DINCON 2017
CONFERÊNCIA BRASILEIRA DE DINÂMICA, CONTROLE E APLICAÇÕES
30 de outubro a 01 de novembro de 2017 – São José do Rio Preto/SP

Feedback Linearization Controllers for ROV Depth Control

Marcella P. Lazar[1]
Engenharia Elétrica, UNIFOR - Universidade de Fortaleza, CE
J. E. Bessa Maia[2]
Ciência da Computação, UECE - Universidade Estadual do Ceará, Fortaleza, CE
Engenharia Elétrica, UNIFOR - Universidade de Fortaleza, CE

Resumo. The nonlinear differential equation describing the depth dynamics of remotely operated underwater vehicles (ROV) is linearized by feedback and linear controllers are developed and evaluated by a realistic simulation. Considering two important performance criteria for depth control of ROVs, which are overshoot and settling time, the experiments show satisfactory performance for these controllers. However, some drawbacks are recorded which can drive new controller design approaches.

Palavras-chave. Feedback Linearization, Remotely Operated Underwater Vehicle (ROV), Linear Control.

1 Introduction

The remotely operated vehicles (ROVs) found applications ranging from oil prospecting and inspection of underwater oil derricks to exploration of sea resources. Their development has been motivated by the the enormous risk to life with working under water and the high cost of human divers.

The modeling and control of these vehicles are challenging tasks because they are nonlinear systems operating in heterogeneous environments subject to critical operational restrictions. The equations of motion for underwater vehicles with respect to the body-fixed reference frame, can be expressed in the following vectorial form [1]:

$$\mathbf{M}\dot{\nu} + \mathbf{k}(\nu) + \mathbf{h}(\nu) + \mathbf{g}(\mathbf{x}) + \mathbf{d} = \tau \tag{1}$$

where $\nu = [v_x, v_y, v_z, \omega_x, \omega_y, \omega_z]$ is the vector of linear and angular velocities in the body-fixed reference frame, $\mathbf{x} = [x, y, z, \alpha, \beta, \gamma]$ represents the position and orientation with respect to the inertial reference frame, $\mathbf{M}$ is the inertia matrix, which accounts not only for the rigid-body inertia but also for the so-called hydrodynamic added inertia, $\mathbf{k}(\nu)$

[1]marcellaplazar@edu.unifor.br, Bolsista do Programa PRH-53 da Agência Nacional do Petróleo (ANP)
[2]jose.maia@uece.br

is the vector of generalized Coriolis and centrifugal forces, $\mathbf{h}(\nu)$ represents the hydrodynamic quadratic damping, $\mathbf{g}(\mathbf{x})$ is the vector of generalized restoring forces (gravity and buoyancy), $\mathbf{d}$ stands for occasional disturbances, and τ is the vector of control forces and moments. A dot on a variable represents its derivative.

It should be noted that in the case of remotely operated underwater vehicles (ROV), the metacentric height is sufficiently large to provide the self-stabilization of roll (α) and pitch (β) angles. This particular constructive aspect also allows the order of the dynamic model to be reduced to four degrees of freedom, $\mathbf{x} = [x, y, z, \gamma]$, and the vertical motion (heave) to be decoupled from the motion in the horizontal plane.

For low relative velocities, taking advantage of the decoupling characteristics, and noting that the quadratic damping can be written as $c\dot{z}\,|\dot{z}|$, the differential equation governing a ROV's depth dynamics (z-axis) can be written as [2]

$$m\ddot{z} + c\dot{z}\,|\dot{z}| + g + d = u \tag{2}$$

where u is the thrust force, the control input, d the disturbance caused by external forces, c the coefficient of the hydrodynamic quadratic damping, m represents vehicle's mass plus the hydrodynamic added mass and $g = -(W - B)$ is the restoring force given by the difference of the gravitational W and buoyant forces B. In the following the restoring forces are in equilibrium, making $g = 0$. Under this condition, Equation 2 is used as the dynamic model of the plant for the controllers' design.

As can be seen on Equation 2, the plant's dynamic model presents nonlinearities. An important approach, namely feedback linearization, can be applied in this equation in order to transform this nonlinear dynamics into a fully or partly linear one. As a result, linear control techniques can be applied on the linearized model [3]. This paper is organized as follows. Section 2 presents the feedback linearization controllers for depth control of ROVs. In Section 3 the results of the simulation performance are presented and discussed. The conclusion is in Section 4.

2 The Controllers Design

This section briefly describes the design of PID, Pole Placement (PP) and LQR controllers. The project goals in this work were: maximum overshoot at 1%, null steady error and vertical velocity limited at 0.5 m/s for SIRI, 0.2 m/s for RRC and 0.6 m/s for NEROV. In each case it is desirable to obtain minimum settling time (t_s). The standard operating condition considered is the response to a step test input of 8 m, for which settling time of around 50 seconds is considered satisfactory. The experiments were repeated for three ratios of values of m and c present in the literature: m = 180 kg and c = 150 kg/m, from NEROV ROV [8], m = 115 kg and c = 104,4 kg/m, from RRC ROV [7] and m = 123,275 kg and c = 72,5 kg/m, from SIRI ROV. The maximum force of the thruster in each ROV are equal to 9.8 kgF, 4.5 kgF and 3.0 kgF for SIRI, RRC and NEROV, respectively. SIRI is a ROV designed at ARMTEC tecnologia em robótica [10].

As will be noted below, it is not possible to reach these specifications, without saturation, with only the second order Linearization Controller (FLC). Thus, the strategy in this work was to get an initial approximation of the specifications with the FL Controller and then design an additional controller to meet the specifications. In addition, the steady error and unmeasured and slowly varying or constant disturbances are compensated for by including integral action in the controllers. This approach is reflected in Figure 1.

2.1 Feedback Linearization Controller

With regard to the application of this technique on the proposed system, consider a class of nth-order nonlinear systems, with it dynamics represented in the companion form:

$$x^{(n)} = f(\mathbf{x}, t) + b(\mathbf{x}, t)u + d \tag{3}$$

where the control input is defined by u, the scalar variable x is the output of interest, $x^{(n)}$ is the n-th time derivative of x, $\mathbf{x} = \left[x, \dot{x}, ..., x^{(n-1)}\right]$ is the system state vector, $f, b : R^n \to R$ are both nonlinear functions of the states and d is assumed to represent all uncertainties and unmodeled dynamics regarding system dynamics, as well as any external disturbance that can arise [4].

With the aim of tracking a desired trajectory $\mathbf{x}_d = \left[x_d, \dot{x_d}, ..., x_d^{(n-1)}\right]$, is necessary to formalize a control law that assure the exponentially convergent tracking, i.e. that $\tilde{\mathbf{x}} \to 0$ as $t \to \infty$, where the related tracking error is $\tilde{\mathbf{x}} = \mathbf{x}_d - \mathbf{x} = \left[\tilde{x}, \dot{\tilde{x}}, ..., \tilde{x}^{(n-1)}\right]$.

Thus, a simplified control law can be obtained assuming that: the state vector x is available to be measured, the functions f and b are well known, with $|b\left(\mathbf{x}, t\right)| > 0$ and the system dynamics is perfectly known, leading to no external disturbance ($d = 0$) nor modeling imprecision [4]. Hence, the nonlinearities can be canceled by using the control input as:

$$u = b^{-1}\left(-f + x_d^{(n)} - k_0\tilde{x} - k_1\dot{\tilde{x}} - ... - k_{n-1}\tilde{x}^{(n-1)}\right) \tag{4}$$

This input ensure that $\mathbf{x} \to \mathbf{x}_d$ as $t \to \infty$, if the coeficients $k_i, i = 0, 1, ..., n-1$ make the polynomial $p^n + k_{n-1}p^{n-1} + ... + k_0$ a Hurwitz polynomial, i.e with all its roots allocated in the left-half complex plane [3].

The convergence of the closed-loop system could be easily established by substituting the control law (4) in the nonlinear system (3). The resulting dynamical system could be rewritten by means of the tracking error: $\tilde{x}^{(n)} + k_{n-1}\tilde{x}^{(n-1)} + ... + k_1\dot{\tilde{x}} + k_0\tilde{x} = 0$, where the related characteristic polynomial is Hurwitz.

Now, to apply the above-mentioned approach in order to control vertically a remotely operated vehicle, a few reasonable and ordinary assumptions need to be made, regarding the vertical dynamic model (Equation 2). First, as assumed on [6], the added mass is independent of the wave frequency, which implies that $\mathbf{M}$ in (1) has it first derivative null, i.e. $\dot{\mathbf{M}} = 0$ and $\mathbf{M} = \mathbf{M}^T > 0$. Second, the center of gravity and center of buoyancy are coincident, which leads to $g = 0$. Third, the origin of the body fixed coordinate system coincides with the center of gravity. Fourth, the vehicle is initially at rest, oriented in conformity with the inertial frame ($\phi = \theta = \varphi = 0$) [2]. Finally, the parameters c and d are both unknown but bounded, as also adopted on [1].

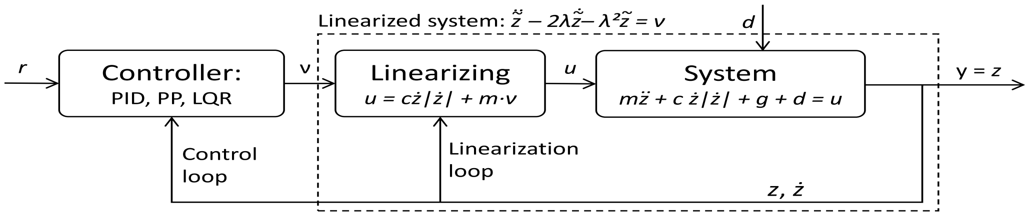


Figure 1: Feedback Linearization Controller block diagram.

Thus, in order to cancel the nonlinearities of the model, arbitrating that the system is critically damped ($\zeta = 1$) with poles in $-\lambda$, the control law can be designed as:

$$u = c\dot{z}\,|\dot{z}| + m\left(\ddot{z}_d - 2\lambda\dot{\tilde{z}} - \lambda^2\tilde{z}\right) \tag{5}$$

where λ is a positive constant, which guarantees the exponential convergence to zero. Finally, the closed-loop system dynamics is: $\ddot{\tilde{z}} + 2\lambda\dot{\tilde{z}} + \lambda^2\tilde{z} = 0$. Then, the state-space dynamic representation, $\dot{\mathbf{x}} = A\mathbf{x} + \mathbf{B}u$, can be written as (where $\tau_1 = \dot{\tilde{z}}$ and $\tau_2 = \ddot{\tilde{z}}$):

$$\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\lambda^2 & -2\lambda \end{bmatrix} \begin{bmatrix} \tilde{z} \\ \dot{\tilde{z}} \end{bmatrix} + \begin{bmatrix} 0 \\ 1/m \end{bmatrix} [u] \tag{6}$$

Note that for the output equation $\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}u$, $\mathbf{C} = [1\ 0]$ and $\mathbf{D} = \mathbf{0}$

The Figure 1 presents the block diagram of feedback linearization control to this system. The controller block design will be developed in the following subsections. Considerations regarding the physical dynamics and the thruster limitation led us to fix $\lambda = 0.1$. Simulation studies, not shown by space constraint, show that there is no saturation in $u(t)$ or in $\dot{z}$ for input steps of up to 3.0 m amplitude.

The design is based on the measurement of depth z and vertical velocity $\dot{z}$, two variables normally measured in ROVs for which accessible sensors are available. Although feedback linearization represents a very simple approach, an important disadvantage is the requirement of a perfectly known dynamical system, i.e., full state measurement, in order to ensure the exponential convergence of the tracking error.

2.2 PID controller

The major control system on industry field operates with a PI and PID controllers, since they aim to reduce the system's error based on the difference between the expected input and the measured output. As stated before, the error is defined as $\tilde{x}$, so, generic PID control action can be represented as follows [9]:

$$u = k_P\left[\tilde{x} + \frac{1}{T_i}\int \tilde{x}dt + T_d\dot{\tilde{x}}\right] \tag{7}$$

Where k_P is the proportional gain, $k_i * \frac{1}{T_i}$ is the integral gain, $k_D = k_P * T_d$ is the derivative gain and T_i and T_d are, respectively, the integral time and derivative time.

Among methods used to tuning PID parameters from the system response, there are Ziegler-Nichols and Cohen-Coon [9]. In this paper, it is used Ziegler-Nichols first method, in which is analyzed the step-response and then obtained parameters L, representing time delay, and time constant τ. With those values in hand, K_P, K_I and K_D gains can be respectively calculated according to [9]:$K_P = 1.2 * \frac{\tau}{L}$, $T_i = \frac{1}{2L}$ and $T_d = 0.5 * L$. The K values obtained by the Ziegler-Nichols method were further refined using the matlab tool. As a result, after applying this method to each ROV, the PID parameters estimated are exposed on Table 1.

2.3 PP controller

The pole placement control is a linear strategy that allows the designer to impose a desired system's dynamics from the determination of the poles of the closed-loop system. An advantage of this control technique is that the system's stability can be guarantee, since all poles can be allocated in the left-half complex plane by applying a state feedback with an appropriate gain matrix [6]. Given that the ROV's depth dynamics with the Feedback Linearization Controller included do not have an pure integrator it is necessary to increase the representation of the plant as in Equation 8:

$$\mathbf{Aa} = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ -\mathbf{C} & 0 \end{bmatrix}, \quad \mathbf{Ba} = \begin{bmatrix} \mathbf{B} \\ 0 \end{bmatrix}. \tag{8}$$

After, K feedback gains can be calculated, regarding the desired pole positions. Through simulation exercises the location of poles for ROVs, meeting design specifications and avoiding saturation of physical limitations, resulted in: $[-0.625\ \ -0.675\ \ -38.20]$ for SIRI, RRC and NEROV.The values of the K gains are in Table 1.

2.4 LQR controller

The LQR control can be roughly described as a systematic way to obtain K matrix. After eliminating the steady state error, by using the same plant calculated by the aforementioned standard equations, the objective of this control strategy turns to be the determination of feedback $\mathbf{k}$ matrix so that the index of performance,

$$J = \int_0^\infty \left(\mathbf{x}'\mathbf{Q}\mathbf{x} + u'\mathbf{R}u\right) dt \tag{9}$$

is forced to be minimum [6]. In this function, $\mathbf{Q}$ and $\mathbf{R}$ matrices define the importance of the error and the cost of energy and u is the control signal defined as $u = -\mathbf{kx}$ [5]. The value of the gain vector $\mathbf{k}$ that minimizes the index (9) is obtained in two steps. First, solve the Reduced Algebraic Riccati Equation (10) to obtain the symmetric matrix $\mathbf{P}$. Then $\mathbf{k}$ is calculated by the formula $\mathbf{k} = \mathbf{R}^{-1}\mathbf{B}'\mathbf{P}$.

$$\mathbf{A}'\mathbf{P} + \mathbf{PA} - \mathbf{PB}^{-1}\mathbf{B}'\mathbf{P} + \mathbf{Q} = \mathbf{0}. \tag{10}$$

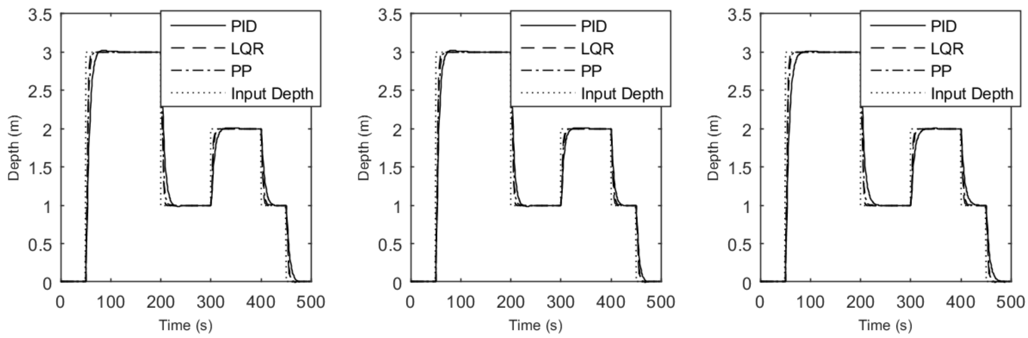
Then, is necessary to find the appropriate values for $\mathbf{Q}$ and $\mathbf{R}$ matrices. This is done without reference to any criterion, because there is no methodology or stepwise to obtain such matrices [5]. Therefore, values for **Q** and **R** were tested on simulations by analyzing the change of the behavior of ROV's dynamic parameters, such as, settling time and overshoot, until the time when the variables determining the vertical movement of the underwater vehicle were controlled. The values of the K gains are in Table 1.

	PID			PP			LQR		
	SIRI	RRC	NErov	SIRI	RRC	NErov	SIRI	RRC	NErov
$K_1(K_p)$	.613	.316	.915	.610	.520	.620	.905	.911	.706
$K_2(K_d)$	.206	.221	.022	.010	.020	.020	.002	.007	.004
K_i	.233	.295	.296	.505	.652	.050	.052	.756	.950
$t_s(s)$	56.2	61.9	58.5	59.4	63.2	56.3	58.1	63.5	60.4

Table 1: Results of controllers' projects.

3 Results and Discussion

The effectiveness of the three designed control strategies was simulated considering Gaussian measurement disturbance with mean zero and variance equal to 25% of the measured maximum value added to the position value. Thus, it was simulated the performance of those control strategies for each ROV, SIRI, RRC and NEROV, on tracking a trajectory with different depth set points. As can be seen from Figure 2 and Table 1, the



(a) SIRI ROV (b) RRC ROV (c) NEROV ROV

Figure 2: Results for the controlled system.

results for the three linear controllers are very similar when viewed on an extended time scale. The interpretation is the constraints of the project left little room for differentiation enter the linear controllers. Note also that this approach is dependent on the proper functioning of feedback linearization.

Two limitations to the controller determine these results: the maximum speed, which is a design specification originated from the application, and the maximum power of the propellers that a constructive limit related to the cost, weight or geometry of the vehicle.

The main drawback of the feedback linearization approach is the need for accurate model knowledge in addition to accuracy in depth and velocity measurements.

4 Conclusion

Feedback linearization was applied to the dynamic model of ROVs to support the design of linear controllers. The design of the PID, PP and LQR controllers was restricted to meeting the specifications of 1 % of maximum overshoot, null stationary error and vertical velocity limited, seeking the minimum settling time. The simulations showed that it was possible to tune up satisfactory controllers and the PP controller obtained settling time slightly better. The simulations included effects of disturbances representing measurement noise and imprecision in the model. The continuation of this study, which is underway, is the comparison with non-linear controllers.

References

[1] W. M. Bessa, M. S. Dutra, E. Kreuzer, An adaptive fuzzy sliding mode controller for remotely operated underwater vehicles, RAS, vol. 58, pp. 16-26, (2010).

[2] S. M. Zanoli, G. Conte, Remotely operated vehicle depth control. Control engineering practice, v. 11, n. 4, p. 453-459, (2003).

[3] J. J. E. Slotine, W. Li, Applied Nonlinear Control. Prentice Hall, New Jersey, (1991).

[4] M. C. Tanaka, J. Maria, D. M. Fernandes, W. M. Bessa, Fuzzy Feedback Linearization with Applications to the Control of Mechanical Systems, Proc. XVII Int. Symp. on Dynamic Problems of Mechanics, (2015).

[5] S. Rodriguez, M. Pena, and R. Ramirez, Dynamic control design LQR PI vectorial of remotely operated underwater vehicle,3rd International Congress of Engineering Mechatronics and Automation, (2014).

[6] T. I. Fossen, C. G. Källström, Guidance and control of ocean vehicles, Wiley, (1994).

[7] C. Chin, Systematic modeling and model-based simulation of a remotely operated vehicle using matlab and simulink, International Journal of Modeling, Simulation, and Scientific Computing, v. 2, n. 04, p. 481-511, (2011).

[8] T. I. Fossen, Nonlinear Modeling and Control of Uderwater Vehicles, Master's Dissertation in Engineering Cybernetics, Norwegian Institute of Technology (1987).

[9] K. J. Åström, T. Hägglund, Advanced PID Control, Research Triangle Park, NC: Instrumentation, Systems, and Automation Society, 2006.

[10] ARMTEC TECNOLOGIA EM ROBÓTICA (Brasil) (Org.). Rel. de desenvolvimento SIRI.V1.0: Submarino Integrado para Resgate e Investigação. Fortaleza, 72 p., (2016).