Classification of Elemental Manoeuvres Observed during Ship Handling Training Employing Manned Ship Models

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Abstract

The paper presents a concept of elemental manoeuvres that may be used for analysis of ship handling training (including the training with manned model ships) and for simulation of complex manoeuvring scenarios. It shows a set of postulated elemental manoeuvres. A fuzzy clustering method is introduced and applied for the classification of manoeuvring patterns. The fuzzy clustering algorithm is used for the extraction of elemental manoeuvres from the records of ship handling manoeuvres of LCC model ship. The best set of variables for the extraction of elemental manoeuvres consists of normalised ship velocities and controls.

Keywords: *Manoeuvring, Elemental manoeuvres, Fuzzy Clustering, Trajectory, Manned models*

INTRODUCTION

The complex task of ship handling – the manoeuvring of ships – has to be analysed at various circumstances to discover and to provide control models constituting the task. These control models are looked for by people assisting the ship handling training (Figure 1) by people creating ship manoeuvring simulations for various design purposes and for people designing ship control systems themselves.

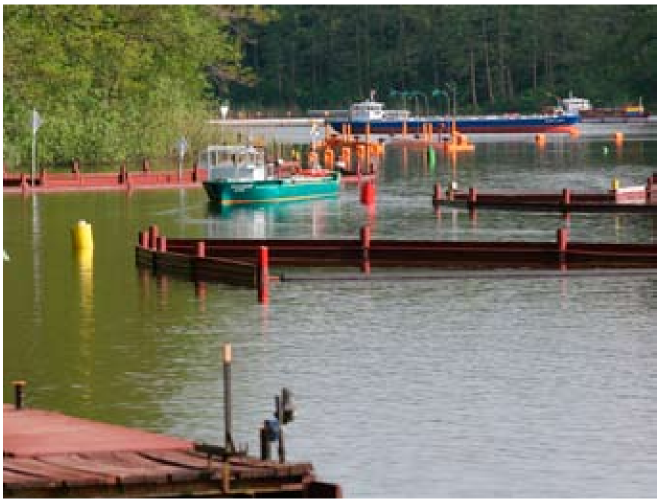

Fig. 1. *Ship models manoeuvring at the Ilawa Research and Ship Handling Centre*

The ship handling training that uses manned ship model simulation technology is more efficient when the instructor may rationally analyse the sequences of controls employed by the trainee and the results of these control actions on the model ship responses. The understanding of these relations helps in the explanations of the model ship behaviour to the trainee. The questions that arise when analysing the sequences of ship's manoeuvres consist of the following: How to evaluate the manoeuvres? What are the quality criteria of the performance in a specific manoeuvre? Which fragments of the training should be repeated and why the execution of these fragments was judged as a sub-standard one? What control strategies are used by trainees – ship masters and ship pilots – during ship handling? It would be of importance when aiding such analyses to discover, to describe and to verify the existence of manoeuvring patterns that are employed by pilots and masters during manoeuvring planning and execution. The manoeuvring patterns would allow to focus on individual parts of the whole manoeuvring scenario and to analyse manoeuvres of different ships within various environments using a common framework of manoeuvring patterns. These manoeuvring patterns will be presented in the paper and they are called elemental manoeuvres. Figure 1 shows a snapshot from a ship handling training – a ship is passing through bent waterway – the trainee has to follow the designed track, proceeding through connected straight – line segments and changing ship's course when moving from one waterway segment to another.

Other problems arise when one uses ship handling manoeuvring computer simulations for ship design, harbour assessment or waterway safety studies. The control models used for simulations should be understandable and easy to explain to pilots, ship masters and people ordering the simulations. It is possible when a control model has a direct reference to the practice of ship handling onboard a real ship. Figure 2 shows a simulation model for the assessment of limiting wind condition (maximum wind speed) for a given ship with specified

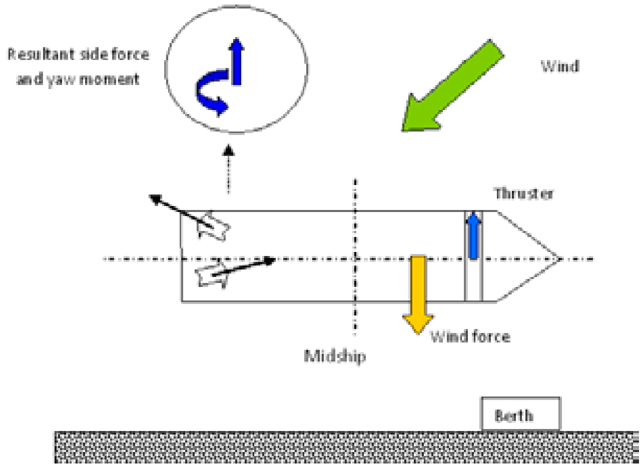

Fig. 2. *Model of control in a manoeuvring computer simulation (for ship design)*

azimuthing propellers and bow thruster – the model assumes position keeping and constant heading: the question is whether such a pattern is used for manoeuvring and whether assumed controls (propellers' angles and bow thruster settings) would be used in reality.

Another problems arising in manoeuvring computer simulations are related to the questions like: Does the control model used in simulations refer to the control strategy employed onboard a real ship? How to show and to prove to customers ordering the simulations that the employed control model is used in reality by pilots and ship masters? What structure should the control model for simulation have?

The problem that is the subject of the research presented in the paper is the following: to present the concept of elemental manoeuvres and subsequently to discover and to point out the elemental manoeuvres (manoeuvring patterns) appearing in recordings of ship handling manoeuvres; and to do this in some automated (programmed) way that would allow to use such a method for processing of many data records gathered during ship handling training employing manned ship models.

The concept of elemental manoeuvres was first mentioned by Kose et al [1][2][3] for analysing the manoeuvring in harbours. It was also used by Sousa et al [4][5] for simplification of control schemes for ROV (a creation of a set of simple controllers for a set of simple tasks).

The paper is organised as follows. First the author presents the concept of elemental manoeuvres (manoeuvring patterns). Next the study objective is presented. It is followed by the description of the methodology used for discovering the elemental manoeuvres – a data clustering method is used. Next the author shows the results of clustering on sets of real data – the effect of selection of clustering variables, number of clustering centres and the interpretation of clustering in terms of fuzzy rules. Finally, the author discusses the results of the study and shows the direction of future research.

The Concept of Elemental Manoeuvres

We at the Foundation for Safety of Navigation and Environment Protection recognise that the complex manoeuvring scenario consists of simpler manoeuvring tasks. These simpler tasks are generic for different types of ships – these simple tasks become a kind of parametric templates that are used by the master or the pilot to manoeuvre the ship – the pilot or master follows some learned patterns while adopting the controls to the actual manoeuvring situation and the ship system at hand.

During ship handling training we gather the following information about the ship model state:

- The ship model trajectory information,
- The information about model ship's heading (attitude),
- The information about the propeller revolutions, rudder deflection and tugs' action (control state).

These data are used for velocity and acceleration estimations.

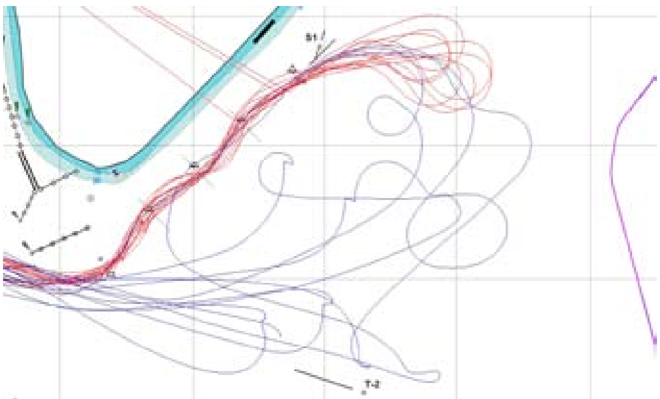

Fig. 3. Part of tracks recorded during the first day of a ship handling course.

The information gathered is quite complex and the amount of data is significant - Figure 3. Therefore we strive for automation of the information processing when presenting the information to instructors and trainees.

It is desirable to create control models – templates of ship control – that would describe the ship manoeuvres occurring during ship handling. These manoeuvring templates would represent simple manoeuvring tasks. The simple tasks would serve as building blocks that might be assembled into a complex manoeuvring scenario (bottom-up synthesis approach) or that might be used as elemental blocks which the complex scenarios would be divided into (top-down analytic approach).

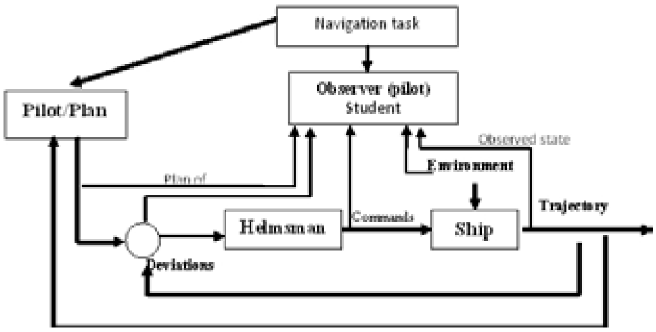

Fig. 4. Model of hierarchical control system in ship handling - with the aspect of the trainee learning

Figure 4 shows that the ship handling tasks have some control structure. We know that people (e.g., pilots or ship masters) perform complex tasks using learned procedures and patterns. Similarly, a direct control of a system (e.g., a ship by a helmsman) relies on some earlier learned behaviour (procedures, patterns and reflexes). Not all learned procedures are obvious to an expert (pilot) – therefore it is important to us to show them the patterns and to relate the ship controls and observed ship's responses to these manoeuvring patterns.

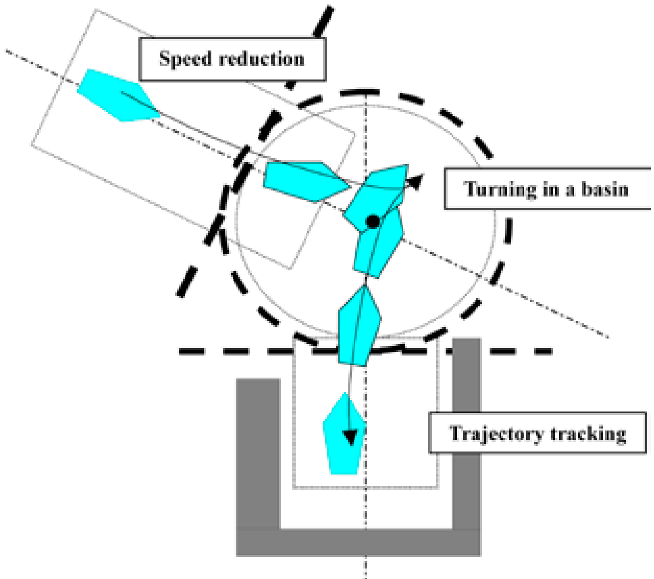

Fig. 5. Manoeuvring scenario separated into three simpler, elemental tasks.

Here we introduce the concept of elemental manoeuvres. The complex manoeuvring scenario can be divided into series of simple manoeuvring tasks – as in Figure 5 - called elemental manoeuvres. This example shows that the approach to the basin, turning and entering the basin may be separated into simpler tasks.

Through the observation of the recorded manoeuvres and applying the control engineering approach one may deduce an initial, hypothetic list of elemental manoeuvres.

The elemental manoeuvre is a ship handling task where one may easily discern the following features, arising from the analysis of the ship model control process:

- It has a well defined manoeuvre objective – allowing to present the art of ship handling as a sequence of rational tasks and to determine the control objective in every task,
- It has well defined initial and final state, allowing to create the control trajectories leading from the initial to the final state,
- It has defined the control strategy – accounting for the available control devices - that should be used to reach the manoeuvre objective,
- It has defined the control objective and the performance criteria of the control process.

It is also possible to create a set of standards for the realisation of the elemental manoeuvre and a set of boundary constraints for performing the elemental manoeuvre (for example, constraints limiting the manoeuvring space, limits on allowable ship model speed, or limits on allowable power of control devices like tugboats). By applying the elemental manoeuvre concept it is possible to obtain the following objectives in ship handling training support and in manoeuvring simulation analyses:

- To isolate a relatively small set (5-6) of elemental manoeuvres, representing a rich world of ship handling procedures, which in turn allows to analyse the complex ship manoeuvres and to define the standards for manoeuvre execution parameters which are directly related to the ship handling task,
- To divide a complex manoeuvring scenario into a set of simple elemental manoeuvres, which helps in the analysis of manoeuvres performed by a trainee by focusing on a well defined manoeuvring templates,
- To generalise the analysis across ship types – through employing the elemental manoeuvre concept for various ship types we may concentrate on patterns and templates common for these various ships and to define the templates specific to a given ship type,
- To define the templates for standards of performing of each of the elemental manoeuvres - the templates are the methods for the evaluation of the manoeuvre execution; the definition of such templates (methods) allows to assign specific numerical values that describe the criteria of manoeuvre execution for a specific ship.

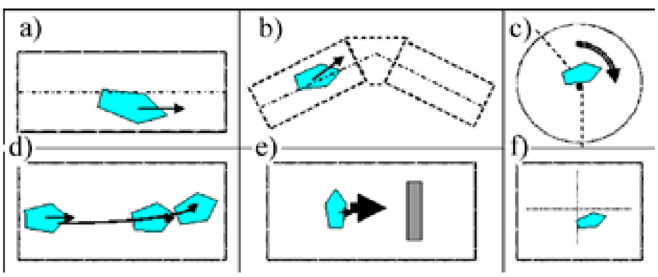

Fig. 6. Sketches of proposed elemental manoeuvres

Figure 6 shows proposed elemental manoeuvres. The list of elemental manoeuvres is as follows:

a) Course – or track – keeping,
b) Course change during advancing of the ship,
c) Turning the ship at close to zero advance speed (in place),
d) Stopping the ship (advance speed reduction),
e) Moving the ship sideways (crabbing, for example, toward a pier),
f) Maintaining a prescribed ship position (station-keeping at zero advance speed).

One needs to verify the posed above hypothesis about the elemental manoeuvres. In particular, one needs to check, whether such manoeuvring patterns exist in the recorded ship handling time histories. Also one checks the number of such elemental manoeuvres and their parameters. Another interest lies in fact how to recognise the elemental manoeuvre in time history of a ship handling scenario.

Figure 7 shows registered tracks, recorded during ship handling training performed onboard LCC and VLCC model ships (tankers). There are marked example areas with hypothetical elemental manoeuvres – the shape of the trajectory and the knowledge of the control of the ship suggests that such manoeuvring patterns (turning at speed, turning in a basin at zero speed, course-keeping and crabbing). It would be of interest to find the confirmation of such hypotheses and to show a tool for doing this in an automated way.

Research on Discovering of Elemental Manoeuvres

Below are presented the methodology and results of investigation on discovering of elemental manoeuvres.

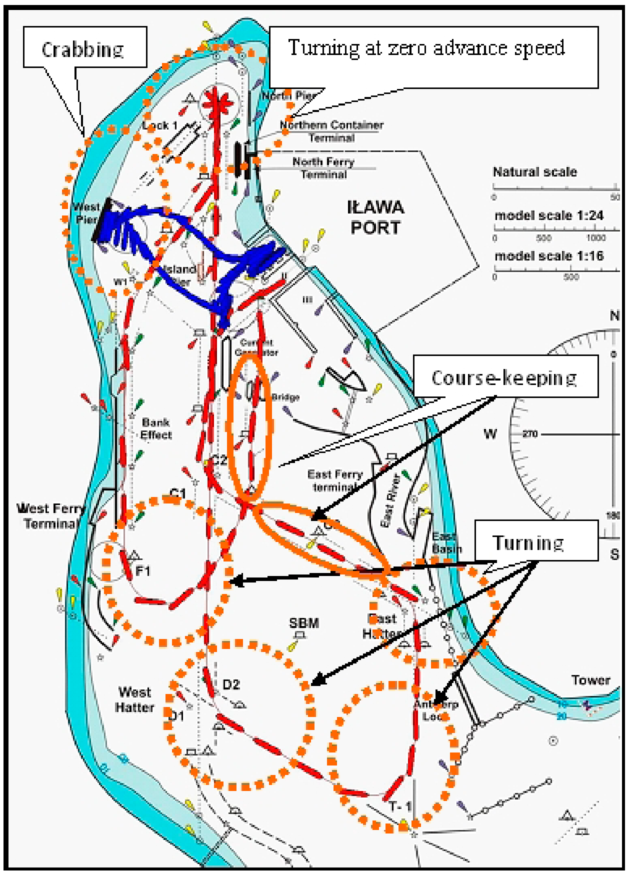

Fig. 7. Trajectory of tanker model ships with marked potential elemental manoeuvres.

Purpose of the Research

The objectives of the research are as follows:

a) to present the concept of elemental manoeuvres of ships with application to ship handling training and to manoeuvring simulation,
b) to attempt an extraction of elemental manoeuvres in real observed ship manoeuvring sequences (from ship handling training onboard manned ship models),
c) to evaluate the effectiveness of one of specific methods of data grouping (clustering), namely the C-means clustering algorithm, when applied to such a problem:

a. can the method point out different data sets that might be assigned to specific elemental manoeuvre,
b. which data (variables) are best suited for the elemental manoeuvres pattern discovery,
c. how this particular method performs in the task (can it find out unique data patterns? Does it miss some data patterns?).

The Research Method

The method originates in the analysis of a phase space of ship's state and control vectors. When observing data in properly selected phase space one may discover distinct groupings of data. For example, a ship maintaining its position and heading during station keeping will have all linear and angular velocities components close to zero, so when one constructs a phase space using velocity components then all phase trajectories will group around the origin of the phase space system. When proper phase space representation is selected then one may use a data clustering algorithm for grouping of the data into separate data sets that can be identified within the phase space due to their distinct locations.

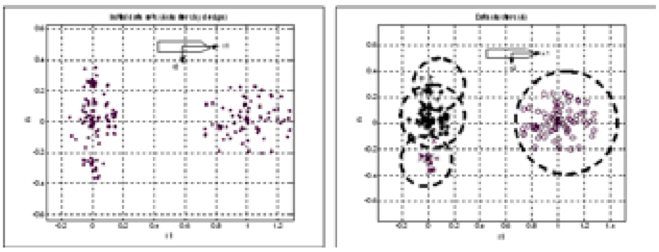

Fig. 8. *Example of clustering method: data (left), identified data cluster (right).*

The phase space in the presented problems will contain ship model kinematics (variables like velocities and accelerations) and control variables (propeller revolutions and rudder deflection angles).

An Example of the Clustering Method

A simple example is given. The data about a hypothetic ship motion consist of 2 components of ship's velocity: surge x1 and sway x2. These data are artificially generated and they are grouped in 4 clusters. The objective is to characterise the ship's motion. Figure 8 shows the data and it can be seen that the data may be grouped into following subsets:

a) motion ahead (large values of surge velocity x1, small absolute values |x2| of sway velocity),
b) motion sideway (small values of surge velocity x1 and large absolute values |x2| of sway velocity),
c) other transient data.

To find the data clusters a procedure fcm from MathWorks MATLAB FuzzyToolbox is used. The clustering method selects data points to become so called cluster centres and next assigns the remaining data to one of clusters as to minimise the total sum of distances between centres of clusters and their data points.

Figure 8 shows the action of the MATLAB procedure fcm. On the right figure one can see the identified 4 data clusters – as it was designed in the original data set. However, the procedure of clustering may not be able to work properly – its result depends on proper indication by the user of the number of data clusters: if the number is incorrect then the localisation of the cluster centres is wrong. The procedure subclust may help in selecting the proper number of data clusters, but here one may also face the incorrect prediction of the number of clusters. Also, even when the number of data clusters is correctly predicted then fcm may give incorrect data – depending on the data characteristics – if the clusters overlap, then the "wrong" location of centres may be assigned. Therefore the results of clustering must be verified by other means.

The Details of Data Analysis Method

The data that were analysed are the so called "night exercises" records of : LCC "Warta" and VLCC "Blue Lady" , as shown in Figure 9.

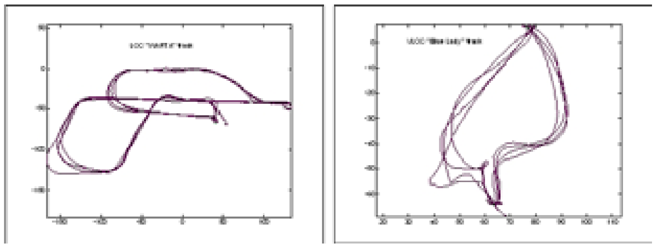

Fig. 9. *Examples of recorded tracks used for the cluster analysis*

The variables that were taken into account during cluster analysis were the following: components of the model ship linear velocity, model ship angular velocity, components of the model ship linear acceleration, model ship angular acceleration, rudder deflection angle, propeller revolutions.

The analysis method was the C-means clustering algorithm (fcm function from MATLAB Fuzzy Toolbox), together with developed software for data processing and for the estimation of the cluster data number (using subclust MATLAB function). Three versions of sub-cluster ing data sets were used to produce the estimation of the cluster numbers.

Data Form for the Analysis

All data were converted into non-dimensional forms. We did it because we searched for patterns that did not depend on absolute values of some motion variables. For example, the crabbing motion is characterised by the drift angle close to 90 degrees, irrespective of the translation speed being 1 knot or 0.1 knots. Similarly, the control variables should be normalised

$$X_1 = [|u'|,|v'|,|\omega'|]$$
$$X_2 = [|u'|,|v'|,|\omega'|,|\tfrac{du'}{dt'}|,|\tfrac{dv'}{dt'}|,|\tfrac{d\omega'}{dt'}|]$$
$$X_3 = [|u'|,|v'|,|\omega'|,|\delta'|,|rpm'|]$$
$$X_4 = [|u'|,|v'|,|\omega'|,|\tfrac{du'}{dt'}|,|\tfrac{dv'}{dt'}|,|\tfrac{d\omega'}{dt'}|,|\delta'|,|rpm'|]$$

using the maximum available control command, so the relative data allow to compare manoeuvres for various ships.

The following rules were used for data normalisation:

a) The velocities and accelerations were normalised using the instantaneous model ship's speed and model ship's length,
b) The rudder deflections were normalised using the maximum rudder deflection,
c) The propeller revolutions were normalised using the maximum propeller revolutions.

Variable Sets for Cl uster Analysis

Various combinations of variables (variable sets) were used for the analysis. We wanted to know which data sets would serve best for the different manoeuvring patterns (elemental manoeuvres) separation. Four variable sets (X_1 – X_4) were selected for the analysis:

Variable set X_1 represents pure kinematics – just velocities. It is less sensitive to errors in the acceleration estimation than the set X_2 which also represents kinematics. The set X_3 represents kinematics and control – it is a set X_1 extended by the vector of control variables (rudder angle and propeller revolutions). The set X_4 represents both full kinematics (set X_2) and the control variables.

The observed data of interest are the following:

a) the localisation of the data clusters on the model ship trajectory (to find the elemental manoeuvres),
b) interpretation of the centres of clusters from the view point of control engineering.

The Example of Data Analysis and Interpretation

The example concerns the manoeuvre of the course change for a model ship proceeding at speed within a waterway. The fcm function shows that there are 2 separate clusters, however, in fact there is just a single cluster, corresponding to the course-change manoeuvre. Figure 10 shows the trajectories and the interpretation of the data using the phase planes of velocities. The phase-plane data show that the rate of turn r' is high for both clusters, while sway velocity v' remains relatively low – it suggests that the data concern course change manoeuvre with large surge (advance) velocity u'. This example shows that the clustering can separate the data, but at the same time care should be taken of the interpretation of the results, since there are possibilities of misclassification.

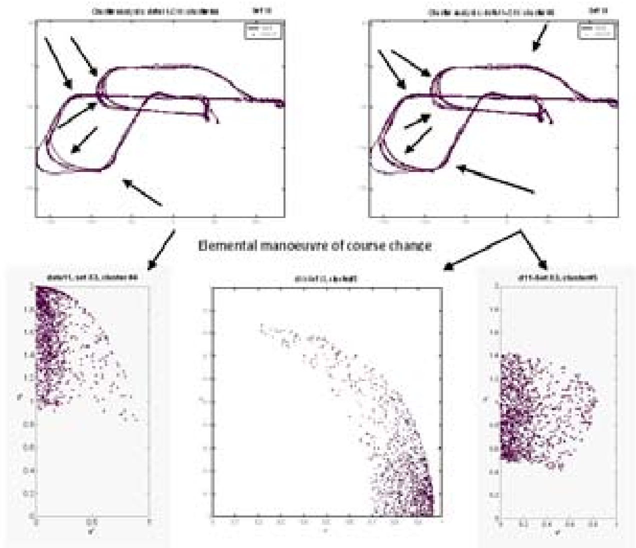

***Fig. 10**. The trajectories of the manoeuvres and the phase planes of clusters corresponding to course-change*

Some of the Results of Investigations

Figure 11 and Table 1 show some clusters obtained through clustering procedure when conducted on the variables consisting of kinematics (velocities) and control (rudder deflection). Figure 11 shows two data sets that may be identified as

***Table 1.** Data cluster centres and interpretation (6 data clusters)*

	u'	v'	r'	δ'	Interpretation
1	0.4560	0.8361	0.1354	0.0760	Turning with small amount of rudder (advancing) – (medium surge velocity, large sway velocity, small yaw rate, small rudder)
2	0.9645	0.1314	0.1696	0.6787	Course-change with large amount of rudder (large surge velocity, small sway velocity, small yaw rate, large rudder)
3	0.2714	0.1874	1.8048	0.0420	Turning with small amount of rudder (advancing) – (medium surge velocity, small sway velocity, large yaw rate, small rudder)
4	0.4974	0.1456	1.6179	0.8393	Turning with large amount of rudder (advancing) – (medium surge velocity, small sway velocity, large yaw rate, large rudder)
5	0.8313	0.2144	0.8504	0.1556	Course-change with small amount of rudder (advancing) – (large surge velocity, small sway velocity, medium yaw rate, small rudder)
6	0.9813	0.1085	0.0972	0.0777	Course-keeping with small amount of rudder (large surge velocity, small sway velocity, small yaw rate, small rudder)

***Table 2**. Data cluster centres and their interpretation (4 clusters)*

Cluster	u'	v'	r'	Interpretation
1	0.4839	0.8272	0.1137	Turning with small advance velocity (in basin) (medium surge velocity, large sway velocity, small yaw rate)
2	0.8176	0.1883	0.9599	Course – change while advancing (large surge velocity, small sway velocity, large yaw rate)
3	0.9832	0.1047	0.1135	Course-keeping while advancing – and course-change (large surge velocity, small sway velocity, small yaw rate)
4	0.3175	0.1655	1.7894	Turning with small advance velocity (in basin, on spot) (small surge velocity, small sway velocity, large yaw rate)

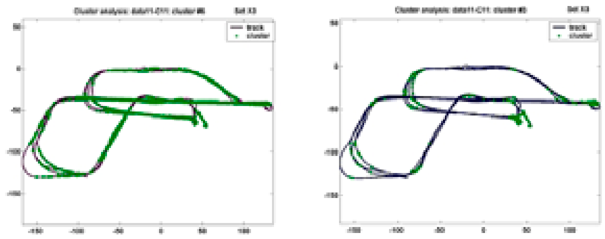

Fig. 11. *Variables (kinematics + control), 6 data clusters; course-keeping pattern (#6) and course-change pattern (#3)*

a course-keeping and course-changing patterns.

Table 1 shows the interpretation that may be assigned to the centres of the data clusters.The separation of the data into 6 clusters works relatively well, especially because the variables include the control data (rudder deflection). However, some data seem still to be misclassified.

More misclassification happens when the clustering variables include only the kinematics (velocities). In this case the best results were obtained with 4 cluster centres. However, as Figure 12 and Table 2 show, the points are more often misclassified. Still the procedure can find different clusters (cf. the Table 2 as it shows the different data and interpretation).

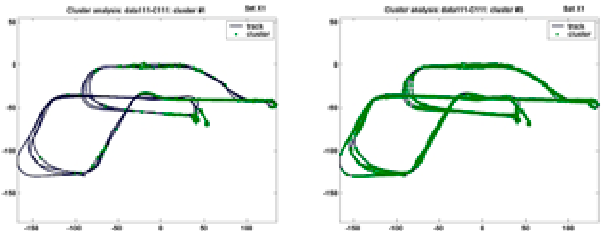

Fig. 12. *Variables (kinematics), 4 data clusters, turning pattern (#1) and course-keeping pattern (#3)*

Conclusions

The clustering analysis confirms the existence of elemental manoeuvres (manoeuvring patterns) in ship handling. It is possible to automate the search for the fragments of records of ship handling representing data from a specific elemental manoeuvre. The fuzzy clustering method (MATLAB implementation of C-means algorithm) has been used and it is capable of classification of ship handling data into clusters representing the elemental manoeuvres.

When selecting the variables for data clustering the best results were obtained using the following sets of variables:

a) the velocities (linear and angular) and controls (rudder angle and propeller revolutions),
b) the velocities (linear and angular).

A great sensitivity was seen of fcm (clustering function) to the the variations of accelerations. Typical of the clustering method is its sensitivity to the number of data clusters – when they are specified incorrectly (the number differs from the observed number of data clusters) then misclassification results.

Other methods of data clustering – specially the ones designed for analysis of time series – might be investigated.

As for the application of the presented approach we see the following:

a) the possibility to classify the manoeuvres performed in selected areas – after the data classification it would be possible to determine whether the timing and the sequence of manoeuvres in the area were correct (it is important when analysing the results of the ship handling training),
b) when connecting the specific elemental manoeuvres to the type of the navigation area and the manoeuvring task (so, when using the concept of elemental manoeuvres in motion trajectory planner) it would be possible to use specific automatic controller for manoeuvring the ship in a given elemental manoeuvre – it is important when developing ship handling simulations.

Further Studies

The author sees the necessity of further studies in the following areas:

a) The use and assessment of effectiveness of other method of data clustering specific for analysis of time series (in this case, for the records of ship handling manoeuvres),
b) The use of neural networks for the data set classifications, in particular, for data that are time series of recorded ship handling manoeuvres,
c) Identification and the determination of characteristic parameters that would describe the elemental manoeuvres appearing during ship handling training,
d) Identification of control models typical of specific elemental manoeuvres.

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