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Visual Image Based Dynamical Positioning Using Control Laws with Multipurpose Structure

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Abstract: Dynamic positioning systems are widely used now to support marine operations of various types. In this paper the problem of dynamic positioning using nonlinear visual feedback control with special multipurpose structure is considered. The control objective is to stabilize the difference between given and actual position of the observed visual points in the image plane. The additional complexity of the problem is determined by presence of external disturbances, such as waves and wind. In this paper joint mathematical model of a ship and screen image dynamic is obtained. Using special unified multipurpose structure of control law, mentioned problem is decoupled into particular separated problems. The resulting nonlinear controller provides asymptotic stability and desirable dynamic properties of the closed-loop system regarding external disturbances.

Keywords: dynamical positioning, control law, visual control, stability, external disturbances.

1. INTRODUCTION

Dynamical positioning (DP) systems are widely used for the various types of marine vessels in different areas such as hydrography, inspection of marine construction, wreck investigation, underwater cable laying, and so on. The exhaustive survey of DP control systems is done in Sørensen, 2011. Some central theoretical and practical issues providing basic background of DP control are presented in Fossen, 1994 and 2011, Sørensen, 2012.

The mathematical validation for the special structure of DP nonlinear control laws on the base of nonlinear asymptotic observers is given in Fossen and Strand, 1999, Loria, Fossen, and Panteley, 2000. In these papers sufficient conditions of the global asymptotic stability are derived and the possibility of independent tuning for observers and state space control laws is proven by analogy with a separation principle for LTI systems.

The alternative approach to DP control systems design is the theory of multi-purposes control laws synthesis, which was presented in Veremei and Korchanov, 1989. Central ideas of this approach are reflected on the modern level in Veremey, 2010 and 2013, Sotnikova and Veremey, 2013. The multi-purpose control laws synthesis is based on the optimization methods with the goal to raise the effectiveness and quality level of the systems to be designed.

The special multipurpose structure includes some basic part and several separate elements to be adjusted for the specified conditions of a vessel motion. These elements can be switched on or off as needed to provide the best dynamical behaviour. The main adjustable element of the structure is so called dynamical corrector. This term of control law provides an integral action of the controller and a notch filtering effect.

The dynamical corrector synthesis is based on the ideas of H-optimization theory. Correspondent mathematical background for LTI marine autopilot design was discussed in Veremey, 2012.

In this paper we design nonlinear visual feedback control law for DP problem. We consider that the DP vessel is equipped with a camera. The control objective is stabilizing the difference between actual and given positions of the observed visual 3D points in the image plane. The proposed control design algorithm is based on the multipurpose structure and includes two stages. At first stage we find visual feedback control for the image plane and obtain correspondent desired camera and DP vessel motion. At the second stage the control law for given camera velocity tracking by DP platform is designed. The resulting controller provides closed-loop system asymptotic stability and desirable system dynamics in the presence of external disturbances.

2. MODELS OF SHIP AND SCREEN IMAGE

Let introduce two coordinate frames. First frame $Ox_s y_s z_s$ is attached to DP vessel and its axes have usual directions as described in Fossen, 1994. The second coordinate frame $OXYZ$ is attached to the camera and its axes are directed as follows: axis OZ coincide with optical axis of a camera and axis Ox_s, axes OX and OY are in the normalized image plane of the camera and their directions are the same as for the axes Oy_s and Oz_s correspondently (Szeliski, 2011). We will consider that the origin for both coordinates' frames is the same. The camera is fixed on board of the DP vessel and can rotate only together with the vessel.

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Let consider a traditional nonlinear 3DOF model of a DP vessel in the following form

$$\mathbf{M}\dot{\mathbf{v}} = -\mathbf{D}\mathbf{v} + \boldsymbol{\tau} + \mathbf{d}(t),\quad \dot{\boldsymbol{\eta}} = \mathbf{R}(\boldsymbol{\eta})\mathbf{v}, \tag{1}$$

where the vector $\mathbf{v} = (u\ v\ p)^T$ represents velocities in a vessel-fixed frame, $\boldsymbol{\eta} = (x\ y\ \psi)^T$ is a joint position (x, y) and a heading angle ψ vector relative to an Earth-fixed frame. Vector $\boldsymbol{\tau} \in E^3$ implies a control action generated by the propulsion system, vector $\mathbf{d} \in R^3$ is provided by the external disturbances of any nature. Matrices $\mathbf{M}$ and $\mathbf{D}$ with the constant elements are positive definite, $\mathbf{M} = \mathbf{M}^T$.

The only nonlinearity of the system (1) is determined by the yaw angle orthogonal rotation matrix

$$\mathbf{R}(\boldsymbol{\eta}) = \mathbf{R}(\psi) = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{2}$$

Let us take into account that usually measurements of the vessel velocities are not available for DP automatic system, so any control law must be designed only on the base of position and heading measurements.

Now let describe the dynamic in the image plane. To this end, consider a 3D point $P(X_p, Y_p, Z_p)$ representing, for example, some point on the surface of the observed landmark or object of interest. The corresponding image plane point $\boldsymbol{p}$ coordinates is given by:

$$x_p = \frac{X_p}{Z_p},\ y_p = \frac{Y_p}{Z_p}. \tag{3}$$

Such point can be extracted and tracked in video sequence using SIFT detector (Lowe, 2004). Using theoretical mechanics (Chaumette, 2006) we get following equations for the relative motion between camera (DP vessel) and 3D space point:

$$\dot{X}_p = -v - rZ_p,\quad \dot{Y}_p = 0,\quad \dot{Z}_p = -u + rX_p. \tag{4}$$

From (1) and (2) we can obtain:

$$\begin{pmatrix} \dot{x}_p \\ \dot{y}_p \end{pmatrix} = \begin{pmatrix} \frac{x_p}{Z_p} & -\frac{1}{Z_p} & -1 - x_p^2 \\ \frac{y_p}{Z_p} & 0 & -x_p y_p \end{pmatrix} \begin{pmatrix} u \\ v \\ r \end{pmatrix}. \tag{5}$$

Equations (5) represent a mathematical model describing image point's motion induced by the camera (DP vessel) motion.

Notice that it's not enough to use only one point, representing object of interest, for DP visual control problem. Let consider the extended state vector:

$$\xi_c = (x_p \quad y_p \quad x_a)^T, \tag{6}$$

where x_a is a horizontal coordinate of the second additional point $\boldsymbol{a}$ corresponding to some object point $A(X_a, Y_a, Z_a)$. The coordinates x_a, y_a and X_a, Y_a, Z_a are related by formula (3). Taking into account state vector (6), the dynamics of image points are given by:

$$\dot{\xi}_c = \mathbf{L}(\xi_c, \mathbf{Z}_c)\mathbf{v}, \tag{7}$$

where

$$\mathbf{L} = \begin{pmatrix} \frac{x_p}{Z_p} & -\frac{1}{Z_p} & -1 - x_p^2 \\ \frac{y_p}{Z_p} & 0 & -x_p y_p \\ \frac{x_a}{Z_a} & -\frac{1}{Z_a} & -1 - x_a^2 \end{pmatrix},\quad \mathbf{Z}_c = \begin{pmatrix} Z_a \\ Z_c \end{pmatrix}.$$

Equations (7) must be considered together with the dynamics of depth coordinates $\mathbf{Z}_c$. From (4) we get

$$\dot{\mathbf{Z}}_c = \mathbf{L}_z(\xi_c, \mathbf{Z}_c)\mathbf{v}, \tag{8}$$

where $\mathbf{L}_c = \begin{pmatrix} -1 & 0 & x_p Z_p \\ -1 & 0 & x_a Z_a \end{pmatrix}$. As a result, equations (1),(2) and (7),(8) considered together represents a full mathematical model in the dynamical positioning problem with visual information. So, the mathematical model is given by

$$\mathbf{M}\dot{\mathbf{v}} = -\mathbf{D}\mathbf{v} + \boldsymbol{\tau} + \mathbf{d}(t),\quad \dot{\boldsymbol{\eta}} = \mathbf{R}(\boldsymbol{\eta})\mathbf{v}, \tag{9}$$

$$\dot{\xi}_c = \mathbf{L}(\xi_c, \mathbf{Z}_c)\mathbf{v} + \mathbf{d}_c(t),\quad \dot{\mathbf{Z}}_c = \mathbf{L}_z(\xi_c, \mathbf{Z}_c)\mathbf{v}. \tag{10}$$

Here $\mathbf{d}_c \in R^3$ is an additional external disturbances of any nature. The measurement output is represented by vectors $\boldsymbol{\eta}, \xi_c, \mathbf{Z}_c$. The depth $\mathbf{Z}_c$ is considered to be known from stereo vision or using nonlinear asymptotic observers (Szeliski, 2011).

The goal is the construction of a nonlinear dynamic control law of the form

$$\dot{\boldsymbol{\rho}} = \mathbf{f}(\boldsymbol{\rho}, \boldsymbol{\tau}, \boldsymbol{\eta}, \xi_c, \mathbf{Z}_c, \xi_d),\quad \boldsymbol{\tau} = \mathbf{g}(\boldsymbol{\rho}, \boldsymbol{\tau}, \boldsymbol{\eta}, \xi_c, \mathbf{Z}_c, \xi_d). \tag{11}$$

where $\boldsymbol{\rho} \in E^k$ is a state space vector of the controller, $\xi_d \in E^3$ is the desired given position of the 3D points P and A in the image plane, that is the vector ξ_d represents desired object of interest position in the image plane of the camera. The controller (11) must provide desirable equilibrium position, that is

$$\lim_{t\to\infty} \xi_c(t) = \xi_d. \tag{12}$$

The controller (11) must provide global asymptotical stability (GAS) for equilibrium position (12) and to ensure certain desirable features of a closed-loop dynamics. Here we will consider an integral action of control with respect to slow varied components of the external disturbances $\mathbf{d}(t)$