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Linear active disturbance rejection control of the hovercraft vessel model

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ABSTRACT

A linearizing robust dynamic output feedback control scheme is proposed for earth coordinate position variables trajectory tracking tasks in a hovercraft vessel model. The controller design is carried out using only position and orientation measurements. A highly simplified model obtained from flatness considerations is proposed which vastly simplifies the controller design task. Only the order of integration of the input-to-flat output subsystems, along with the associated input matrix gain, is retained in the simplified model. All the unknown additive nonlinearities and exogenous perturbations are lumped into an absolutely bounded, unstructured, vector of time signals whose components may be locally on-line estimated by means of a high gain Generalized Proportional Integral (GPI) observer. GPI observers are the dual counterpart of GPI controllers providing accurate simultaneous estimation of each flat output associated phase variables and of the exogenous and endogenous perturbation inputs. These observers exhibit remarkably convenient self-updating internal models of the unknown disturbance input vector components. These two key pieces of on-line information are used in the proposed feedback controller to conform an active disturbance rejection, or disturbance accommodation, control scheme. Simulation results validate the effectiveness of the proposed design method.

1. Introduction

Over the last two decades, a great amount of research has been conducted regarding the regulation marine control systems. They are employed in applications such as dredging operations, recovery of lost man-made objects, cable laying operations, towing operations, military operations, among others (Yuh, 2000; Fossen, 1994, 2011). These applications typically require the accurate tracking of trajectories thus implying the need for high performance controllers. Although ships are usually fully actuated, several other vessels are under-actuated. Control strategies for the under-actuated ship models cannot be asymptotically stabilized by continuous time-invariant feedback control laws (Brockett, 1983). In Kaminer et al. (1998) is proposed a gain-scheduled controller to track reference trajectories in the inertial reference frame. The stabilization problem towards a desired equilibrium is treated in Reyhanoglou (1997). A time-varying feedback control law is proposed in Petersen and Egeland (1996), achieving exponential state stabilization. In Lebefer et al. (2003), a theoretical and experimental result is developed using Lyapunov-based controllers. In Behal et al. (2002) is presented a transformation of the error dynamics into a skew-symmetric form and achieves practical convergence. High-frequency feedback control signals, in combination with averaging theory and back-stepping, have been proposed in Pettersen and Nijmeijer (1998) to achieve practical stabilization of the ship toward a desired equilibrium. They were also extended for trajectory tracking tasks. In Wondergem et al. (2011) is presented an observer-controller scheme which takes into account the complete model dynamics, including Coriolis and centripetal forces and nonlinear damping, and results in a semi-globally uniformly stable closed loop system. Other recent approaches are optimal control (Prasanth Kumar et al., 2005), robust trajectory control based on direct estimation of system dynamics (Prasanth Kumar et al., 2007) or backstepping techniques (Repoulias and Papadopoulos, 2007), among others.

The hovercraft model used here is based on the work of Fantoni et al. (2000), where the vessel's dynamics are derived on the basis of the under-actuated ship model extensively studied in Fossen (1994). Planning and control of hovercraft systems can be considerably simplified by using the *differential flatness* property (Sira-Ramírez and Aguilar, 2000; Sira-Ramírez, 2002), obtained by specific design conditions. Differential flatness was proposed and developed in Fliess et al. (1995) (see also the book by

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Sira-Ramírez and Agrawal, 2004 for diverse engineering applications of this concept). In this paper, we propose a linearizing, global, approach to the robust output feedback controller design for output trajectory tracking tasks in the earth coordinate position variables of a hovercraft vessel. The solution is carried out with position and orientation measurements alone. The linear observer-based controller design approach, presented here, is most suitable for the ubiquitous class of differentially flat systems. The proposed observer based control approach, called Generalized Proportional Integral (GPI) observer-based control (Fliess et al., 2002), rests on using highly simplified models (defined in Fliess and Join, 2009), on the input-to-flat output models derived from the flatness property. The perturbation input lumps both external disturbance inputs and state-dependent nonlinear terms, into a single uniformly absolutely bounded disturbance function that need to be on-line estimated, and canceled, from the controller. After input gain matrix cancelation, the resulting system is constituted by pure integration (linear) perturbed systems with time-varying additive disturbances. The effects of the unknown disturbance input on the output reconstruction error dynamics (at the observer stage) may be attenuated via a suitable linear combination of iterated injections of the output estimation errors. A set of linear extended observers, here called GPI observers, are subsequently specified which internally model the state dependent additive nonlinearities as time-polynomials of reasonable low orders. The observers' state estimation errors are shown to satisfy a set of decoupled, perturbed, linear differential equations with assignable constant coefficients. The designed observers estimate each individual flat output's associated string of phase variables as well as the time-varying perturbation, or disturbance, input components. Reported results for other applications, such as control of wheeled mobile manipulators (Morales et al., 2014c), control of induction motors (Sira-Ramírez et al., 2013), or the control of combinations of electrical machines and dc-to-dc power converters (Sira-Ramírez and Oliver-Salazar, 2013) encourage the use of GPI control schemes as an alternative of improvement in relation to classic control schemes.

The paper is structured as follows: Section 2 presents the hovercraft model and establishes their flatness property. Additionally, a simplified model is proposed which radically simplifies the disturbance observer and feedback controller design tasks and the problem to be solved is formulated. Section 3 presents the fundamental background results under which the proposed control methodology is established and the generalities about GPI observers. The results obtained are applied to the stabilization and trajectory tracking problem of the hovercraft vessel model. In this section, the state dependent disturbance estimation-disturbance elimination linear output feedback strategy is also developed. Section 4 is devoted to digital computer simulations depicting the performance of the proposed GPI observer-based linear controllers on the hovercraft system under large initial errors, unmodeled unmatched perturbations and model parametric uncertainties. Finally, Section 5 presents the conclusions of the work.

2. Problem formulation

2.1. The hovercraft model and its flatness property

The equations of motion for a rather general surface vessel dynamics can be written in the following form (Fossen, 1994):

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{D}\boldsymbol{\nu} = \boldsymbol{\tau}$$
$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\boldsymbol{\nu} \quad (1)$$

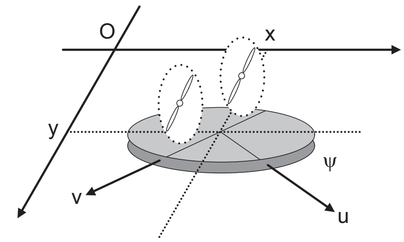

Fig. 1. Simplified hovercraft system.

where

$$\mathbf{C}(\boldsymbol{\nu}) = \begin{bmatrix} 0 & 0 & -m_{22}v \\ 0 & 0 & m_{11}u \\ m_{22}v & -m_{11}u & 0 \end{bmatrix}, \quad \mathbf{J}(\boldsymbol{\eta}) = \begin{bmatrix} C_\psi & -S_\psi & 0 \\ S_\psi & C_\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

with $\mathbf{M}$ being the inertia matrix, $\mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu}$ is the vector of Coriolis and centripetal terms and $\mathbf{D}\boldsymbol{\nu}$ is the vector of friction and hydrodynamic damping terms. The vector $\boldsymbol{\nu} = [u, v, r]^T$ denotes the vehicle linear velocities in surge, sway and angular velocity in yaw expressed in the vehicle-fixed reference frame. The vector $\boldsymbol{\eta} = [x, y, \psi]^T$ expresses the position and orientation in a earth-fixed reference frame and $C_\psi \equiv \cos\psi$ and $S_\psi \equiv \sin\psi$. The vector $\boldsymbol{\tau} = [\tau_1, \tau_2, \tau_3]^T$ defines the vector of forces acting on the vehicle in surge and sway and the torque on the vehicle acting on the yaw. The matrices $\mathbf{M}$ and $\mathbf{D}$ are, both, diagonal and given by

$$\mathbf{M} = diag\{m_{11}, m_{22}, m_{33}\}, \quad \mathbf{D} = diag\{d_{11}, d_{22}, d_{33}\} \quad (3)$$

In this work, we consider the model of the underactuated hovercraft vessel system illustrated in Fig. 1. A mathematical model for such vessel system was derived in Fantoni et al. (2000) taking into consideration the following assumptions:

Assumption 1. The vessel system is assumed to be symmetric with regard to the axes u and v, i.e. $m_{11} = m_{22}$.

Assumption 2. The control force acting in sway is zero, i.e. $\tau_2 = 0$.

Assumption 3. The hydrodynamic damping coefficients d_{11} and d_{33} are both zero, i.e. $d_{11} = d_{33} = 0$. In the case that these damping terms were actually present, they could be compensated by partial state feedback though the control terms τ_1 and τ_3.

Finally, the following mathematical model is proposed for the underactuated hovercraft vessel system:

$$\begin{aligned} \dot{x} &= uC_\psi - vS_\psi \\ \dot{y} &= uS_\psi + vC_\psi \\ \dot{\psi} &= r \\ \dot{u} &= vr + \tau_u \\ \dot{v} &= -ur - \beta v \\ \dot{r} &= \tau_r \end{aligned} \quad (4)$$

where $\tau_1 = m_{11}\tau_u$, $\tau_3 = m_{33}\tau_r$ and $\beta = d_{22}/m_{22}$.

The hovercraft model given in (4) is differentially flat, with flat outputs given by the position in earth fixed reference frame ($[x, y]$), i.e. all system variables in (4) can be differentially parameterized solely in terms of x and y, and a finite number of their time derivatives. Their expressions are as follows:

$$\psi = \arctan\left(\frac{\ddot{y} + \beta\dot{y}}{\ddot{x} + \beta\dot{x}}\right)$$
$$u = \frac{\dot{x}(\ddot{x} + \beta\dot{x}) + \dot{y}(\ddot{y} + \beta\dot{y})}{\sqrt{(\ddot{x} + \beta\dot{x})^2 + (\ddot{y} + \beta\dot{y})^2}}$$
$$v = \frac{\dot{y}\ddot{x} - \dot{x}\ddot{y}}{\sqrt{(\ddot{x} + \beta\dot{x})^2 + (\ddot{y} + \beta\dot{y})^2}}$$