set/actual deviations' (Process 2.1) within automatic track control are compiled in DFD 2.1 (Figure 10). The corresponding lower level functionality 'Monitoring of set track' is illustrated in DFD 2.1.1 (Figure 11).

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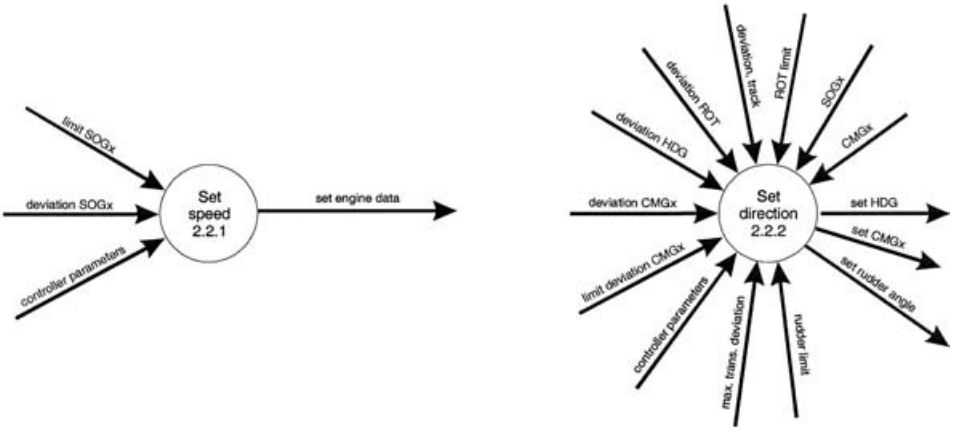


Figure 12. Task 'Determining set values' (DFD 2.2).

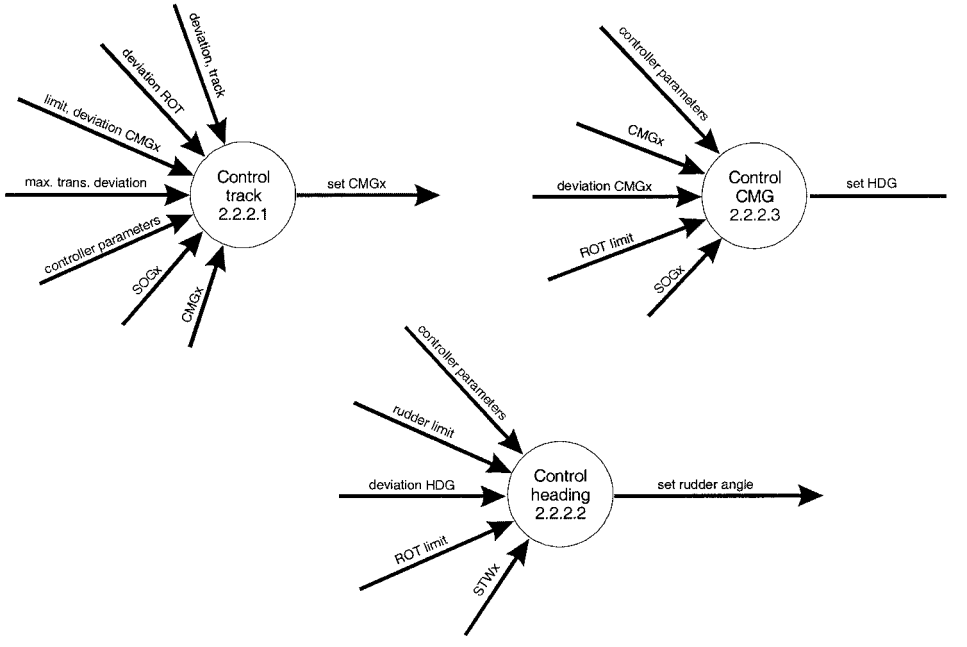


Figure 13. Functionality 'Set direction' (DFD 2.2.2).

7.2.2. *Task* '*Determining set values*'. Similarly, DFD 2.2 represents the task 'Determining set values' including both speed and direction (Figure 12). One level lower, DFD 2.2.2 represents e.g. the functionality 'Set direction' (Figure 13). The diagram assumes a nested structure of the control process (see Part A). The central element of track control is formed by an adjustment process for the heading, which determines a set value for the rudder angle from the control deviation of the heading. In a control loop above, the set value for the heading is determined from a set value for course made good. In the outer loop, the actual 'track control' that determines a set value for course made good from the current track deviation is located. The advantage

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of this approach is that all theoretically possible degrees of automation can be reproduced by this model, from manual control to the different adjustment modes of modern track control systems ('heading/course/track control').

Analogue top-down data flow diagrams are given for the task areas 'Management of data and reference parameters', 'Unplanned incidents' and 'Recording the current situation'.

PART C – TEST REQUIREMENTS FOR INTEGRATED NAVIGATION SYSTEMS.

8. INTRODUCTION. The purpose of this part is to derive requirements for the testing of integrated navigation systems from the generic model of integrated navigation outlined in Part B. The analysis of the model has shown that the explicit allocation of requirements to certain processes is difficult since it cannot be clearly established in which system component the data-supplying process is located. One example is the treatment of set values and limits for executing course changing manoeuvres. These may be defined in a specialised functional component '*Drafting the voyage plan* (1)' during the planning phase or in the component '*Voyage execution and monitoring* (2)'. Several possibilities thereby arise:

(a) Set values and limits are fixed in '*Drafting the voyage plan* (1)';
(b) The values are transferred to (2);
(c) The manoeuvres are carried out with the transmitted values (2);
(d) Limits set locally in (2) may not act in delimiting manner on the transferred planning data;
(e) If limits set in (2) are not modifiable, signalling occurs in the event of conflict situations between the values from (1) and from (2) before execution of the manoeuvre.

or:

(a) The definition of set values and limits is dispensed with in (1);
(b) No transfer of these values to (2) takes place;
(c) In the functional components for (2), local input options and administration arrangements are retained for these values.

All conceivable solutions may lead to a consistent system philosophy. The formulation of requirements permitting only a certain implementation would constitute an undue restriction. Therefore, the formulation of test requirements is concentrated on the exchanged data flows. The starting point in each case is the information sinks. The logic chain produced from the generation of primary information in the sources, further processing and derivation of information up to the point of usage of information in information sinks, is followed back when specifying requirements. From the functionality of the information sinks, requirements on the received data are produced (e.g. with regard to quality or consistency). From these requirements, necessary properties of information sources can be derived.

9. CATEGORIES OF DATA QUALITY. In order to make the catalogue of test requirements for creation, application and maintenance manageable, an

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appropriate structuring of the requirements is necessary. In this report, the test requirements are first of all structured according to the particular processing procedure and the data type considered. As a further classification criterion, a process of categorisation of the requirements on input information was undertaken. In the following, the categories used are explained in detail.

9.1. *Origin*. Special requirements on the origin of information or specification as to which data must be given information on their origin as an attribute.

9.2. *Validity*. The concept of validity involves an attribute of an item of information that is set by the particular information source. Since no other independent information sources are used for determining this attribute, it constitutes an 'internal variable' of the source. This attribute does not make a statement concerning the 'quality' (see below) or 'usability' of a piece of information.

9.3. *Quality*. The quality of an item of information is the deciding criterion in assessing the usability as an input for the execution of a certain function. The term 'quality' comprises three aspects:

(a) Accuracy as a tolerance range ('true value' vs. 'determined value').
(b) Topicality, i.e. age of an item of information or frequency with which the information is updated.
(c) Plausibility, i.e. compatibility of an information item with information from independent sources. Information of the same type must not contradict one another.

9.4. *Harmonisation*. This term covers requirements that deal with the joint processing of information from different sources. It should be required practice that items of information that are compared with one another have a uniform reference system.

9.5. *Criticality*. Requirements may result from a special 'protection need' for a certain item of information; e.g. prohibition on modifying the track section of the current voyage plan presently being followed.

9.6. *Alarm facilities and limit values*. List of all necessary limit values and alarm facilities are necessary for the information concerned.

9.7. *Representation/display*. This criterion initially appears as a break with the underlying functional approach. However, since the human being still represents an essential link in the navigation process, it is absolutely necessary to demand an appropriate visual display method for certain data. It is thus inadequate, for example, to merely request the presence of sea chart information. Its application is always governed by suitable chart representation in the minimal case.

For the requirements, a 'top-down approach' is used following the procedure developed in Parts A and B for breaking down the process of integrated navigation. The particular test requirements are represented in forms, which are orientated to the structuring according to, processes as outlined above (i.e. task areas, tasks, functionalities, functions). In the heading of each form, the process and data flow of the form are listed. In the body, the requirements differing according to categories are contained.

10. EXAMPLE: TASK AREA 'VOYAGE EXECUTION AND MONITORING'.

Monitoring and execution of the voyage constitute the central task area of the process 'integrated navigation'. This area supplies the

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fundamental output variables necessary (Laux, 1991), in the form of set values for machinery data and rudder angle. These output variables are determined from the following fundamental input variables:

(a) Set parameters for voyage execution:
  (i) current voyage plan;
  (ii) set values for direction and speed of the ship from other processes than track planning. The sources for this may be both internal (unplanned incidents) or external (VTS).
(b) Variables for describing the current actual state:
  (i) ship data;
  (ii) geographical data;
  (iii) state variables;
  (iv) environmental data.

Table 5 shows an example of the input information requirements listed above.

Table 5. Example of the requirements for input information.

Process:	2. *Monitoring and execution of the voyage*		Name	Date
----------	----------	Created:	Mathes	26.2.98
Data flow:	State variables	Checked:		

1. *Origin*.

(a) The source of state variables must be known; in the case of derived variables, this includes the state variables used as a basis.

2. *Validity*.

(a) The validity of state variables must be checked from the particular sources. The test result must be made available to processing procedures.
(b) In the case of derived state variables, the validity of the underlying variables must likewise be taken into account and relayed.

3. *Quality*.

(a) Parameters that influence the quality of state variables must be transmitted (e.g. number of satellites in the case of satellite-based position determination).
(b) The accuracy of state variables must be made available to processing procedures.
(c) The age and frequency of updating of state variables must be known; the frequency of updating must be in appropriate proportion to the time constants of the process.
(d) State variables must be checked for plausibility by comparison with independent sources. The result of the check must be provided; this requirement applies in particular to monitoring the position and speed by comparison with data from an independent measuring method.

4. *Harmonisation*.

(a) The reference systems underlying the particular state variable must be known. This applies particularly to the measurement reference (e.g. ground/water-related variables), the measuring point on the ship and the geodetic datum of the position determination.
(b) The processing or interlinking of data is permitted only where the reference systems are identical. This applies in particular to plausibility checks and set/actual comparisons.
(c) State variables that are linked with one another are likewise to be harmonised with regard to their accuracy.

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5. *Criticality*.

(a) If different state variables of the same type are available, mechanisms for selection or prioritisation should be provided.

6. *Limit values and alarm facilities*.
Messages or alarms must be provided for the following states:

(a) loss of validity
(b) change in source for a state variable type
(c) change in the reference system
(d) changes in the data quality (accuracy, topicality, plausibility)
(e) exceeding set/actual deviations

7. *Representation/display*.

(a) An alphanumeric display of the state variables must be provided. The accuracy of display should reflect the accuracy of the particular sensor technology used.
(b) For the ship's fundamental movement variables (position, course, speed, heading), a graphical display in the radar/ARPA and/or in the sea chart must be provided.

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