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# Adaptive ship course-keeping system

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**ABSTRACT**
The article presents an original adaptive ship course-keeping system. The control algorithm is based on a knowledge base. Its integral part – a computer ship movement dynamical model – uses a set of signals obtained from the object's input and output. In this way we avoid problems arising while designing classical control algorithms for a complex, non-linear ship model. Approximators utilizing base functions of the model are used for model adaptation. The presented methodology is general as it can also be applied in other ship control tasks or to other dynamic objects. The proposed intelligent course-keeping system has been verified by simulation.

**KEYWORDS: ship course keeping, intelligent control system**

## 1. Introduction

In recent years we can observe increased requirements concerning the accuracy of vessel movement in various control tasks: tracking a present trajectory, dynamic positioning, anticollision systems). The higher standards are due to economic reasons and the need to improve the safety, particularly on fairways with high intensity, in restricted waters such as straits, channels and in the high seas. In terms of automatic control we can consider steering a ship along a preset trajectory, or course stabilisation in particular. The latter task is a simple problem of automatic vessel control, but the object complexity (the model non-linearity, uncertainty due to external disturbances) makes this problem a difficult one.

When kept on a designated course under conditions of external disturbances, the vessel will not proceed along a straight line, her trajectory being an irregular curve. A similar case occurs when, after course alteration, we bring the vessel on the previous one. In reality, a vessel usually covers a longer track than that desired by the helmsman. The larger the alteration of the set course, the longer the actual track of the ship is. Deviations by the vessel caused by non-optimal steering with the rudder result in the reduction of average speed, longer voyage, higher fuel consumption and, eventually, increased operating costs. Uncontrolled yawing may also cause a collision, especially on fairways with dense traffic.

Therefore, researchers face a demand for still higher degree of automation, and first of all, optimization of the course-keeping and returning on the set course processes. Although many solutions of automatic course stabilisation systems (autopilots) exist [6,8,9], enhanced requirements of performance quality of autopilots necessitate further research into this issue, along with the problem of constructing an intelligent course-keeping system. The author describes a solution of the mentioned problem using computer methods.

## 2. System description

The operation of the ship course stabilisation under consideration (Fig.1) [7] can be described as follows: in the controller, for a given output from object $(\mathbf{y})$, on the basis of values drawn from the knowledge base $(\mathbf{B}_y)$, a control decision $(\mathbf{u})$ is worked out, i.e. a new rudder angle $(\delta_z)$ is set. Naturally, the rudder is positioned so as to stabilise the set value $(\mathbf{x}_z)$, that is ship's course $(\psi_z)$. This process is repeated every time unit $(\Delta t)$.

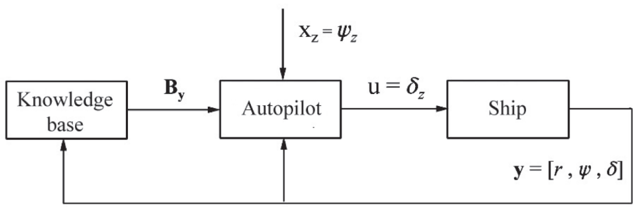


**Fig. 1. Structure of the proposed system of ship's course stabilisation [7]**

The notations in Fig. 1 are as follows:
$\mathbf{x}_z = \psi_z$ - ship's course,
$\mathbf{u} = \delta_z$ - control decision (rudder angle),

$\mathbf{y} = [r, \psi, \delta]$ - object output (angular speed, deviation from the course, rudder angle),

$\mathbf{B}_y$ - vector of values extracted from the knowledge base, required to make a controlling decision for output **y**.

In the sections below we will discuss individual components of the system: computer model of ship movement dynamics (section 2.1), knowledge base (section 2.2), controller (section 2.3). Finally, system adaptation is presented synthetically in section 2.4.

## 2.1 Computer model of ship movement dynamics

Three matrices provide a basis for the computer model of vessel dynamics: **R** , **Ø** , **Ä**. Their respective components, or output signals: angular speed, deviation from the course, rudder angle, depend on the state of the object and control decisions (selection o rudder positions). The output signal is understood as object state measured after one time unit $(\Delta t)$.

Let a symmetric, closed interval: $\langle r_{\min}, r_{\max} \rangle$ be a set of all angular speeds the vessel can achieve. After discretisation, the following set is obtained:

$$\{r_{\min}, r_{\min} + \Delta r, r_{\min} + 2\Delta r, \ldots, r_{\min} + (n_{\max r} - 1)\Delta r = r_{\max}\} \tag{1}$$

Similarly, as a result of quantisation of all possible positions of the rudder, we obtain this set:

$$\{\delta_{\min}, \delta_{\min} + \Delta\delta, \delta_{\min} + 2\Delta\delta, \ldots, \delta_{\min} + (n_{\max\delta} - 1)\Delta\delta = \delta_{\max}\} \tag{2}$$

Because the ship's course-keeping task consists in bringing the object to the state, in which the values of angular speed, course error and rudder angle are close to zero, $\Delta r$ and $\Delta\delta$ should be possibly low and selected so that zero belongs to sets (1) and (2).

The value $n_\delta$ is the power of the largest subset of control decisions (2), for which the system response after one time unit $(\Delta t)$ will be different. Thus, for the steady state (at instant *t*): $r(t) \in (1)$, $\psi(t) \in \langle -\pi, \pi \rangle$, $\delta(t) \in (2)$ the system will respond with different values, and only for the control decisions of this form:

$$\left\{ \delta(t) - \frac{n_\delta - 1}{2}\Delta\delta, \ldots, \delta(t), \ldots, \delta(t) + \frac{n_\delta - 1}{2}\Delta\delta \right\} \tag{3}$$

Element $r_{i,j}$ ($\psi_{i,j}, \delta_{i,j}$) of matrix $\mathbf{R}_{n_{\max r} \times n_{\max\delta} \cdot n_\delta}$ ( $\mathbf{\Psi}_{n_{\max r} \times n_{\max\delta} \cdot n_\delta}$ , $\mathbf{\Delta}_{1 \times n_{\max\delta} \cdot n_\delta}$ )

is equal to angular speed (and respectively, deviation from the course, rudder angle) which the object will reach after one time unit $(\Delta t)$, when at an instant (*t*) the state of the object is described by the vector:

$$\left[ r_{\min} + (i-1)\Delta r, 0, \delta_{\min} + \left( \left\lceil \frac{j}{n_\delta} \right\rceil - 1 \right)\Delta\delta \right] \tag{4}$$

and the control decision is equal to $j - (\lceil j/n_\delta \rceil - 1)n_\delta$ of the set element (3) [7].

Let the state of the object at an initial instant (*t*) be described by the vector: $[r(t), \psi(t), \delta(t)]$, and control decisions will have a form like the elements of set (3). Then, using linear interpolation, the object output is determined according to the formulae:

$$\begin{aligned} r(t+\Delta t) = \mathrm{inter}\big( & \mathrm{inter}(r_{n_1, n_3+i}, r_{n_2, n_3+i}, r(t), \Delta r, n_1, n_{\max r}), \\ & \mathrm{inter}(r_{n_1, n_4+i}, r_{n_2, n_4+i}, r(t), \Delta r, n_1, n_{\max r}), \\ & \delta(t), \Delta\delta, n_5, n_{\max\delta} \big) \end{aligned} \tag{5}$$

$$\begin{aligned} \psi(t+\Delta t) = \mathrm{inter}\big( & \mathrm{inter}(\psi_{n_1, n_3+i}, \psi_{n_2, n_3+i}, r(t), \Delta r, n_1, n_{\max r}), \\ & \mathrm{inter}(\psi_{n_1, n_4+i}, \psi_{n_2, n_4+i}, r(t), \Delta r, n_1, n_{\max r}), \\ & \delta(t), \Delta\delta, n_5, n_{\max\delta} \big) + \psi(t) \end{aligned} \tag{6}$$

$$\delta(t+\Delta t) = \mathrm{inter}(\delta_{1, n_3+i}, \delta_{1, n_4+i}, \delta(t), \Delta\delta, n_5, n_{\max\delta}) \tag{7}$$

where:

$$\mathrm{inter}(x_1, x_2, x_3, x_4, x_5, x_6) = \frac{(x_2 - x_1)(x_3 - x_4(x_5 - (x_6 + 1)/2))}{x_4} + x_1,$$

$$n_1 = \left\lfloor r(t) / \Delta r \right\rfloor + \frac{n_{\max r} + 1}{2},$$

$$n_2 = \left\lceil r(t) / \Delta r \right\rceil + \frac{n_{\max r} + 1}{2},$$

$$n_3 = \left( \left\lfloor \delta(t) / \Delta\delta \right\rfloor + \frac{n_{\max\delta} - 1}{2} \right) n_\delta,$$

$$n_4 = \left( \left\lceil \delta(t) / \Delta\delta \right\rceil + \frac{n_{\max\delta} - 1}{2} \right) n_\delta,$$

$$n_5 = \left\lfloor \delta(t) / \Delta\delta \right\rfloor + \frac{n_{\max\delta} + 1}{2},$$

$i$ - number of control decision taken $(1 \le i \le n_\delta)$.

## 2.2 Knowledge base

The knowledge base of object dynamics is represented by the matrices: **R**, **Ψ, Δ** (discussed in the previous section) and a three-dimensional data cube, **Region**. For further considerations, the following definitions will be introduced.

Definition 1. A closed zero region $(O_0)$ is a set of object states in the form:

$$O_0 = \{(r, \psi, \delta) : |r| \le r_{\max O_0} \wedge |\psi| \le \psi_{\max O_0} \wedge |\delta| \le \delta_{\max O_0}\} \tag{8}$$

where

$r_{\max O_0}$ - close to zero value belonging to set (1), determined arbitrarily $(r_{\min O_0} = -r_{\max O_0})$,

$\psi_{\max O_0}$ - close to zero positive value determined arbitrarily $(\psi_{\min O_0} = -\psi_{\max O_0})$,

$\delta_{\max O_0}$ - close to zero positive value belonging to set (2), determined arbitrarily $(\delta_{\min O_0} = -\delta_{\max O_0})$.

Definition 2. *k*-th closed region $(O_k)$, where $k \in \mathrm{N}_+$ is a set of object states for which there exists a continuum, not longer than *k*, of control decisions made every time unit $(\Delta t)$, bringing the state to the zero region $(O_0)$.

Definition 3. The value $k_{\max}$ represents the smallest natural number, for which the following relationship holds:

$$O_{k_{\max}} = \langle r_{\min}, r_{\max} \rangle \times \langle -\pi, \pi \rangle \times \langle \delta_{\min}, \delta_{\max} \rangle \tag{9}$$

thus set $O_{k_{\max}}$ is equal to all possible object states.

In the three-dimensional data cube **Region** [7] the region edges are recorded (def. 1, def. 2) for $k \in \{0,\dots,k_{\max}\}$.

## 2.3 Control

The control of the discussed vessel course stabilisation system by rudder action is based on knowledge base. For the object output $\mathbf{y} = [r(t), \psi(t), \delta(t)]$ at instant *t*, the state of the object after one time unit: $[r(t+\Delta t), \psi(t+\Delta t), \delta(t+\Delta t)]$ is first determined by means of vector $\mathbf{B_y}$ components, on the basis of computer dynamics model: (5), (6), (7), then the minimal region index that the determined state will hit, for a control decision in the form like elements of set (3). On the basis of calculations made the following vectors will be generated:

$$\mathbf{K} = \begin{bmatrix} k_1,\dots,k_{n_\delta} \end{bmatrix}; \quad \mathbf{J} = \begin{bmatrix} j_1,\dots,j_{n_\delta} \end{bmatrix} \tag{10}$$

where

$k_i$ - denotes the minimum range of the region the object state will reach at moment $t+\Delta t$, if at moment *t* a control decision was made in the form of i-th element of set (3) $(1 \le i \le n_\delta)$,

$j_i$ - denotes value $\psi^2(t+\Delta t) + \lambda\left(r(t)/\dot{\delta}_{\max}\right)^2 \delta^2(t+\Delta t)$ (*vide* (11)), if at moment *t* a control decision was made in the form of i-th element of set (3) $(1 \le i \le n_\delta)$,

$\dot{\delta}_{\max}$ - maximum rate of rudder deflection.

The most proper control decision is the one that accurately corresponds to the smallest coordinate value of vector $\mathbf{K}$ (object state returns to the zero region as fast as possible) and vector $\mathbf{J}$ (to get the lowest possible value of quality index:

$$J = \int_0^{\Delta t} \left(\psi^2 + \lambda\delta^2\right) dt \tag{11}$$

where $\lambda$ coefficient larger than zero, interpreted as a compromise between course deviation (yawing) and change of rudder angle (load on the steering gear).

Unfortunately, both these conditions are often contradictory and we have to decide which condition is more essential. When slight deviations from the course are caused only by disturbances, and thus the object output belongs to a region with low index, it seems purposeful to select the position of the rudder based on minimisation taking account of the coordinates of vector $\mathbf{J}$. Therefore, let the control decision be the one that corresponds to the smallest value from the set of those elements of vector **J**, for which the proper coordinates of vector **K** are equal to $\min(\mathbf{K})$ or $\min(\mathbf{K})+1$.

In the case of course change manoeuvre, when the object output is at a considerable distance (in the sense of Euclidean metrics) from the zero region, the control decision should correspond accurately to the smallest value of the vector $\mathbf{K}$ coordinate. This condition, however, may prove insufficient, as it will be fulfilled by most possible control decisions (because the larger the region index to which the target output belongs, the more elements of vector **K** are equal to $\min(\mathbf{K})$). In such circumstances another vector should be generated:

$$\mathbf{K}^* = \begin{bmatrix} k_1^*,\dots,k_{n_\delta}^* \end{bmatrix} \tag{12}$$

where

$k_i^*$ - denotes power of the set $\{k : k = \min(\mathbf{K}_i)\}$ $(1 \le i \le n_\delta)$,

$\mathbf{K}_i$ - vector of minimal indexes of regions to be reached by the states (at an instant $t+2\Delta t$ ) if (at an instant t) the control decision was made in the form like *i*-th element of the set (3).

Which describes the object dynamics at moment $t+2\Delta t$. The maximization condition taking account of the coordinates of vector $\mathbf{K}^*$ should thus contribute to a more accurate selection of the control decision. Hence, in the considered case let the control decision be the one that corresponds to the smallest value of the set of those elements of vector $\mathbf{J}$ for which the corresponding coordinates of vector $\mathbf{K}$ are equal to $\min(\mathbf{K})$, and the corresponding coordinates of vector $\mathbf{K}^*$ are equal max $\max(\mathbf{K}^*)$.

Thus, in successive instants the control decisions are so defined that the target state should make it to the region with a decreasing index, and when it reaches the zero region it should remain close to zero in the sense of Euclidean metrics, minimising the index of control quality (11). In [7] the stability of the proposed system has been proved.

## 2.4 System adaptation

The problem of adapting the considered ship's course stabilization system consists in the identification of matrices: **R, Ψ, Δ,** a basis for the operation of computer dynamics model and a creation of 3D data cube **Region** (Fig. 2). The approximators used for the adaptation are based on base functions of the model [13, 14] to assure an on-line identification of the mathematical model of object dynamics. On this basis, matrices **R, Ψ, Δ,** are first created at time unit intervals, then the 3D data cube **Region**.

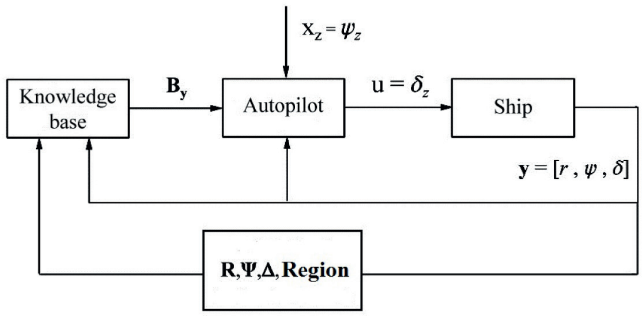


**Fig. 2. The structure of the proposed system of ship's course stabilization with adaptation [own study]**

The application of adaptive control built on base functions of the model that use a controller linearizing with feedback

[13,14] leads to the generation of unknown model characteristics. However, when a model has already been identified, the control described in section 2.3 is characterized by higher quality than the controller linearizing with feedback. In this connection, to ensure stability and adaptation of the proposed system, control should be appropriately switched:

- from the proposed control to feedback linearization adaptive control [13,14] (then the matrices:**R, Ψ, Δ,** and adaptation of a 3D data cube **Region** will be performed currently ), in cases when $n_{pr\text{-}LF}$ of consecutive control decisions does not lead to the reduction of object state region index or the object state is not maintained close to zero region (in the sense of Euclid's metrics);
- from feedback linearization adaptive control [13,14] to the proposed control, (then neither current identification of matrices: **R, Ψ, Δ,** nor adaptation of the 3D data cube **Region** will take place), in cases when $n_{LF\text{-}pr}$ of consecutive control decisions leads to the reduction of object state region index or the object state is not maintained close to zero region or ensures the maintenance of object state close to zero region (in the sense of Euclid's metrics).

The values $n_{pr\text{-}LF}$, $n_{LF\text{-}pr}$ are assumed arbitrarily.

# 3. Simulation experiments

The calculation experiments have been conducted in a Matlab/Simulink environment. De Witt-Oppe's model has served as a real object (ship) [3], with consideration to steering gear dynamics [9].

Computing experiments consisted in a series of simulations aimed at a comparison of the operation of herein proposed controller and the feedback linearization adaptive controller. In both cases it is assumed that de Witt-Oppe's model is not known. The values $n_{pr\text{-}LF} = 5$, $n_{LF\text{-}pr} = 5$ are adopted arbitrarily. The other parameters are adopted according to [7,14].

Fig. 3 presents the results of an example computing experiment. The charts depict movement trajectories and off course deviations of a ship performing two subsequent turns (course alterations: 90° to starboard and 90° to port). The firm line corresponds to the proposed controller operation, while dashed line corresponds to the adaptive control by feedback linearization. In both turns of the ship the time to keep the ship on a new course was shorter when the proposed controller was in use.

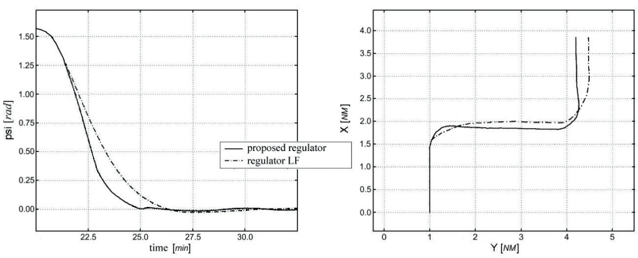


**Fig. 3. Off-course deviations and ship movement trajectories for an example computing experiment [own study]**

The conclusions from the computing experiments:

- in all examined cases the time to get on a new course set by the proposed control algorithm was shorter,
- observed reduction of time required to stabilize the ship's course ranged from 1% to 28%.

# 4. Conclusion

The intelligent adaptive system of ship course stabilization proposed by this author, based on a knowledge base, has been verified through computing experiments. The results confirm that the method assures high control quality. The improvement refers to both control time and the scope of abrupt course alteration. The results of described experiments are therefore positive. The proposed adaptive algorithm of ship course stabilization, based on a knowledge base, will be implemented in the executive module of NAVDEC, a navigational decision support system [11,15]. The executive and other modules (e.g. data fusion [1,2,4,5,10]) make up an implemented system of navigational decision support in the process of safe vessel conduct (invention [12]).

The developed system concerns the vessel course stabilisation, yet the presented methodology may easily be expanded and used for a synthesis of the multitask trajectory autopilot. In the context of the proposed approach, it seems viable to widen the range of tasks and controlled objects. The proposed methodology represents a new branch of intelligent control systems.

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