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Output Control Algorithms of Dynamic Positioning and Disturbance Rejection for Robotic Vessel ⋆

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Abstract:
In this paper two control problems for a surface robotic vessel are addressed. One is design of a dynamic positioning (DP) system. The other deals with advanced dynamic positioning (ADP) which is extended by an unknown disturbance rejection. Considered plant is represented as a MIMO system which comprised of three independent SISO channels. For the DP problem all SISO channels are controlled by virtual control inputs generated using a robust approach, so called, "consecutive compensator". Then after an inverse MIMO transformation real control signals are calculated for robotic actuators. For the APD problem we design the cancellation scheme for channels with input delays that may be caused by a command transmission via the radio channel or computational complexity of the image processing. To finalize the investigation proposed DP algorithm is applied to the robotic complex of vessel motion modeling.

Keywords: Output control; Robust control; Nonlinear systems, MIMO.

1. INTRODUCTION

This project is devoted to a design the control system for robotic vessel and testing it on the real equipment. There are two fundamental studies in the article. The first one is the dynamic positioning (DP) system that provides stabilization of the plant in the desired point (linear coordinates x and y) with the specified orientation (the heading z). And the other one is an advanced dynamic positioning (ADP) which is extended by unknown disturbance rejection.

For DP problem it is possible to apply any control approach appropriate for an uncertain nonlinear system, (see, e.g. Freidovich and Khalil (2007); Khalil (1999); Kokotovic and Arcak (2001); Krstic and Kokotovic (1996); Krstic (2010); Park et al. (2010); Rusnak (2011); Zhang (2009)). In this work we use a robust output principle "consecutive compensator" that was considered in Bobtsov (2005 a,b); Bobtsov and Nikolaev (2005); Bobtsov et al. (2007).

In works Bobtsov (2005 a); Bobtsov and Nikolaev (2005); Bobtsov et al. (2007) models consisting of a linear part with unknown parameters and a static nonlinear block are considered. Pacification approach (see Fradkov (1974, 2003)) is in the basis of proposed method. The controller has a simple structure and can be implemented as a proportional feedback providing strictly positive realness of the closed-loop system. In this sense developed algorithm is very close to results introduced in Barkana (1987, 2004); Kaufman et al. (1998), but with weaker requirements for the plant. Specifically, it is known that almost strictly positive realness property is equal to hyper minimum phaseness Andrievsky et al. (1994). In turn Hurwitz numerator of the transfer function is proved to be sufficient condition for our algorithm application in SISO case. Thus, we extended the approach for open-loop unstable systems with an arbitrary relative degree of the linear part. It

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became allowable owing to the development of the linear filter of a special structure.

2. ROBOTIC VESSEL COMPLEX

The robotic vessel complex (shown in Fig. 1) has been constructed to develop fundamental study of the controller design for a class of MIMO robotic systems. It is comprised of a special pool, digital camera (for computer vision), vessel model, PC, and joystick (for remote control). Connection between the vessel model and PC is provided by a radio channel. The proper computer vision is realized by a digital camera attached to a tripod above the pool. On real vessels the task of coordinates determination is accomplished, as usual, by satellite navigation systems and gyrocompasses. PC ensures all calculations and control signal forming and then it transmits obtained data to the vessel by the already mentioned radio channel.

An appearance of the vessel model is shown in Fig. 1. It has three actuators. The first one is the main engine thrust, where the propeller is located in the rotatable steering nozzle. The second and third ones are the bow and stern thrusters.

Algorithm of computer vision through digital camera captures the model as white rectangle and detects its orientation (angle coordinate z) in accordance to the red bow.

Fig. 1. The robotic vessel complex and an appearance of the vessel model

It is known that typical surface vessel can be represented as MIMO system since it consists of three independent channels of linear coordinates x and y and the heading z Fossen (2002, 2011). So, let us start from the corresponding mathematical description of MIMO systems control applied to investigated robotic plant.

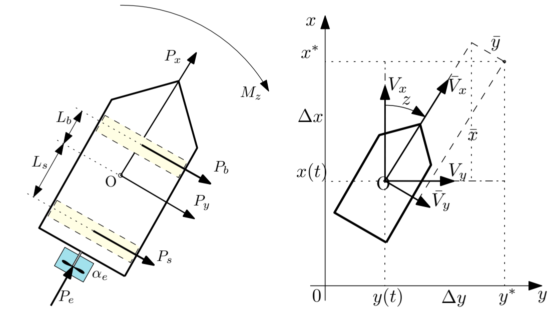
3. PROBLEM FORMULATION

Consider the actuator configuration of the vessel shown in Fig. 2a. P_e is the main engine thrust, where the propeller is located in the rotatable steering nozzle, P_b is the bow thruster, and P_s is the stern thruster.

Then the MIMO model of the vessel becomes

$$\begin{cases} x = F\left(P_e, P_b, \alpha_e, P_s\right), \\ y = G\left(P_e, P_b, \alpha_e, P_s\right), \\ z = H\left(P_e, P_b, \alpha_e, P_s\right), \end{cases} \tag{1}$$

where the longitudinal coordinate x, transversal coordinate y, and heading z are the output variables; P_e, P_b, and P_s are the input actuators; $F(\cdot)$, $G(\cdot)$, and $H(\cdot)$ are



(a) Actuator configuration of the vessel and generalized forces (b) Coordinate systems and coordinates

Fig. 2. Schemes of the vessel

nonlinear differential operators, α_e is steering value which will be avoided (fixed) in our control because the small scale of the workspace does not allow to use it since a large radius occurs upon turning motion. Instead of it the bow and stern thrusters will be used to rotate the boat.

Let us to decompose the nonlinear dynamic model on a static MIMO function and independent SISO dynamical channels. Each channel will be assigned with the corresponding output variable x, y, or z. For every channel we will introduce virtual control inputs of the longitudinal force P_x, transversal force P_y, and moment of turn M_z (see Fig. 2a), which represent superposition of all real actuators forces.

So, perform the decomposition and write the expression for the result forces applied to the center of mass

$$\begin{cases} P_x = P_e, \\ P_y = P_b + P_s, \\ M_z = -\alpha_e P_e L_e + P_b L_b - P_s L_s, \end{cases} \tag{2}$$

where P_x, P_y, and M_z are applied force and result moment, L_e is a distance from the center of mass to the engine, L_b is a distance from the center of mass to the bow thruster, and L_s is a distance from the center of mass to the stern thruster.

Since we have done the decomposition, let us consider a particular mathematical model of the vessel. According to the linearized 1st order ship model Nomoto, the coordinates of the vessel satisfy the following differential equations

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} + \begin{bmatrix} \cos(z) & -\sin(z) \\ \sin(z) & \cos(z) \end{bmatrix} \begin{bmatrix} \bar{x} \\ \bar{y} \end{bmatrix}, \tag{3}$$

$$\ddot{\bar{x}}\left(t\right) = \frac{1}{T_x}\left(-\dot{\bar{x}}\left(t\right) + k_x P_x\left(t\right)\right), \tag{4}$$

$$\ddot{\bar{y}}\left(t\right) = \frac{1}{T_y}\left(-\dot{\bar{y}}\left(t\right) + k_y P_y\left(t\right)\right), \tag{5}$$

$$\ddot{z}\left(t\right) = \frac{1}{T_z}\left(-\dot{z}\left(t\right) + k_z M_z\left(t\right)\right), \tag{6}$$

where x_0, y_0 are the initial point, $\bar{x}$ and $\bar{y}$ denotes the offsets in longitudinal and transversal directions in the system coordinates assigned with the ship (Fig. 2b), k_x, k_y, k_z are the transfer coefficients, and T_x, T_y, T_z are the time constants of each channel. These parameters may be unknown.