Wind Disturbance Suppression in Autopilot Design

Potiskivanje utjecaja vjetra u projektiranju autopilota

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Summary

Environmental conditions affects ship's course. Hence, it affects velocity, and efficiency of fuel consumption, which is an important research topic nowadays. Therefore, it is important to take it into account in the design of ship's autopilots. In this paper a method is proposed to compensate for wind's influence, which is based on wavelet transform by introducing the so called wavelet anti-filter. The anti-filter is added to the feed-forward branch of the classic autopilot design scheme, which consists of feedback loop and PID controller. The anti-filter branch represents a modification of the classic scheme.

KEY WORDS
wavelet
anti-filter
feed-forward control
ship's autopilot
PID control
MISO

Sažetak

Utjecaj okolišnih uvjeta na kurs broda te, u skladu s time na brzinu i učinkovitost potrošnje goriva, vrlo je važno područje istraživanja. Zbog toga ih je važno uzeti u obzir pri projektiranju brodskih autopilota. U ovom je članku predložen način kompenzacije utjecaja vjetra, koji se temelji na valićnoj transformaciji, uvođenjem valićnog anti-filtra. Anti-filtar je dodan u unaprijednu granu klasičnog sustava s povratnom vezom i PID regulatorom. Tako je izvršena modifikacija sheme autopilota.

KLJUČNE RIJEČI
valići
anti-filtar
unaprijedno upravljanje
brodski autopilot
PID upravljanje
MISO

1. INTRODUCTION / *Uvod*

The most frequently used autopilot design involves the PID controller. It remains the standard aboard ships worldwide despite many ideas to change the type of controller. Failure to implement an advanced autopilot design in wide production is caused by inability to guarantee the performance robustness and stability [1]. Intelligent solutions are continuously reported for unmanned, surface and underwater vehicles. So, although intelligent solutions exist and are sporadically implemented, the application of such solutions is not usual aboard manned vehicles.

Examples of the advanced control solutions are presented in many papers. Commercial fuzzy autopilot was implemented in 1995 [2]. There were also attempts to implement artificial neural networks (ANN) or to combine fuzzy approach with ANNs. Fuzzy, fuzzy-neural and neuro-fuzzy autopilots have been proposed in [3 -5]. Fuzzy wavelet network was used in [6]. Fast convergence of such network was the key advantage. It enabled robust close loop control. Integrated hybrid control was presented in [7]. An interest for marine fuzzy autopilots was increased due to research in [8]. Adaptive fuzzy course controller with rudder dynamics was proposed in [8]. The ship's model was described by nonlinear model of the third order, which incorporates virtual control gain function. The advantage of the proposed method is in the fact that explosion of complexity is avoided.

Wavelets were used in the system identification (SI), which is necessary for the closed loop control system design based on the model predictive design [9]. A wavelet based SI method has been proposed in [10]. Discrete wavelet transform (DWT) has been used in for SI of the autopilot for uninhabited surface vehicles (USV) [10]. Research in [11] showed a problem in the system identification based on wavelets. Namely, the system's impulse response can be estimated only at the half of resolution (half number of needed points). This problem has been solved with oversampling in [11] where it has been shown that better results could be obtained than the ones using conventional SI methods. Wavelet implementation in model predictive control (MPC) was utilized in [12]. The experimental implementation of MPC was presented for path following on a ship model in [13].

However, there are no direct implementations of wavelets to the ship's autopilot. Most of the novel methods tend to be self-standing. On the contrary, in this article, an improvement to a classic PID control using wavelets is proposed, with no intention of developing a novel control method.

An idea to improve PID controller performance presented in this paper is based on wavelet anti-filter which is added to compensate for wind influence. The filter is placed in feed-forward part of the control system. The paper is organized as follows. The second section presents a problem of wind formulation. The third section describes a minimum of the necessary wavelet theory. The forth section presents the proposed autopilot design. The final section are conclusions and guidelines for the further research.

2. WIND / *Vjetar*

Depending on the research subject, the ship can be modeled as multiple input and multiple output model (MIMO System), as it is shown on Figure 1.

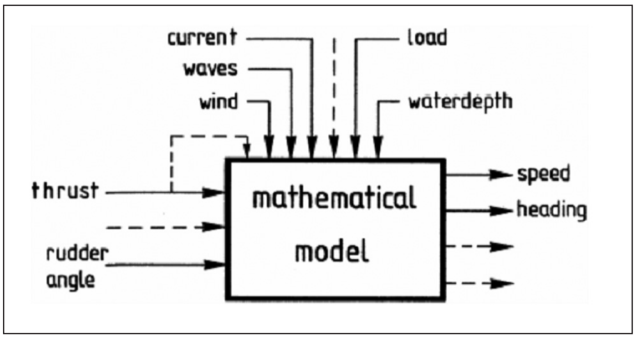


Figure 1. Mathematical model of the ship described as MIMO system

Slika 1. Matematički model broda kao MIMO sustava

Some of the ship's model inputs are not controllable and can be classified as shown in the Figure 2. The inputs that are not controllable are called disturbances.

From the Figure 2 it can be seen that the wind is input disturbance that is not directly controllable. So, in order to reduce the impact of the wind as input it is common practice to use feed-forward controller.

In marine practice, there is no doubt that wind influences ship's course and voyage efficiency. It is the reason why wind measurements are normally carried out. Other environmental influences could be sea currents and waves. All these parameters influence dynamic positioning as well, which is also an interesting topic. Attempt to incorporate wind influence utilized the assumption that waves are wind-generated. Waves contribution could be measured by pitch and roll measurements [14]. However, the natural frequency of the vessel can over dominate the wave frequency. Moreover, waves can occur even when there is no wind (i.e. dead sea). Furthermore, wind also interacts with the ship's hull, and aerodynamics efficiency, as function of consumption can be of importance.

Perez [15] used power spectral density (PSD) of the wave sea surface elevation, $S_{\zeta\zeta}(\omega)$, which is also called wave spectrum. Under a Gaussian assumption, the process implies that $E[\zeta(t)] = 0$ or:

$$E\left[\zeta(t)^2\right] = \int_0^\infty S_{\zeta\zeta}(\omega)d\omega \tag{1}$$

Based on [16], if 6 DOF (degrees of freedom) marine vessel equation of motion is considered, vessel kinetics can be expressed as (2):

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau + w \tag{2}$$

where v is linear and angular velocity matrix, M the system's inertia matrix, C Coriolis-centripetal matrix, D damping matrix, g vector of gravitational forces and moments, τ vector of control inputs, w vector of environmental disturbances (including currents, wind and sea). Vector w can be divided into low and high frequency forces. The high frequency forces cannot be counteracted by the feed-forward controller. This is the reason that the high frequency forces are usually discarded from models. Some modern controllers already take into account wind parameters to compensate disturbances caused by wind. The control law can easily be extended with feed-forward terms as:

$$\tau = \tau_{PID} + \tau_{FF} \tag{3}$$

where τ_{PID} is the control input of the PID controller and τ_{FF} control input of the feed-forward controller.

$$\tau_{FF} = D\dot{v}_d + Mv_d \tag{4}$$

Wind is characterized by a direction and a velocity, v_d; see [14]. Therefore the effect of wind on the ship's dynamics can be expressed in terms of speed and velocity. This can function in theory. The problem arises in the expression of the wind's dynamics. There are constant winds, winds of low-frequency. There are also winds with a little time period of sudden change

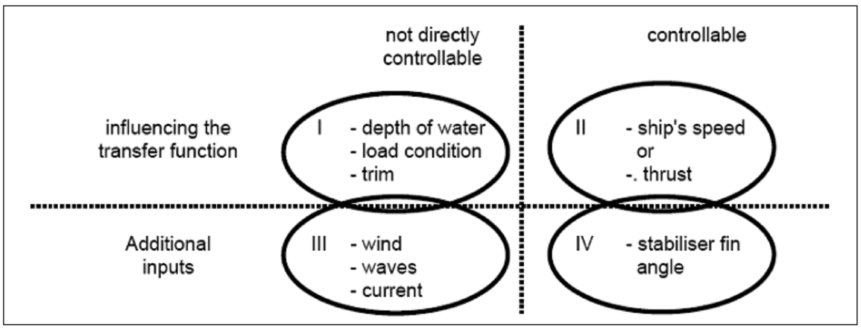


Figure 2. Designations of controllable and not directly controllable inputs and disturbances

Slika 2. Upravljivi I izravno neupravljivi ulazi i smetnje and then slower decline. Example is north-east wind of Adriatic with Croatian name *bura*. This wind can be interpreted as Gaussian bell function with periodic character. So, influence of wind bura can be approximately modeled as repeated Gaussian function. Influence of constant wind can be interpreted as a step function.

3. WAVELETS / *Valići*

Theory of wavelets can be found in many references [17 - 21]. Therefore, only the origin of the Gaussian wavelet, used for controller design in the next section, will be presented here. Gaussian wavelets can be real or complex. Real Gaussian wavelet is built from the Gaussian function:

$$f(x) = Ce^{-x^2} \quad (5)$$

by taking the *p*-th derivate. Variable *x* represents indexed time. The value *p* should be an integer and *C* is normalization constant that satisfies:

$$\left\| f^{(p)} \right\|^2 = 1 \quad (6)$$

where *f*(p) is the *p*-th derivate of *f*.

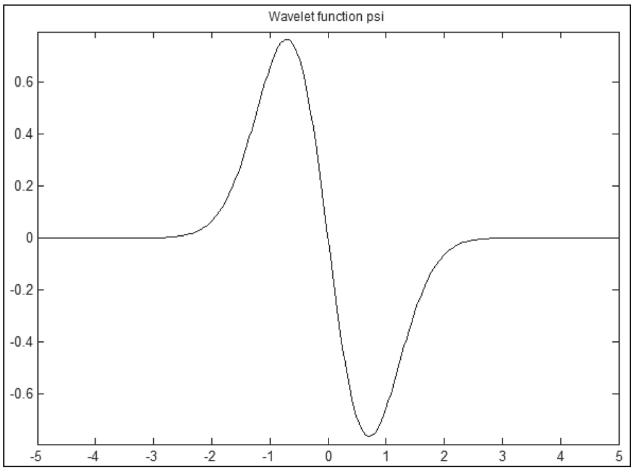
Complex Gaussian wavelets are originated in the complex Gaussian function:

$$f(x) = Ce^{-x^2 - ix} \quad (7)$$

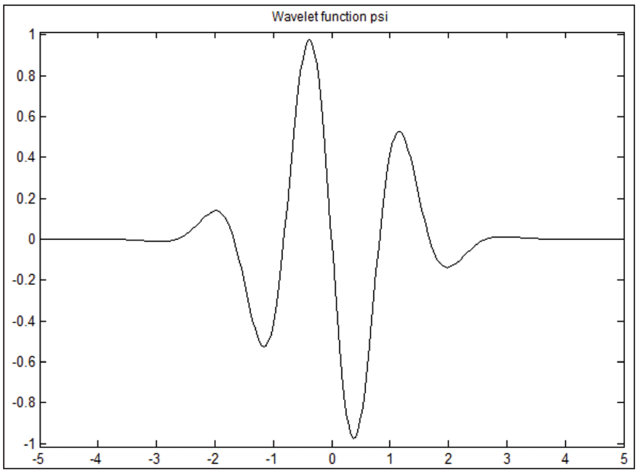
where *i* is the imaginary unit.

4. PROPOSED CONTROLLER DESIGN / *Predložena shema kontrolera*

Classic autopilot with PID controller includes feedback loop design. Environmental disturbances are included via sum of the PID output and the disturbance signal between PID and the control object (ship). This is dashed line in Figure 4.



a)



b)

Figure 3. a) Gaussian wavelet of the 1st order, b) Gaussian wavelet of the 7th order

Slika 3. a) Gaussov valić prvog reda, b) Gaussov valić sedmog reda

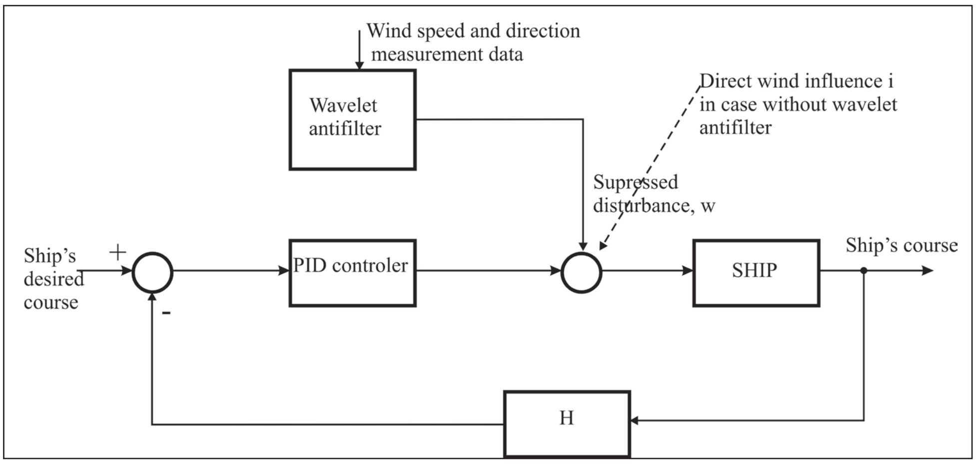


Figure 4. Proposed controller design for wind influence suppresion

Slika 4. Predložena shema kontrolera za potiskivanje utjecaja vjetra

The basic idea behind the proposed scheme is to compensate the influence of wind by applying anti-filter, which adds the compensation signal to the control loop. Since there is only one output of the system, and there are two inputs, the system can be considered as MISO (multi input single output).

Wavelet anti-filter design can be explained as MSE method (Mean Square Error method) of wind spectra and wavelet spectra. If the disturbance is equal to zero, there is no compensation signal and we obtain classic PID design. In theory, it is possible to cancel the wind spectra in total, but not in practice and especially not in real time. That is the reason to call the proposed as suppression. There is always small difference, which could be un-significant.

Based on mentioned above, a four step algorithm can be proposed:

1. Measure wind characteristics (speed and direction)
2. Calculate wind's influence to the ship's course, w_1
3. Calculate wavelet anti-filter to minimize wind's influence. Minimization is performed by MSE and a known general formula of the Gaussian wavelet. Since w→0, it is obvious that:

$$\sqrt{w_1^2 - w_2^2} \rightarrow 0 \quad (8)$$

where w_1 is the wind's influence to the control signal, which is calculated by measurement data, and w_2 is the output of the anti-filter. Taking account spectra, the minimization is obtained by:

$$\sqrt{W(\omega)_1^2 - \left(Ce^{-\omega^2}\right)^2} \rightarrow 0 \quad (9)$$

where W_1 can be considered as known parameter, since wind's characteristics are measured by the wind sensor. Therefore, C should be estimated to minimize the expression.

4. Apply anti-filter to correct controller signal.

There are two major reasons to take Gaussian wavelet. Firstly, a wind component can be divided into a constant part and variable part. This variable part is random and in the model can be described as Gaussian noise. The second reason is in imitation of usual behaviors of some specific winds. In our case, this is north-east wind called "bura". Constant component of wind can be approximated with Haar wavelet. Different wind strength can be approximated with the scaling factor in the Haar wavelet.

5. CONCLUSION / *Zaključak*

In this paper, we propose an introduction of the wavelet anti-filter in the feed-forward branch of the autopilot design. The proposed anti-filter is designed by estimated wavelet parameters to suppress wind's disturbances. The choice of wavelet is based on the spectral wind's characteristics. We propose Gaussian wavelet for Adriatic north-east wind. However, a further research is necessary to find an automatic wavelet selection method for the wind compensation purposes in general for any sea. Although, there were ideas to compensate environmental influences with the feed-forward branch, especially for wind compensation, we propose wavelets for the anti-filter design. This shows the need for developing an effective means of on-line estimation of the wavelet parameters, which should be one way of further research. After such a development, a real-world testing of the developed anti-filter should be planned. The advantage of the proposed is that it is assumed to be a small modification of the current autopilots, which are still mostly PID. Therefore, in order to implement proposed enhancements only software should be upgraded, which produces minimum costs.

REFERENCES / *Literatura*

[1] Roberts, G.N., Trends in marine control systems, Annual Reviews in Control, 2008, 32, pp. 263–269. http://dx.doi.org/10.1016/j.arcontrol.2008.08.002

[2] Polkinghorne, M. N., Roberts, G. N., Burns, R. S., Winwood, D., The implementation of fixed rulebase fuzzy logic to the control of small surface ships, Control Engineering Practice, 1995, 3(3), pp. 321–328. http://dx.doi.org/10.1016/0967-0661(95)00003-D

[3] Amerongen, J., Nauta Lemka, H. van, Veen, R. van der, J. C. T., An autopilot for ships designed with fuzzy sets. IFAC conference on digital applications for process control, 1977, pp. 479–487.

[4] Omerdic, E., Roberts, G.N., Vukic, Z., A fuzzy track-keeping autopilot for ship steering. IMarEST Proceedings: Journal of Marine Engineering and Technology, 2003, A2(2), pp. 23–35.

[5] Sutton, R.,Jess, I.M., Adesign study of a self-organising fuzzy autopilot for ship control. In Proceedings of the IMechE, 1991, Vol. 205, pp. 35–45.

[6] Hussain, A., Essounbouli, N., Hamzaoui, A., Adaptive variable structure fuzzy wavelet network based controller for nonlinear systems. Proceedings of the 3rd IFAC Advanced Fuzzy and Neural Network Workshop, Valenciennes, France, October 2007, pp.1-6.

[7] Dong, N.T., Design of Hybrid Marine Control Systems for eDynamic Positioning, PhD Thesis, National University of Singapore, 2005.

[8] Sun, H., Yu, F., He, F, Sheng, J., A novel adaptive fuzzy autopilot design based on DSC, 2011 International Conference on Electrical and Control Engineering (ICECE), 16-18 Sept. 2011, pp. 3300 – 3304. http://dx.doi.org/10.1109/ICECENG.2011.6057307

[9] [Annamalai, A.S.K., A review of model predictive control and closed loop system identification for design of an autopilot for uninhabited surface vehicles, Technical Report, Marine and Industrial Dynamic Analysis, School of Marine Science and Engineering, Plymouth University, September, 2012.

[10] Ashino, R., Wavelet analysis for system identification. Japan Society for the Promotion of Science, Japan-U.S. Cooperative Science Program (2003–2004), 2004, pp.1-16.

[11] Kiran, S. R., Raju,S.S.N., Varadarajan,S., Shankar, A., LTI system identification using wavelets. Journal of Theoretical and Applied Information Technology. December 2009, 9(2), pp.1-8.

[12] Kim, B., Necsulescu, D., Sasiadek, J., Autonomous mobile robot model predictive control. International Journal of Control, 2004, 77(16), pp.1438-1445. http://dx.doi.org/10.1080/00207170412331317738

[13] Ghaemi, R., Oh, S., Sun, J., Path following of a model ship using model predictive control with experimental verification. American Control Conference, 30 June – 02 July 2010, Baltimore, MD, USA, pp.5236-5241. http://dx.doi.org/10.1109/acc.2010.5530465

[14] Alme, J., Autotuned Dynamic Positioning for Marine Surface Vessels, MSc thesis, Norwegian University of Science and Technology, 2008.

[15] Perez, T., Ship Motion Control: Course Keeping and Roll Stabilisation Using Rudder and Fins (Advances in Industrial Control), Springer-Verlag London Limited, 2005.

[16] Fossen, T.I., Marine Control Systems: Guidance, Navigation and Control of Ships, Rigs and Underwater Vehicles. Marine Cybernetics, 1st ed, 2002.

[17] Christopher, H., Walnut, D.F., Fundamental Papers in Wavelet Theory, London: Princeton University Press, 2006.

[18] Jansen, M., Oonincx, P., Second Generation Wavelets and Applications, London: Springer – Verlag, 2005.

[19] Mallat, S., A Wavelet Tour of Signal Processing, 3rd Edition, New York: Academic Press, 2009.

[20] Vujović, I., Šoda, J., Kuzmanić, I., Cutting-edge Mathematical Tools in Processing and Analysis of Signals in Marine and Navy, Transactions on Maritime Science, 2012, 1(1), pp. 35-48. http://dx.doi.org/10.7225/toms.v01.n01.005

[21] Vujović, I., Šoda, J., Beroš, S.M., Nadzor u pomorskim sustavima primjenom vremensko-frekvencijskih postupaka, Naše more, 2012, 59(5-6), pp. 254-265