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Fractional Order Dynamic Positioning Controller

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ABSTRACT: Improving the performance of Dynamic Positioning System in such applications as station keeping, position mooring and slow speed references tracking requires improving the position and heading control precision. These goals can be achieved through the improvement of the ship control system. Fractional-order calculus is a very useful tool which extends classical, integer-order calculus and is used in contemporary modeling and control applications. Fractional-order PIλD◎ controller, based on the added flexibility of fractional-order operators, are capable of superior performance compared to their integer-order counterparts. This paper presents the fractional order PIλD◎ controller designed to maintain the ship position and heading and the results were compared with classical integer order PID controller.

1 INTRODUCTION

Dynamic positioning (DP) system for marine vehicles is a challenging practical problem. It includes station keeping, position mooring and slow speed references tracking. Of that three, the main purpose of DP is to maintain a certain accurate position and course, regardless of the interference such as wave and wind. This task should only be achieved under its own propulsion and using navigation systems. An application of the appropriate control method for DP is directly related to the adopted model, its purpose, structure and number of the installed actuators.

The first DP systems were designed using conventional PID controllers in cascade with low-pass and notch filters. Here, the wave disturbances were filtered before feedback was applied in order to avoid unnecessary control action. Model-based controls for dynamic positioning includes also LQG, sliding mode control (Tomera 2010), robust H_∞ control (Grimble et al. 1993, Messer et al. 1993), non-linear backstepping method (Krstic et al. 1995) and another state - space techniques (Fossen et al. 2002). The artificial intelligence (Xu et al. 2011), fuzzy logic (Cao et al. 2001) and neural nets (Cao et al. 2000) were also used for DP. A number of researches were carried out within the scope of application. It is very difficult to derive a relative simple controller based on traditional methods for the vehicle model which represent such a complex system. Nowadays, PID controller is one of the most popular industrial controllers. It is because of its simple control structure, easiness of design, and inexpensive cost. In the last twenty years, fractional calculus have been developed by scientists and engineers and applied in the area of control theory. In the literature a generalization of integer-order controllers by corresponding fractional - order controllers was proposed. The most popular includes (Efe 2011), FO PID (Podlubny 1999), FO MPC (Domek 2013), FO backstepping method, FO sliding mode control (Vinagre et al. 2006). Fractional-order $PI^{\lambda}D^{\mu}$ controller was the first proposed by Podlubny in 1997

(Podlubny et al. 1997). Fractional - order $PI^{\lambda}D^{\mu}$ controllers, based on the added flexibility of fractional-order operators involving an integrator of order λ and a differentiator of order μ. They are capable of superior performance compared to their integer-order counterparts. Fractional-order calculus is a very useful tool in some fields of research. But on the study of vehicle control system, only several literatures were found (Nouillant et. al. 2002, Zhang et. al. 2006). Therefore, the purpose of this paper is to implement a fractional-order PID control scheme as DP controller. The proposed solutions have not been applied for controlling DP units to increase the accuracy of keeping its position and direction.

Presently there exist several tools for working with fractional models and controllers. They include CRONE (Oustaloup et. al. 2000), Ninteger (Valerio 2005) and FOMCON (Tepljakov et. al. 2011) MATLAB toolboxes.

A larger number of control parameters FOPID (five parameters tuned, instead of three), and a larger space values for these parameters (set of real numbers), provides greater flexibility in the design of the controller with respect to the standard PID controller. However, this also implies that the tuning of the controller can be much more complex.

Different methods for the design of a FOPID controller have been proposed in the literature (Monje et. al. 2008). They include a frequency domain approach (Vinagre et. al. 2000), Ziegler-Nichols tuning rules and also optimization methods such as Particle Swarm Optimization (PSO) (Karimi et. al. 2009). In this paper the Genetic Algorithm method was used to tune the parameters of the controller.

2 DYNAMIC POSITIONING SYSTEM

The main control loop of dynamic positioning system consists of the following modules: position and heading controller, control allocation system, dynamics of propellers, dynamics of the DP ship as the object of control, and the observer of current estimated output quantities for position, course, and longitudinal, lateral and angular speed components as shown in Figure 1. Based on the comparison of the vector of set position and direction values η_d with the vector of current estimated values η obtained from the observer. DP controller calculates the vector of the required surge, sway forces and yaw moment τ to compensate deflections from the given values, according to the assumed error of control. In this system the ship position and direction controller controls the motion of this object independently in three degrees of freedom, calculating the set values of τ for the drive allocation control system.

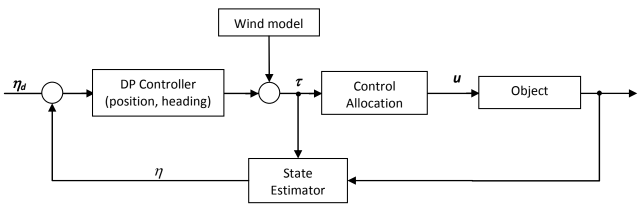

Figure 1. Dynamic ship positioning system.

Basic problems to be solved when designing DP systems include:
– filtration of signals and estimation of measured and non-measured quantities,
– selection of the control method and the DP controller,
– allocation of drive controls (Witkowska 2014).

In the paper the second task will be the aim of analysis.

During the study of controller properties it was assumed that the control allocation system and actuators were neglected, ie. produced by thrusters resultant forces and moment are equal to the calculated by the DP controller.

2.1 *Mathematical model of DP vessel*

Kinematic and dynamic properties of DP vessel on the water, are described using a non-linear differential equations in three degrees of freedom taking into account the surge, sway and yaw motion. In this case it is possible to control independently the position components x, y and the rotation r of the ship by changing the angle of ship, bow position with respect to North. Other movements of the ship: rolling pitching and heaving can be omitted provided that the ship is stable laterally and longitudinally moves across the surface of the waters. In addition, at low speed the Coriolis force and centripetal also nonlinear hydrodynamic damping force can be neglected. Given the above assumptions, the mathematical model of ship motion in the horizontal plane is described by the following system of differential equations (Fossen 2002):

$$\frac{d\eta}{dt} = R(\psi)v, \tag{1}$$

$$M\frac{dv}{dt} + Dv = \tau \tag{2}$$

where: $\tau = [\tau_x, \tau_y, \tau_z]^T$ - generalized vector of forces and moment, provided by DP controller, $\eta=[x, y, \psi]^T$ - ship position and heading $0<\psi<2\pi$ of the ship in the earth-fixed frame, $v=[u, \mathrm{v}, r]^T$- linear velocities in surge, sway and angular velocity coordinated in the body fixed frame, $M\in R^{3x3}$, $D\in R^{3x3}$ and $R(\psi)\in R^{3x3}$ denotes respectively matrix of inertia, damping and the transformation matrix of the coordinate system associated with the center of gravity of the ship to the coordinate system with the fixed point of the earth. The rotation matrix $R(\psi)$ with the property $R^T= R^{-1}$ is given by:

$$R(\psi) = \begin{bmatrix} cos\psi & -sin\psi & 0 \\ sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

The first-order wave frequency (WF) part of motion is modeled as a second order linear system for each of the 3 DOF (i=1,2,3), producing signals added to the position and heading measurements.

$$h_i(s)=\frac{2\zeta_i\varpi_{0i}\sigma_i}{s^2+2\zeta_i\varpi_{0i}s+\varpi_{0i}^2} \tag{4}$$

where: ζ_i =0.1 - relative damping ratio, ϖ_{0i} = 0.65 rad/s - dominating wave frequency, σ_i=0.5 m. -wave intensity parameter.

Transmittance input signal is a white noise with zero mean. A simplified wave disturbances model is a linear approximation of the wave spectrum. The output of the transmittance is added to the measured signals - position and heading of the vessel in order to modelling an impact of high frequency component of the ship movement. Transmittance parameters define the significant wave height about Hs ≈ 3 m., which means sea state 5 degrees in the scale of Douglas. The above wave frequency model is widely used in the literature for the simulation tests and to study the observer properties of filtration and estimation.

2.2 *State observer*

The DP control system mostly assumes that only position and heading signals are available through the navigation measurement systems such as GPS, DGPS and gyro. In contrast, immeasurable ship speed which is necessary to derive control laws are estimated from the state observer. In the DP system (Fig. 2) the nonlinear passive observer was considered (Fossen et. al. 1999), which also makes filtering of high frequency wave disturbances.

2.3 *DP controller*

Nowadays, most of DP systems which are a part of the vessels equipment, use the classical PID algorithms to control the position and heading angle.

2.3.1 *Nonlinear PID*

After 1995, nonlinear PID control design have been applied (Fossen 2002) to DP systems with good results. The PID control concept can be generalized to nonlinear mechanical system by exploiting the kinematic equations of motion in the design (5):

$$\tau=-K_I R^T(\psi)\int_0^t(\eta-\eta_d)\,d\tau-K_p R^T(\psi)(\eta-\eta_d)-K_d R^T(\psi)\cdot\frac{d\eta}{dt} \tag{5}$$

In order to take advantages of the observer, the control law was implemented using the estimated states instead of the true one, due to the absence of required measurements, and because of the wave filtering. Thus, the last component of (5) was substituted by (1)

$$\tau=-K_I R^T(\psi)\int_0^t(\eta-\eta_d)\,d\tau-K_p R^T(\psi)(\eta-\eta_d)-K_d\nu \tag{6}$$

where K_I, K_P, K_d $\in R^{3x3}$ - matrixes of integral, proportional and derivative gains, illustrating the influence of individual components in three degrees of freedom; η - vector of estimated ship positions and heading, η_d - vector of desired variable, ν - vector of estimated ship velocities. The Figure 2 presents a block-diagram configuration of nonlinear PID (6).

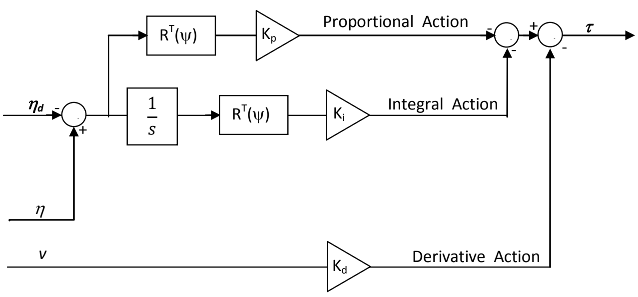

Figure 2. Block-diagram of PID (6).

In this figure the symbol 1/s denotes the Laplacea's form of integral operator.

2.3.2 *Fractional order PID*

All the classical types of PID controllers are the special cases of the fractional $PI^{\lambda}D^{\mu}$ controller involving an integrator of order λ and differentiator of order μ.

According to nonlinear PID controller (5) and fractional calculus the vector of control signals τ can then be expressed in the time domain as:

$$\tau=-K_I R^T(\psi)D_t^{-\lambda}(\eta-\eta_d)-K_p R^T(\psi)(\eta-\eta_d)-K_d R^T(\psi)\cdot D_t^{\mu}\eta \tag{7}$$

where $\lambda=[\lambda_x, \lambda_y, \lambda_\psi]>0$ is the vector of integral orders, $\mu=[\mu_x, \mu_y, \mu_\psi]>0$ is the vector of derivative orders. Here D^q (q=-λ, q=μ) is the differintegral operator with the fractional order q, combined differentiation-integration operator commonly used in fractional calculus. This operator is a notation for taking both the fractional derivative and the fractional integral in a single expression and is defined by (8)

$$D_t^q=\begin{cases}\dfrac{d^q}{dt^q} & q>0\\ 1 & q=1\\ \int_0^t(d\tau)^{-q} & q<0\end{cases} \tag{8}$$

Clearly, selecting λ = [1,1,1] and μ=[1,1,1], a nonlinear PID controller (5) can be recovered.

According to nonlinear PID controller (6) and fractional calculus the vector of control signals τ can then be expressed in the time domain as:

$$\tau=-K_I R^T(\psi)D_t^{-\lambda}(\eta-\eta_d)-K_p R^T(\psi)(\eta-\eta_d)-K_d\nu \tag{9}$$

The Figure 3 presents a block-diagram configuration of FOPID (9).

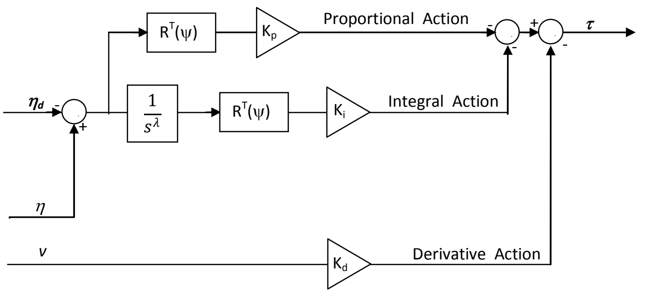

Figure 3. Block-diagram of FOPID (9).

The symbol $s^{-\lambda}$ denotes the Laplacea's form of fractional integral operator.

There are some definitions for fractional derivatives. The commonly used include Grunwald–Letnikov, Riemann–Liouville, and Caputo definitions (Podlubny 1999). Since most of the fractional-order differential equations do not have exact analytic solutions, so approximation and numerical techniques must be used. Several analytical and numerical methods have been proposed to solve the fractional-order differential equations. One of the best-known approximations is due to Oustaloup (Oustaloup 2000).The method based on approximating a fractional-order operator s^q, where $0 < q < 1$, in a specified frequency range $\omega = (\omega_b, \omega_h)$ and of order N.

Figure 4 presents an example of approximation of integrals of constant function in time. There was considered integral orders (λ = 0.1, 0.2, 0.3, 0.4, 0.6, 0.8,1), zero initial conditions, frequency range ω = (0.01, 1000) rad/s and order 5.

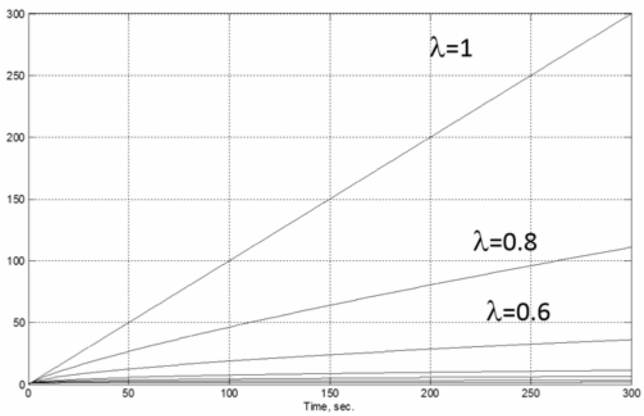

Figure 4. The approximation of integrals of constant function for different orders (λ = 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 1) in frequency range ω = (0.001, 1000) rad/s and of order 5.

3 SIMULATION TEST RESULTS

The mathematical model of supply vessel was used as a case study (Godhavn et. al. 1998) and nonlinear passive observer (Witkowska 2013). The vessel system matrices were given below.

$$M = \begin{bmatrix} 1.1274 & 0 & 0 \\ 0 & 1.8902 & -0.0744 \\ 0 & -0.0744 & 0.1278 \end{bmatrix} \tag{9}$$

$$D = \begin{bmatrix} 0.0358 & 0 & 0 \\ 0 & 0.1183 & -0.000124 \\ 0 & -0.000041 & 0.0308 \end{bmatrix} \tag{10}$$

A model of supply vessel was used to illustrate the performance of DP system (Fig. 1.) with fractional order PID controllers (7), (9). For this purpose the FOMCON toolbox for Matlab was used for simulations. The FOMCON toolbox allow us to implement, simulate and analyze FOPID controllers easily via its functions. Also in this library, one can find the *Fractional PID* block which implements FOPID controllers in Simulink. In fractional order PID controller there the only aproximation of differintegral operator s^q was needed with specified frequency range and order. In the simulation studies the Oustaloup method was assumed within the frequency range (0.01, 1000) rad/s and the number of zeros and poles sited to 5. Simulations were carried out in time domain.

The simulation tests aim at checking the operation correctness of DP system with fractional PID controllers (7) and (9) in comparison with classical PID controller (5) tuned by GA. During a simulation tests the initial conditions were chosen as: $\eta(t_0)=(0,0,0)$, $\nu(t_0)=(0,0,0)$ and the initial values of all estimates were set as zero. Desired position and orientation were set as $\eta_d(t)=(5, 5, 0)$. The simulation studies were carried out in the presence of wave disturbances (4). The amplitudes of the wave were set as 2 m., 2 m., 3^0 respectively for surge, sway and yaw direction.

Figure 5 presents ship trajectory in DP system with PID (6) and FOPID (9) controllers and for different vectors λ. As can see the changes of integral orders have an significant influence on ship position and heading changes.

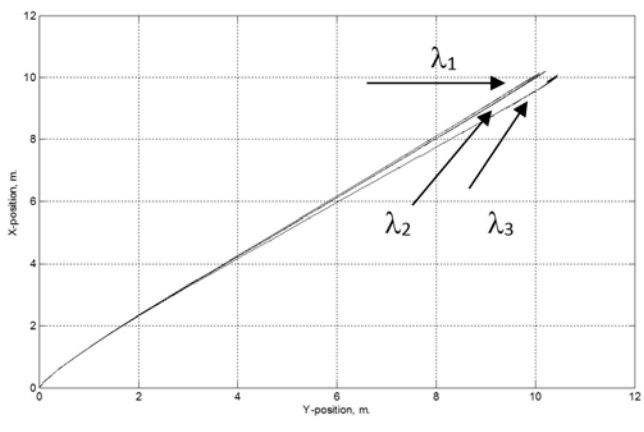

Figure 5. Ship trajectory in DP system for different integral orders (λ_1 = [0.1,0.1,0.1], λ_2 = [1,1,1], λ_3 = [0.5,0.3,0.1]).

The parameters of classical PID controller were tuned by GA method and received parameters were next sited for fractional controllers. Thus only vector of integrator orders λ and differentiator orders μwere finally selected. Such an approach is commonly used in the literature. The controller parameters were collected in Table1. It can be noted that FOPID controller described by equation (9) has been reduced to PD controller.

Table 1. Set parameters

Parameter	Value[-]	Controllers
K_p	(10)^4*[2*2.0213 0 0; 0 2* 1.700990 0; 0 0 2000.49]	PID, FOPID(7),
K_d	(10)^8*[0.0207 0 0; 0 0.0155 0.0439; 0 0.0439 4.05]	FOPID(9)
K_I	(10)^2*[1.01274 0 0; 0 0.8902 0; 0 0 0.1278]	
λ	[1,1,0]	FOPID (9)
λ	[0.93333, 0. 7333, 0.86667]	FOPID (7)
μ	[1 1 0]	

Figures 6-9 present time-series of ship position and heading, estimated and measured velocities, forces and moments acting on a hull and ship trajectory in DP system with controllers with (6), (7), (9) after tuning (PID (6) - black solid line, FOPID (7) - grey line, FOPID (9) - black dotted line).

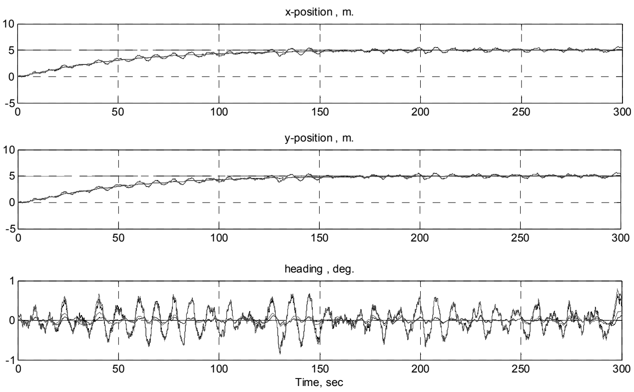

Figure 6. Measured and filtered position and heading in DP system (PID (6) - black solid line, FOPID (7) - grey line - only measured, FOPID (9) - black dotted line).

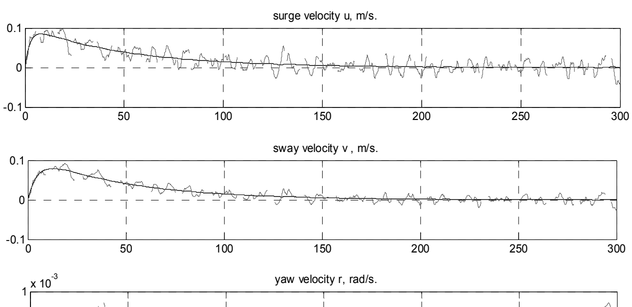

Figure 7. Estimated and measured surge, sway and yaw velocities in DP system (PID (6) - black solid line, FOPID (7) - grey line, FOPID (9) - black dotted line).

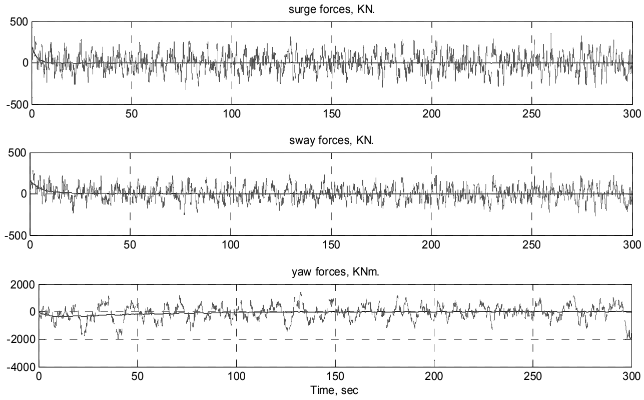

Figure 8. Forces and moments in surge, sway and yaw direction in DP system (PID (6) - black solid line, FOPID (7) - grey line, FOPID (9) - black dotted line)

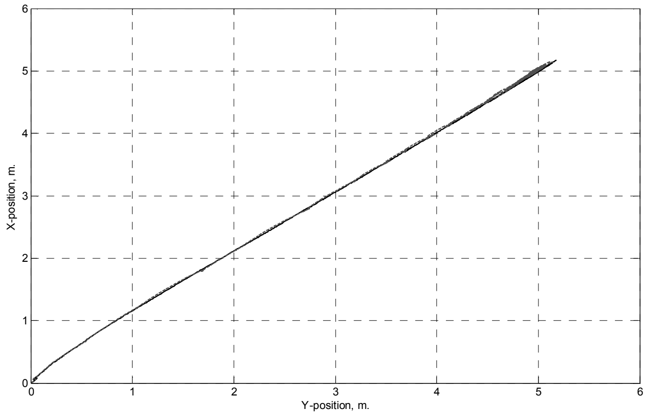

Figure 9. Ship trajectory in DP system (PID (6) - black solid line, FOPID (7) - grey line, FOPID (9) - black dotted line).

The computer simulations shown in Figure 6 present the convergence of position and heading to their desired values. The time-histories confirm a good ability of all controllers to keep fixed position and heading. In comparison with PID (6), the FOPID (7), (9) methods gives close time quality coefficients of position and heading such as rise time, and time control.

The surge, sway velocities and yaw angle (Fig. 7) were estimated from observer considering (6) and (9) control laws other than (7) where the information about velocities was calculated from position and heading introducing undesirable oscillations. Not including the observer in the equation (7) is also the reason of disturbed forces and moment signals (Fig. 8) and ship trajectory (Fig. 9) in contrast to the smooth forces and moment signals received from (6) and (9) control laws.

4 CONCLUSIONS

PID control method has been a widely used control technique due to its practicality and suitability for a large class of systems which are linear or nonlinear. The paper present covers the integer order case and the preliminary studies extends for the use of FOPID technique in classical (no fractional order) DP system. Two cases were considered. The first case FOPID include only integrator because of the need to use the information about estimated velocities from the observer. For this case when we used none fractional DP system with observer, the results have not substantially improved. It can be noted that fractional controller has been reduced to classical PD controller. The second case assumed the DP system without observer. For this case two integrator and differentiator were tuned, the results have been worse in comparison with classical PID controller.

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