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Implementation and verification of course controllers in the inland navigation simulator (InSim)

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Key words: InSim, shiphandling simulation, PID controller, fuzzy controller, ship's course control algorithm

Abstract
The formal verification of performance properties of a ship's course control algorithm used in the InSim simulator of Maritime University of Szczecin is presented in the paper. Implementation of fuzzification, fuzzy rules and defuzzification techniques allowed the construction of a controller tuned in accordance to expert knowledge as an alternative to the industry PID standard. Both controllers' structures are analysed. Their verification leads to the assessment and comparison of dynamic properties of a modelled ship's course control. Further development of course controllers into track controllers has been discussed as well.

Introduction

The desired ship's motion both, in reality and simulation, can be achieved by control of the vessel's momentary vector state parameters. In restricted water areas two basic cases of ship's steering are distinguished:

1) while proceeding via straight or curved route segments between consecutive waypoints with fixed allocation of engine / thrusters;
2) while manoeuvring with variable allocation of engine / thrusters.

Two types of autopilot have been implemented into the Inland Navigation Simulator (InSim) developed in Maritime University of Szczecin for navigator's support in case No. 1: PID and fuzzy. These autopilots monitor 4 variables of the state vector: course tracking error $\Delta\psi(t)$, derivative of course $\omega_z = d\psi(t)/dt$, transverse shift of ship's body origin (usually centre of gravity) from the set trajectory $\Delta y(t)$ and linear speed of this displacement v_y. Additionally, for realistic steering gear model implementation, the rudder angle offset $\Delta\delta_R(t)$ is monitored. In the article the structure of autopilots' course control module (monitoring the first two variables) is analysed and its performance validated (Fig. 1).

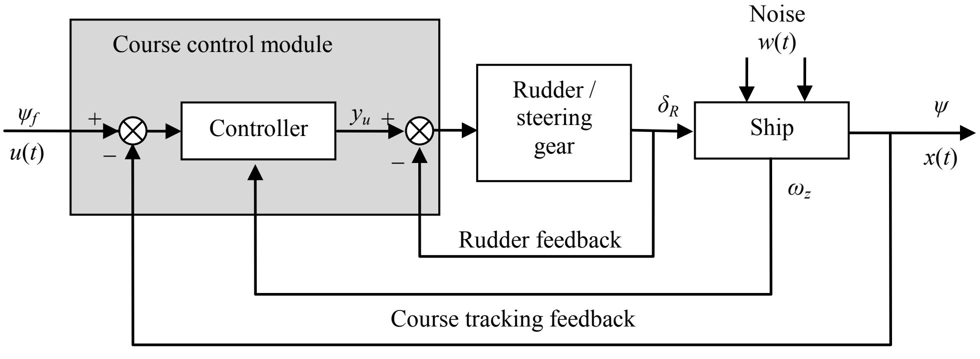


Fig. 1. Diagram of a ship's course control

Symbols in the figure 1 mean:

$u(t)=\psi_f$ – preset course value (set point);

$x(t)=\psi$ – instantaneous course value;

ω_z – instantaneous course derivative value (angular velocity);

y_u – steering gear allocation value (allocated rudder angle);

δ_R – measured rudder angle;

w – noise vector;

and: $\Delta\psi=\psi_f-\psi$, $\Delta\delta_R=\delta_R-y_u$.

The track keeping function which requires monitoring of the displacement variables $\Delta y(t)$ and v_y, is implemented via cascade control arrangement in which another controller's output drives the set point of a course controller. The structure of this second "displacement" controller is equivalent to the first "course" controller and its performance can be verified accordingly.

PID controller of ship's course

PID (Proportional–Integral–Derivative) controller is the most popular device used contemporary either in continuous or discrete control systems [1, 2, 3, 4]. Application of a PID controller guarantees better dynamic properties (control time, control curve-trajectory) and static properties (error) in relation to the P, PI, PD type controllers. There are following parameters of a PID controller:

- gain (proportional) coefficient k_p;
- integration time T_i;
- differentiation time T_d.

Generally, the impact of these parameters on the controlled process (achievement and maintaining of set course) can be interpreted as follows:

- the proportional component compensates current deviation between the set and the instantaneous (current) value of the controlled parameter;
- the integral component compensates for the accumulation of these deviations in the past;
- the derivative component compensates for the expected deviations in the future.

Dynamic time characteristics (output $y_u(t)$ as a result of application of the input signal $\Delta\psi(t)$ in the time t) of the PID controller in the basic, continuous form are described by the equation [5]:

$$y_u(t)=k_p\left(\Delta\psi(t)+\frac{1}{T_i}\int_0^t\Delta\psi(t)\,\mathrm{d}t+T_d\,\frac{\mathrm{d}\Delta\psi(t)}{\mathrm{d}t}\right)\tag{1}$$

For modelling purposes it is convenient to introduce the equation (1) in the operator form – by means of a continuous time transfer function to a domain of complex variable s:

$$G_{PID}(s)=\frac{Y_u(s)}{\Delta\Psi(s)}=k_p\left(1+\frac{1}{sT_i}+sT_d\right)\tag{2}$$

Switching from the continuous to discrete time transfer function (as used in the simulator) requires substitution of the variable s in equation (2), after numerical forward Euler integration, by:

$$s=\frac{z-1}{T_s}\tag{3}$$

where:

T_s – sampling time.

Derivative action of a PID controller can cause amplification of the noise (interference) in the measured process value $\Delta\psi(t)$ and, consequently, cause unnecessary changes or oscillations of the output signal $y_u(t)$. To avoid this undesirable effect, a filter element is introduced to the architecture of the controller in its derivative component. Therefore, an ideal PID controller, after substituting (3)

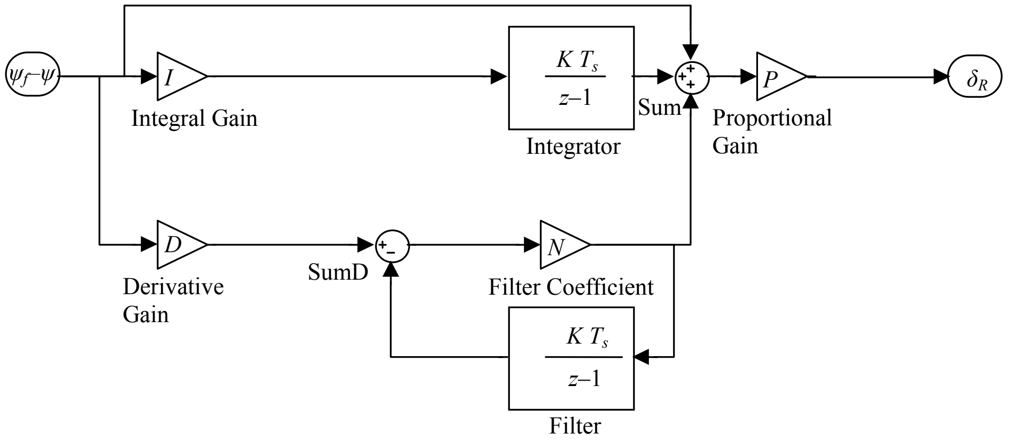


Fig. 2. Diagram of the InSim discrete PIDF controller

in (2), takes the form of a PIDF (Proportional – Integral – Derivative – Filter) as in formula (4):

$$G_{PIDF}(z) = k_p\left(1 + \frac{1}{z-1}\frac{T_s}{T_i} + \frac{T_d}{\frac{1}{N}+\frac{T_s}{z-1}}\right) \qquad (4)$$

where: N – is the filter coefficient.

Block diagram of the InSim PIDF controller architecture in discrete time domain (4), designed in MATLAB / Simulink is shown in the figure 2.

Symbols in the figure 2 mean:

K – gain value, $P = k_p$, $I = \frac{1}{T_i}$, $D = T_d$.

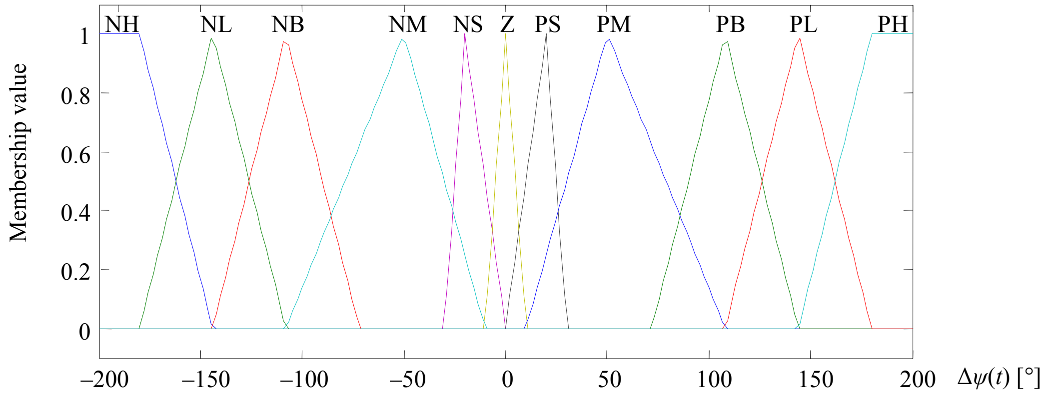


Fig. 3. Membership functions to the fuzzy sets of course error

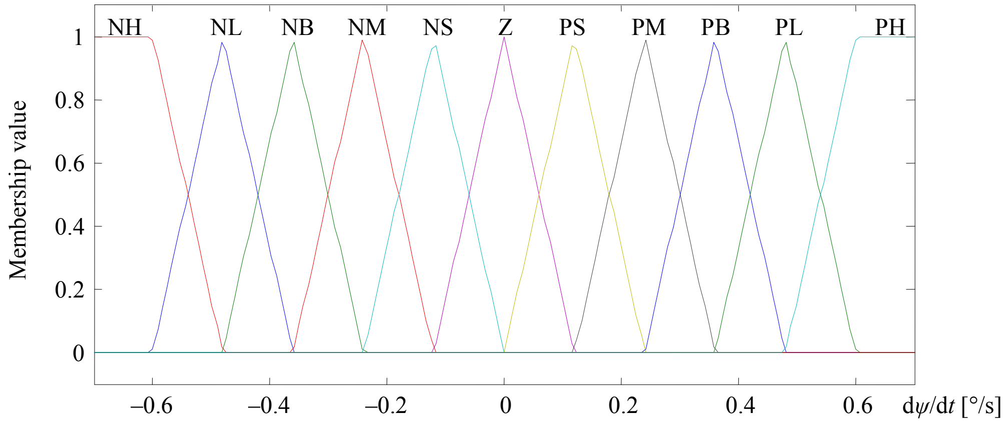


Fig. 4. Membership functions to the fuzzy sets of rate of change of course error

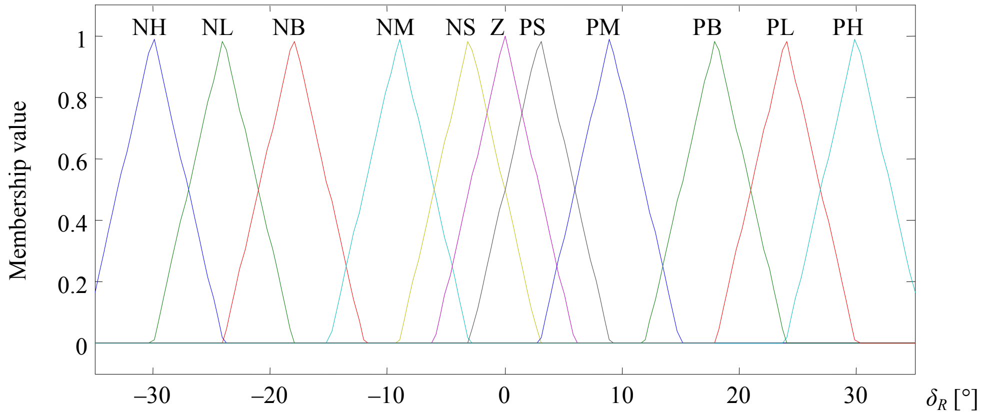


Fig. 5. Membership functions to the fuzzy sets of rudder angle allocation

Fuzzy controller of ship's course

According to assumptions given in the introduction, input variables in a fuzzy controller of ship's course, correspondingly to the PID controller are: difference between the set course value and the current course value – course's deviation (error) $\Delta\psi(t)$, rate of change of the course's deviation – course's derivative $\omega_z = \mathrm{d}\psi(t)/\mathrm{d}t$, and the output variable is: allocated rudder angle $y_u = \delta_R(t)$.

Membership functions of each variable of the controller to the fuzzy sets marked linguistically *NH* (negative high), *NL* (negative large), *NB* (negative big), *NM* (negative medium), *NS* (negative small), *Z* (close to zero), *PS* (positive small), *PM* (positive medium), *PB* (positive big), *PL* (positive large), *PH* (positive high) are presented in the figures 3, 4 and 5.

Introducing fuzzy rules, all the major components of the navigator's knowledge of ship's steering are directly evident from the fig. 6 in the following manner:

1. If the heading error $\Delta\psi$ and change in heading error ω_z are both, big and have identical signs, then use very big maximum rudder input correspondingly.
2. For zero $\Delta\psi$ and ω_z, the rudder angle should be zero, but if $\Delta\psi$ and ω_z move positive (to starboard), then the rudder should move negative (to port).
3. If ω_z moves significantly positive, then the rudder should move even more negative. Similar reaction follows for $\Delta\psi$ and ω_z negative, where the rudder angle should be made positive. For the case where $\Delta\psi$ and ω_z have opposite signs and depending on the magnitude of the signals, the rudder input should be either positive or negative.

For small $\Delta\psi$ and ω_z, the changes to the rudder position should be smaller and applied slower to keep system's stability and lower heading oscillations (yawing). For instance by lowering the "gain" of the controller near zero the noise will not be amplified. Also, if the ship's angular position is moving sufficiently fast to remove the heading error, then be conservative in using the rudder to further help ship's rotation since this is unnecessary.

These rules can be presented in the form of *If…Then…*, for example:

If $\Delta\psi(t)$ *is NH And* $\mathrm{d}\psi(t)/\mathrm{d}t$ *is NH Then* $\delta_R(t)$ *is PH*
If $\Delta\psi(t)$ *is NH And* $\mathrm{d}\psi(t)/\mathrm{d}t$ *is NL Then* $\delta_R(t)$ *is PH*
If $\Delta\psi(t)$ *is NL And* $\mathrm{d}\psi(t)/\mathrm{d}t$ *is NH Then* $\delta_R(t)$ *is PH*
…

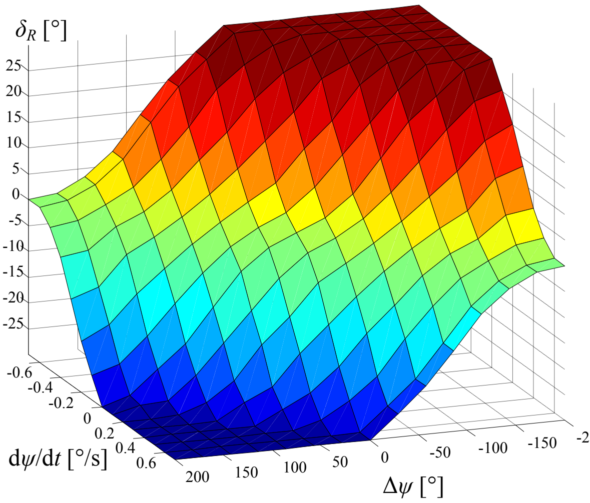


Fig. 6. Relation among rudder angle, course error and course error rate (angular velocity) as 3D response surface

They comprise navigator's expertise of ship's course control. Based on the assumed inputs and outputs there are $11^2 = 121$ such rules, a combination of 11 linguistic variables of fuzzy sets, two inputs and one output presented in the form of the response surface plot in the figure 6.

The principle of determining the "crisp" value of rudder angle δ_{Rc}, using the centre of gravity of the membership function [6], for the fuzzy output with two rules activated (5) is presented in the figure 7.

In the presented case, the small deflection of the rudder to port follows the detection of a small angular velocity to the starboard side at near zero deviation from the set course.

$$\delta_{Rc} = \frac{\int \delta_R m_C(\delta_R)\,\mathrm{d}\,\delta_R}{\int m_C(\delta_R)\,\mathrm{d}\,\delta_R} \tag{5}$$

where: $m_C(\delta_R)$ – membership function of a conclusion set resultant from combination of two activated sets; in the figure 7 these are *Z* and *NS* marked by gray colours.

Verification of implemented course controllers performance

Validation of course controllers implemented in InSim has been designed to verify the performance (evaluation of the dynamic properties) of the provided state vector control. Considering the control of one of the state vector parameters such as vessel course, changing the absolute value of the course in range of 0° to 180°, leads to the ship's response similar to oscillatory process shown in the figure 8.

The analyzed indicators of control quality are [6] (Fig. 8):

1) static accuracy:

$$e_f = \psi_s - \psi_f \tag{6}$$

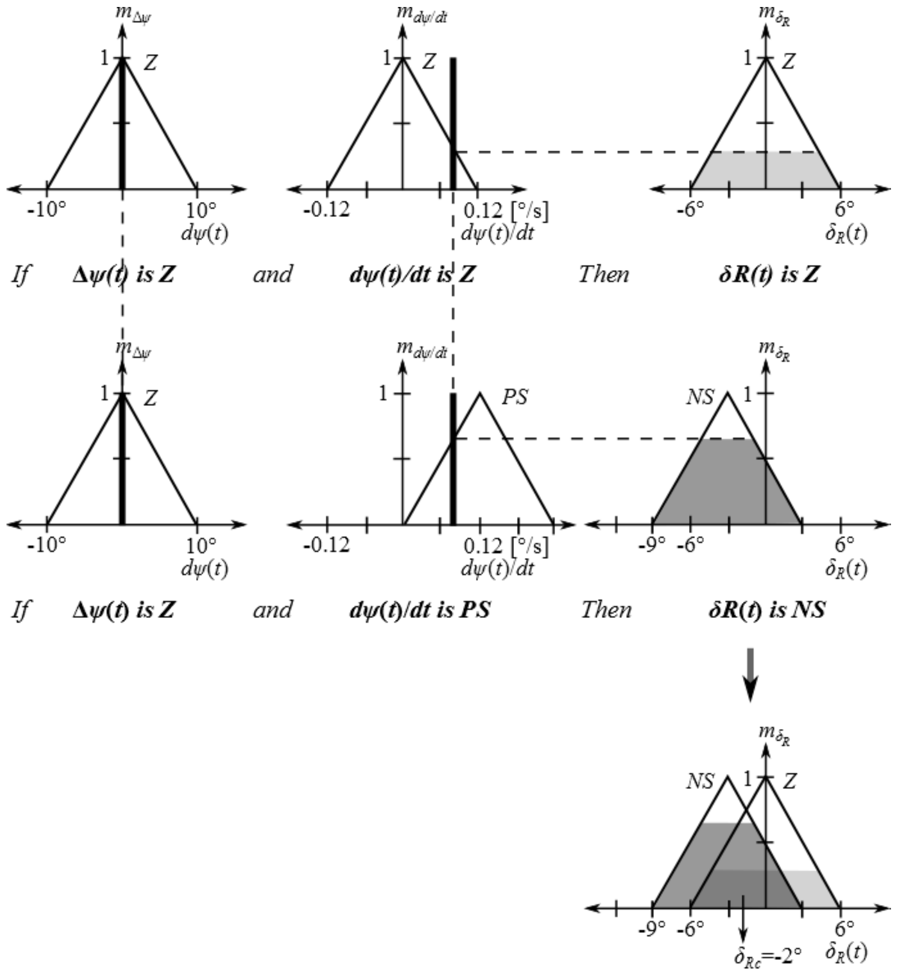


Fig. 7. Determination of the "crisp" value of rudder angle in the fuzzy controller of ship's course

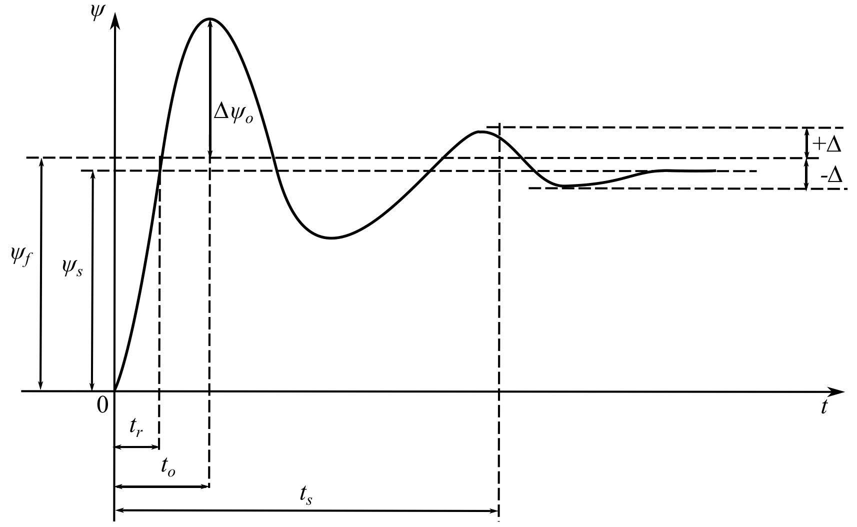


Fig. 8. Oscillatory behaviour of the function of ship's course as a result of controller's actions

2) indicators related to the step response of the control system – the responsiveness to the excitations:
   a) lag or "pseudo dead time" – the time between the output (rudder) change and the point at which the tangent line drawn through the steepest part of the process curve (the point of inflection) crosses the original process line (t_l);
   b) control time (t_s);
   c) rise time (t_r);
   d) the time to reach the maximum response (t_o);

   e) the maximum overshoot ($\Delta\psi_o$):

$$\Delta\psi_o = \psi_{\max} - \psi_s \tag{7}$$

$$\Delta\psi_o[\%] = \frac{\Delta\psi_o}{\psi_s}\cdot 100 \tag{8}$$

3) quality indicators related to the frequency characteristics – stability reserve:
   a) reserve of gain ΔK or module ΔL,

$$\Delta K = \frac{1}{\left|G(j\omega_\pi)\right|} \tag{9}$$

   where: $j \in \mathrm{N}$; $\varphi(\omega_\pi) = -180°$;
   b) reserve of phase $\Delta\varphi$;
4) indices based on integrating the error following a disturbance or set point change:
   a) IAE – Integral of absolute value of error:

$$I_1 = \int_0^\infty \left|e(t) - e(\infty)\right| \mathrm{d}t \tag{10}$$

   b) ISE – Integral of square error:

$$I_2 = \int_0^\infty \left(e(t) - e(\infty)\right)^2 \mathrm{d}t \tag{11}$$

   c) ITAE – Integral of time times absolute value of error:

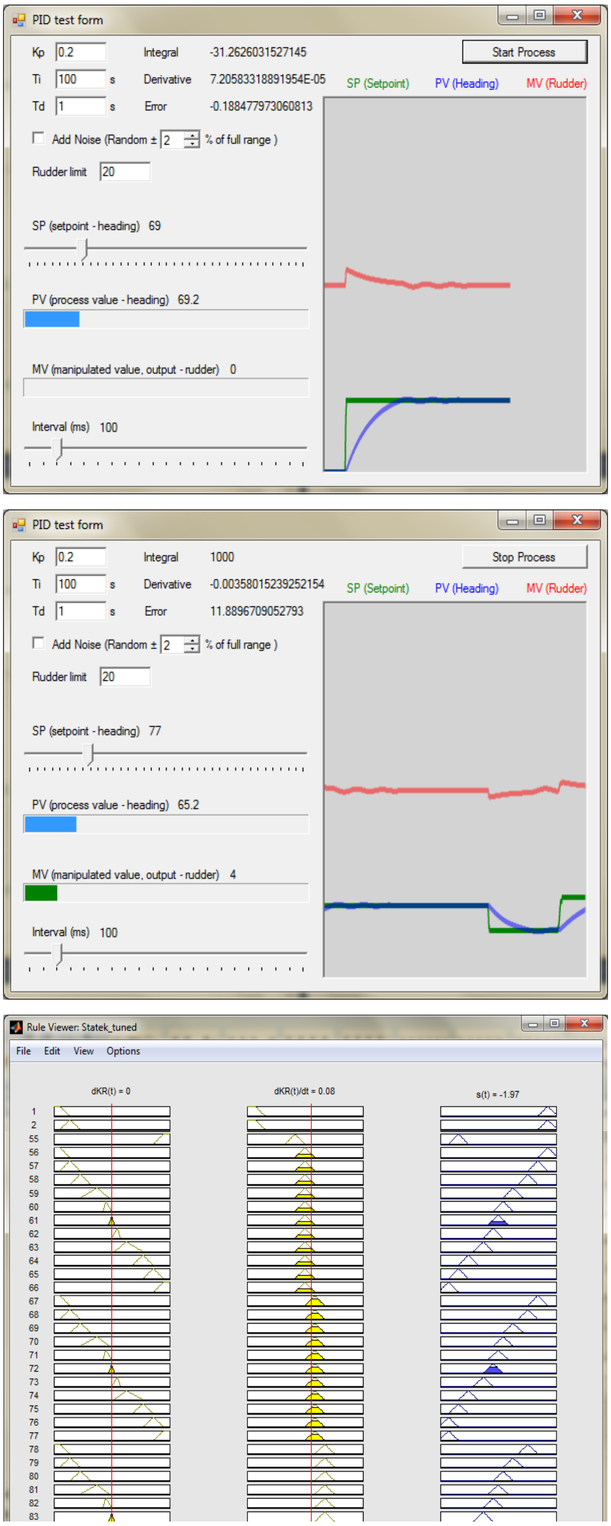
$$I_3 = \int_0^\infty t\left|e(t) - e(\infty)\right| \mathrm{d}t \tag{12}$$

   d) ITSE – Integral of time times error squared:

$$I_3 = \int_0^\infty t\left|e(t) - e(\infty)\right| \mathrm{d}t \tag{13}$$

Tuning the controller parameters according to the criterion of minimizing the quality indicators (Figs 9 and 10) has been performed on the basis of theoretical and empirical knowledge of the process in MATLAB using model of the river barge [7] according to the following steps:

1) determination of the design level of operation (DLO), which corresponds to finding of the expected values of the rudder settings, major disruptions;
2) determination of the controller's parameters by methods based on process approximation (for instance Ziegler Nichols methods for PID, inputs and output membership function changes according to expert knowledge);
3) recording of the controller's output while running simulated process of ship's motion;
4) evaluation of the tuning quality and eventual return to the second stage with the changed parameters of the controller.



Kp 0.2
Ti 100 s
Td 1 s
Integral -31.2626031527145
Derivative 7.20583318891954E-05
Error -0.188477973060813
☐ Add Noise (Random ± 2 % of full range)
Rudder limit 20
SP (setpoint - heading) 69
PV (process value - heading) 69.2
MV (manipulated value, output - rudder) 0
Interval (ms) 100

Kp 0.2
Ti 100 s
Td 1 s
Integral 1000
Derivative -0.00358015239252154
Error 11.8896709052793
☐ Add Noise (Random ± 2 % of full range)
Rudder limit 20
SP (setpoint - heading) 77
PV (process value - heading) 65.2
MV (manipulated value, output - rudder) 4
Interval (ms) 100

dKR(t) = 0
dKR(t)/dt = 0.08
s(t) = -1.97

Fig. 9. Interface of controllers' tuning application in InSim

Conclusions

Two types of controllers have been implemented for the InSim shiphandling simulator. Their assessment and comparison of dynamic properties of resultant modelled ship's course control lead to preliminary conclusion that these controllers can be used alternatively in InSim ships' models.

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