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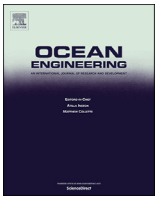

Nonlinear Model Predictive Control for trajectory tracking and collision avoidance of underactuated vessels with disturbances☆

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A B S T R A C T

This paper presents a combined Nonlinear Model Predictive Control (NMPC) for position and velocity tracking of underactuated surface vessels, and collision avoidance of static and dynamic objects into a single control scheme with sideslip angle compensation and environmental disturbances counteraction. A three-degree-of-freedom (3-DOF) dynamic model is used with only two control variables: namely, surge force and yaw moment. External environmental forces are considered as constant or slowly varying disturbances with respect to the inertial frame, and hence nonlinear for the body frame of the vessel. Nonlinear disturbance observer (NDO) is used to estimate these disturbances in order to be fed into the prediction model and enhance the robustness of the controller. A nonlinear optimization problem is formulated to minimize the deviation of the vessel states from a time varying reference generated over a finite horizon by a virtual vessel. Sideslip angle is considered in the cost function formulation to account for tracking error caused by the transverse external force in the absence of sway control force. Collision avoidance is embedded into the trajectory tracking control problem as a time-varying nonlinear constraint of position states to account for static and dynamic obstacles. MATLAB simulations are used to assess the validity of the proposed technique.

1. Introduction

Path following techniques of vessels have gained a lot of interest from both academia and industry; specially for the future expectations of using commercial autonomous vessels or adding an autopilot to assist the crew. To make these techniques practical, collision avoidance should be integrated in the control problem to guarantee safe maneuvering during the trip. Collision risk is increased in the presence of external forces such as those induced by wind and waves. Motivated by these requirements, surface vessels should be able to keep the planned trajectory, while avoiding collision of nearby objects and counteraction external disturbances. The challenge is increased for underactuated surface vessels which are usually equipped with two independent aft thrusters or with one main aft thruster and a rudder, and hence have only two control variables; namely surge force and yaw moment.

In recent years, trajectory tracking has been studied using various control techniques. For instance, Dynamic Surface Control (DSC) technique is used in (Chwa, 2011) for global tracking of underactuated vessel in a modular way that cascaded kinematic and dynamic linearizations can be achieved. In (Peng et al., 2013; Wang et al., 2014), an adaptive form of DSC is used for formation control of autonomous surface vehicles (ASVs) moving in a leader-follower formation under ocean disturbances. In (Kahveci and Ioannou, 2013), an automatic adaptive steering control design for full-actuated vessels is presented. The adaptive law is combined with a control design including a linear quadratic controller (LQR) and a Riccati based anti-windup compensator. The controller also takes into consideration input constraints, wind and wave effects, and parametric uncertainty. In (Dong et al., 2015), a trajectory tracking problem is addressed for a 3-DOF underactuated Unmanned Surface Vessel (USV) using a state feedback based backstepping control algorithm with relaxed persistent exciting (PE) conditions of yaw velocity. In (Jiang and Nijmeijer, 1999), a recursive technique is presented for trajectory tracking of nonholonomic systems by the means of backstepping, and is demonstrated by simulating an articulated vehicle and a knife edge system. In (Do and Pan, 2004), a methodology for designing state and output feedback controller is presented by means of Lyapunov's direct method and backstepping after model transformation to Serret-Frenet frame. Although the aforementioned techniques give good trajectory tracking results, collision avoidance of nearby objects is not addressed.

Model Predictive Control (MPC) has got attention for trajectory

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tracking control problems because of its systematic ability to handle physical constraints of the system (Künhe et al., 2005). In (Guerreiro et al., 2014), NMPC is used for trajectory tracking of a full actuated autonomous surface craft (ASC) in the presence of constant ocean currents. In (Yan and Wang, 2012), MPC is applied for tracking problem of underactuated surface vessels, employing the affine property of the system model. The kinematic is simplified by applying frame transformation to make positions independent of the choice of the inertial frame. Nonlinear functions of the system are evaluated using optimal states obtained at the previous instant which leads to significant numerical errors for large horizons (Mayne, 1016). In (Abdelaal et al., 2015), NMPC is used for trajectory tracking of an underactuated vessels employing direct multiple shooting technique that leads to less numerical error. The aforementioned MPC approaches do not cater for collision avoidance.

Conventionally, collision avoidance is treated as a controller independent planning problem that might not be achievable by the controller and hence degrades the safety of the vessel (Wang et al., 1016). For instance, an evolutionary algorithm is presented in (Smierzchalski, 1999) to find a safe and optimal trajectory of surface vessels in a well known environment by using the vessel's kinematic model. A more sophisticated evolutionary approach is presented in (Szlapczynski, 2011, 2012; Szlapczynski and Szlapczynska, 2012) by adding specialized operators to shape the convergence of the optimization. In (Zhuo, 2014), a fuzzy logic approach is presented for collision avoidance of large ships by formulating the problem into an optimization problem and solving it using a particle swarm algorithm. Fuzzy-neural inference network is also used in (Liu and Shi, 2005) for ship collision avoidance. In (Wang et al., 2017a), collision avoidance is achieved in two steps: a path planning collision avoidance, and an MPC for following the generated path after linearizing the dynamics of the vessel. In (Wang et al., 2017b), a collision avoidance dynamic support system is presented where a mathematical model of ship maneuvering motion and a PID heading controller are employed as well as dynamic calculation model of collision avoidance parameter. A graph-theoretic solution on an appropriately-weighted directed graph representation of the navigation area is presented in (Ari et al., 2013). The graph is obtained via 8-adjacency integer lattice discretization and utilization of the A^* algorithm. Although the aforementioned techniques demonstrate collision avoidance, they either simplify or ignore the dynamics of the vessel, and the effect of external environmental forces.

Recently, control techniques have been developed to include collision avoidance as an objective while designing the controllers. In (Wang and Ding, 2014), MPC is used for the tracking and formation problem of multiagent linear systems with collision avoidance as a constraint for the optimization problem. In (Alrifaee et al., 2014), a centralized MPC is used for collision avoidance of networked vehicles by successively linearizing the nonlinear prediction model using Taylor series. In (Wang et al., 1016), an MPC technique is applied for the nonlinear model of kinematically redundant space robot to approach an un-cooperative target in complex space environment. For the sake of deriving a linearized version of the space robot, feedback linearization is used and hence collision avoidance can be formulated as a linear matrix inequality (LMI). The aforementioned model predictive techniques consider the collision avoidance but they lack handling of external disturbances for underactuated systems. In (Johansen et al., 2016), MPC is used for collision avoidance by pre-computing a finite set of control behaviors, and then simulating on-line these behaviors to check which scenario gives the optimal trajectory.

The objective of this paper is to introduce the concept of integrating collision avoidance into the trajectory tracking controller, based on MPC concepts, to act as a last-line of defense for autonomous vessels. For such critical maneuvering, accuracy is necessary and therefore comes the necessity of employing full planar motion nonlinear dynamics and effect of external disturbances. In this paper, a nonlinear state feedback control law is presented based on solving a finite horizon optimization problem, at every instant, and using the current state measurement as initial condition for the problem. The problem takes into consideration the physical constraints of the vessel by systematically adding them to the optimization problem constraints. Collision avoidance constraints are added to the problem that force the vessel to deviate minimally from the defined path in case of predicting a collision while obeying some of the rules of the International Regulations for Preventing Collisions at Sea (COLREGS). External forces are taken into consideration as unmeasured disturbance and therefore the NMPC law is modified to include the disturbance estimated by NDO, and handle the external transverse force component where there is no corresponding control force to counteract. The output of the problem is an optimal sequence, of length N, of the vesselâ€™s force and moment. The first element only is applied and then the whole process is repeated at the next instant. The finite horizon optimization problem is discretized and then formulated as a quadratic problem (QP) which is solved by the aid of ACADO toolkit (Houska et al., 2011) and qpOASES solver (qpOASES Homepage).

This paper is organized as follows. Section 2 describes the vessel nonlinear dynamics, external disturbance modeling, generation of the reference trajectory, and clarifies the control objective. Controller synthesis is presented in Section 3. A brief introduction of NMPC is given first followed by the Nonlinear Disturbance Observer design. A cost function modification is then presented to include sideslip angle; along with the conditions required to guarantee stability of the nonlinear system, collision avoidance, compliance of some COLREGS rules, discretization, and implementation of the proposed approach. The MATLAB based simulation results are given in Section 4. Section 5 concludes this paper.

2. Problem formulation

The surface vessel model has 6-DOF: surge, sway, yaw, heave, roll, and pitch, which can be simplified to motion in surge, sway, and yaw under the following assumptions (Chwa, 2011):

1. The heave, roll, and pitch modes induced by wind and currents are negligible.
2. The inertia, added mass, and hydrodynamic damping matrices are diagonal.
3. The available control variables are surge force and yaw moment.

Based on that, the 3-DOF model will be (Fossen, 2011):

$$\begin{aligned}
\dot{x} &= u\cos(\psi) - v\sin(\psi)\\
\dot{y} &= u\sin(\psi) + v\cos(\psi)\\
\dot{\psi} &= r\\
\dot{u} &= \frac{m_2}{m_1}vr - \frac{d_1}{m_1}u + \frac{1}{m_1}\tau_u\\
\dot{v} &= \frac{m_1}{m_2}ur - \frac{d_2}{m_2}v\\
\dot{r} &= \frac{(m_1-m_2)}{m_3}uv - \frac{d_3}{m_3}u + \frac{1}{m_3}\tau_r.
\end{aligned} \tag{1}$$

Here, x and y are the positions, ψ is the heading angle of the ship with respect to the earth-fixed frame, u and v are the longitudinal and transverse linear velocities in surge (body-fixed x) and sway (body-fixed y) directions respectively, and r is the angular velocity in yaw around body-fixed z axis (see Fig. 1). The parameters m_1, m_2, m_3 are the ship inertia including added mass effects, and d_1, d_2, d_3 are the hydrodynamic damping coefficients.

External environmental forces induced by the wind and wave current are assumed to be constant with respect to the inertial reference frame and have three components; surge, sway, and yaw. Therefore, the vessel model, written in a compact form, will be modified to be:

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}) + g_1(\boldsymbol{x})\boldsymbol{u} + g_{2b}(\boldsymbol{x})\boldsymbol{w_b} \tag{2}$$

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