POLISH MARITIME RESEARCH 3 (103) 2019 Vol. 26; pp. 163-171
10.2478/pomr-2019-0057

MODEL PREDICTIVE SUPER-TWISTING SLIDING MODE CONTROL FOR AN AUTONOMOUS SURFACE VEHICLE

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ABSTRACT

This paper presents a new robust Model Predictive Control (MPC) algorithm for trajectory tracking of an Autonomous Surface Vehicle (ASV) in presence of the time-varying external disturbances including winds, waves and ocean currents as well as dynamical uncertainties. For fulfilling the robustness property, a sliding mode control-based procedure for designing of MPC and a super-twisting term are adopted. The MPC algorithm has been known as an effective approach for the implementation simplicity and its fast dynamic response. The proposed hybrid controller has been implemented in MATLAB / Simulink environment. The results for the combined Model Predictive Super-Twisting Sliding Mode Control (MP-STSMC) algorithm have shown that it significantly outperforms conventional MPC algorithm in terms of the transient response, robustness and steady state response and presents an effective chattering attenuation in comparison with the Super-Twisting Sliding Mode Control (STSMC) algorithm.

Keywords: utonomous Surface Vehicle, Model Predictive Control, Sliding Mode Control, Super-Twisting Algorithm, Chattering Attenuation

INTRODUCTION

Marine robots have been drastically improved during the last decade until today. Their applications are very extensive, ranging from inspection tasks to accomplishing complex underwater explorations. Based on this, the maritime robotic platforms can be grouped into underwater and surface robots. As for the first group, we can refer to the underwater manipulators, autonomous underwater vehicles and autonomous underwater vehicle-manipulator systems. For the second group, there are unmanned surface vehicles and autonomous surface ships. Designing a high performance control system for the robotic platforms is a paramount challenge, particularly in case of Autonomous Surface Vehicle (ASV). However, due to the high nonlinearity terms in ASV dynamics and uncertainties resulting from inertia parameter variation, a robust control algorithm should be adopted for taking these uncertainties and external disturbances into account. As to the literature about the marine robotic control and navigation systems, some research works upon the navigation area have been accomplished in [20-22]. Regarding marine robotics control area, an optimal SMC was adopted in which the adjustable parameters of the sliding mode controller were estimated by using wavelet mutation [1]. In [2] a robust strategy based on Time Delay Control (TDC) algorithm and Terminal Sliding Mode (TSM) was designed to control an Underwater Vehicle-Manipulator System (UVMS). In this work TDC was regarded to enhance robustness feature and tracking accuracy. Also, the gains of SMC were adaptively tuned by the fuzzy inference system. Concerning chattering reduction of SMC algorithm, the authors of [3] presented a new reaching mode including exponential function to illuminate chattering frequencies. The robustness issue of MPC has always been a challenge in designing robust nonlinear model predictive controllers (NMPC). An NMPC was used for an Unmanned Surface Vehicle (USV) in [4]. In this research a conventional MPC was used in which the robustness however might be not guaranteed. Also, the sea environmental disturbances have not been considered there. In [5], a back-stepping control approach combined with sliding mode control algorithm was designed to cover the trajectory tracking problem of an under-actuated USV. An autonomous robotic boat was presented in [6] and a nonlinear model predictive control (NMPC) was adopted for its controller. However, the uncertain nonlinearities, resulting from the changes in inertia and drag matrices of the robotic boat, were not taken into account there. Another weakness of the work in question was neglecting the influences due to winds, waves and ocean current disturbances. Two kinds of MPC controllers, including NMPC ,were proposed in [7], which solved a constrained multi-variable nonlinear programming problem and Linearized MPC (LMPC), designed to solve a constrained quadratic programming problem by means of on-line iterative optimization. However, again the environmental disturbances (winds, waves and currents) were not taken into account. In [8], a nonlinear disturbance observer was designed to estimate unknown parameters and external disturbances. However, this observer was able to estimate only constant disturbances. A control law for path tracking of marine vessel was adopted in [9], where a singular perturbation method was used to decompose the system into two Lyapunov theory based control subsystems. Some research projects concerning adopting the higher order sliding mode algorithms such as super-twisting for control of the maritime autonomous robots, were carried out in [10,11]. In [12] there were presented two control algorithms for the trajectory tracking of an autonomous marine platform, in which the input constraints and disturbances induced by constant ocean currents were regarded. In this research the first approach was based on a Lyapunov design strategy, while the second was developed by adopting a MPC algorithm. For tuning of gains in a PID controller, in [13] a self-regulator PID was designed in which coefficients have been regulated by the fuzzy rules. A robust multi-loop control scheme including Integral Sliding Mode (ISM) loop and MPC loop has been presented in [16] where the ISM role is to reject uncertain terms due to unknown dynamics. In [17], a novel perturbation compensating algorithm was proposed to reach the more accurate path tracking in the presence of environmental disturbances, which finally led to a robust MPC. As to other kinds of nonlinear control of marine vehicles, some approaches based on back-stepping algorithm have been implemented in [18,19].

In this research, the proposed control law is designed based on the sliding mode function, model predictive control and super-twisting concepts. The motivation is to reach the ability to explicitly deal with state and input constraints as well as fast dynamic response from MPC and the good robustness attributes from SMC and super-twisting, particularly in presence of severe external disturbance. However, we have to face two challenges with adopting the MPC for trajectory tracking goals. The first one is obtaining an acceptable robustness of MPC and the second – avoiding large overshoot caused by fast settling time. Hence, we design an improved MPC based on the sliding function and add a super-twisting part to the control law in order to manage the aforementioned problems.

The rest of this paper is organized as follows. In the next section an ASV dynamical model associated with all of the time-varying external disturbances and uncertainties is described. The third section is dedicated to explain the proposed approach of model predictive super-twisting sliding mode control. In the fourth section the computer simulation results and their mutual comparison are shown to confirm a high performance of the proposed control. Discussion of the simulation results is provided in the fifth section and the conclusion is finally given in the sixth section.

AUTONOMOUS SURFACE VEHICLE

The nonlinear dynamics of ASV can be described in the form of 3- DOF motion as follows

$$\begin{cases} M\dot{\nu} + C(\nu)\nu + D(\nu)\nu = \tau_c + MR^T(\psi)\Gamma \\ \dot{\eta} = R(\psi)\nu \end{cases} \tag{1}$$

where velocity and position vectors are defined as $\nu = [u, v, r]^T$ and $\eta = [x, y, \psi]^T$, respectively. The coordinate frames regarding surge, sway and yaw motions are shown in Fig. 1. In the aforementioned equation, the rotation matrix $R(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$ is used to transfer coordinates from the Body-Fixed Frame (BFF) to the Earth-Fixed Frame (EFF).

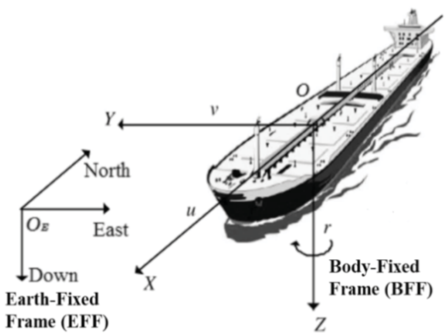


Fig. 1. The earth-fixed frame and body-fixed frame [14]

For presenting the Eq. (1) in a standard form based on position vector, we can rewrite it using the property of the rotation matrix $\dot{\eta} = R(\psi)\nu$ as follows :

$$M(\eta)\ddot{\eta} + C(\eta, \dot{\eta})\dot{\eta} + D(\eta, \dot{\eta})\dot{\eta} = \tau_c + \tau_d \quad (2)$$

where, all the related components of each matrix in the equation (2) were presented by analogy with the dynamics of robotic manipulators [23]. $\tau_c = [\tau_x, \tau_y, \tau_N]^T$ and $\tau_d = MR^T(\psi)\Gamma$ and are control inputs and external disturbances, respectively. These time-varying external disturbances are induced by the winds, waves and ocean currents, which are expressed by the vector of $\Gamma = [\Gamma_u, \Gamma_v, \Gamma_r]^T$. The disturbances are considered for applying to the ASV with 3 DOFs, in which their respective vectors can be modeled as follows [15]

$$\begin{cases} \boldsymbol{\Gamma}_u = 0.1v^3 + 0.06u + 0.01\sin(t) \\ \boldsymbol{\Gamma}_v = ur + 0.1u + 0.01\sin(t) \\ \boldsymbol{\Gamma}_r = 0.4ur + v^2 + 0.01\sin(t) \end{cases} \quad (3)$$

$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \in \mathbb{R}^3$, $M(\eta) \in \mathbb{R}^3$, $C(\eta, \dot{\eta}) \in \mathbb{R}^3$, $D(\eta, \dot{\eta}) \in \mathbb{R}^3$ are constant inertia matrix, time-varying inertia matrix, time-varying Coriolis matrix and time-varying hydrodynamic damping matrix including both linear and nonlinear parts, respectively [23]. Indeed, with taking into account the nonlinear damping parts, the matrix $D(\eta)$ is changed to the form $D(\eta, \dot{\eta})$ and nonlinear coefficients (d_{ij}) are dependent on velocity vector $\dot{\eta} = R(\psi)\nu$.

MODEL PREDICTIVE SUPER-TWISTING SMC

SLIDING MODE-BASED MPC

In the proposed sliding mode model predictive control approach, a control input $u(t)$ is designed for the tracking of a desired trajectory at the next time $(t + t_h)$ by minimization of the following cost function.

$$J = f(\sigma(t + t_h), \eta(t + t_h), \tau_c(t)) \quad (4)$$

where $\sigma(t + t_h)$ is a predicted sliding surface, $\eta(t + t_h)$ is a t_h-step ahead prediction of the output state and $t_h > 0$ is a prediction horizon. The tracking error, sliding surface and its first derivative are defined as:

$$e(t) = \eta - \eta_d \quad (5)$$

$$\sigma(t) = \dot{e} + \lambda e \quad (6)$$

$$\dot{\sigma}(t) = \ddot{e} + \lambda \dot{e} \quad (7)$$

where η and η_d and are actual and desired output states. Let us consider the predicted sliding surface approximately as follows

$$\sigma(t + t_h) = \sigma(t) + t_h \dot{\sigma}(t) \quad (8)$$

We can adopt a state vector of sliding surface as $Q(t) = \begin{bmatrix} \sigma \\ \dot{\sigma} \end{bmatrix}$ and express the prediction model of sliding surface as follows:

$$\sigma(t + t_h) = T(t_h)Q(t) \quad (9)$$

where, $T(t_h) = [I_{nn} \quad t_h * I_{nn}]$ and I_{nn} is an identity matrix.

The cost function based on the predicted sliding surface is presented upon the future horizon as

$$J = \frac{1}{2}\int_0^{t_d} \left(\sigma(t + t_h)\right)^T \left(\sigma(t + t_h)\right) dt_h \quad (10)$$

An acceptable accuracy for the MPC algorithm can be achieved by tuning t_d. By the prediction model of sliding surface (9), the J can be rewritten as follows :

$$\begin{aligned} J &= \frac{1}{2}\int_0^{t_d} (\sigma(t + t_h))^T \sigma(t + t_h)\ dt_h \\ &= \frac{1}{2}\int_0^{t_d} \left(T(t_h)Q(t)\right)^T \left(T(t_h)Q(t)\right)\ dt_h \quad (11) \\ &= \frac{1}{2}\left(Q(t)\right)^T R(Q(t)) \end{aligned}$$

where: $R = \int_0^{t_d} T(t_h)^T T(t_h)\ dt_h$

$$= \begin{bmatrix} t_d * I_{nn} & \left(\frac{t_d^2}{2}\right) * I_{nn} \\ \left(\frac{t_d^2}{2}\right) * I_{nn} & \left(\frac{t_d^3}{3}\right) * I_{nn} \end{bmatrix} \quad (12)$$

Substituting the equation (12) in (11), the cost function can be expressed based on sliding function and its first derivative as follows:

$$J(\sigma, \dot{\sigma}) = \frac{1}{2}t_d\sigma^2 + \frac{1}{2}t_d^2\sigma\dot{\sigma} + \frac{1}{2}t_d^3\dot{\sigma}^2 \quad (13)$$

We can rewrite the dynamic equation of ASV as follows:

$$\ddot{\eta}(t) = -M(\eta)^{-1}(C(\eta,\dot{\eta})\dot{\eta} + D(\eta,\dot{\eta})\dot{\eta})\ldots \\ \ldots + M(\eta)^{-1}\tau_c(t) \tag{14}$$

Also, in accordance to combination of the equations (5), (6) and (7), the first derivative of sliding surface can be obtained as

$$\dot{\sigma} = \ddot{\eta} + \lambda\dot{e} - \ddot{\eta}_d \tag{15}$$

Let us present the cost function as follows:

$$\dot{\sigma} = \ddot{\eta} + \lambda\dot{e} - \ddot{\eta}_d \tag{16}$$

where: $J_1(\sigma) = \frac{1}{2}t_d\sigma^2$ and $J_2(\sigma,\dot{\sigma}) = \frac{1}{2}t_d^2\sigma\dot{\sigma} + \frac{1}{2}t_d^3\dot{\sigma}^2$.

The condition for to minimizing J is

$$\frac{\partial\,(J)}{\partial\tau_c} = 0 \tag{17}$$

Based on the equations of (14) and (15), we can see $\tau_c(t)$ in the second part of cost function $J_2(\sigma,\dot{\sigma})$. Therefore, we can regard the minimization of the J subject to the $\tau_c(t)$ as follows:

$$\frac{\partial\,(J)}{\partial\tau_c} = \frac{\partial\,(J_2)}{\partial\tau_c} = 0 \tag{18}$$

Hence, the optimal control law is:

$$\tau_{mp-smc}(t) = \widehat{M}(\eta)\left(\ddot{\eta}_d - \lambda\dot{e} - \frac{3}{2t_d}\sigma\right)\ldots \\ \ldots + \hat{C}(\eta,\dot{\eta})\dot{\eta} + \widehat{D}(\eta,\dot{\eta})\dot{\eta} + p(\eta,\dot{\eta},\ddot{\eta}) \tag{19}$$

where, $p(\eta,\dot{\eta},\ddot{\eta}) = [\widehat{M}(\eta) - \widetilde{M}]\ddot{\eta} + \tilde{C}(\eta,\dot{\eta})\dot{\eta} + \cdots \widetilde{D}(\eta,\dot{\eta})\dot{\eta} - \tau_d$ is a perturbation part including inherent uncertainties $(\widetilde{M},\tilde{C},\widetilde{D})$ and time-varying disturbances (τ_d).

$\widehat{M}$, $\hat{C}$ and $\widehat{D}$ are regarded as nominal and known parts of the dynamical model. In the next section we adopt a super-twisting term for adding to the equation (19) in order to compensate the perturbation part (p) and improve robustness property in the proposed hybrid control algorithm.

SUPER TWISTING CONTROL LAW

The derivation of sliding surface can be performed as follows:

$$\dot{s} = \ddot{e} + \lambda\dot{e} = \ddot{\eta} - \ddot{\eta}_d + \lambda\dot{e} = \\ \widehat{M}^{-1}\left[\tau_c - \hat{C} - \widehat{D}\right] - \ddot{\eta}_d + \lambda\dot{e} \tag{20}$$

The standard form for a super-twisting algorithm can be expressed as:

$$\begin{cases} \dot{s} = -k_1\xi(s)\mathrm{sign}(s) + z \\ \dot{z} = -k_2\mathrm{sign}(s) \end{cases} \tag{21}$$

where $\xi(s) = \mathrm{diag}(|s_1|^{\frac{1}{2}}, |s_2|^{\frac{1}{2}}, |s_3|^{\frac{1}{2}})$ and k_1, k_2 are diagonal positive matrices.

$$\mathrm{sign}(s) = \begin{cases} 1\ , & s > 0 \\ 0\ , & s = 0 \\ -1\ , & s < 0 \end{cases} \tag{22}$$

By using Eq. (20) and Eq. (21), the super-twisting control law is expressed as follows:

$$\tau_c = \widehat{M}\begin{Bmatrix} \ddot{\eta}_d - \lambda\dot{e} - k_1\xi(s)\mathrm{sign}(s) \\ -k_2\int_0^t \mathrm{sign}(s)dt \end{Bmatrix} + \cdots \\ \ldots \hat{C} + \widehat{D} \tag{23}$$

PROPOSED HYBRID CONTROL LAW

In the proposed approach, to assure robustness of the hybrid control law against external disturbances and uncertainties, the following super-twisting term (τ_{st}) must be added to the optimal control law (19).

$$\begin{cases} \tau_{st}(t) = -k_1\xi(\sigma)\mathrm{sign}(\sigma) + z \\ \dot{z} = -k_2\mathrm{sign}(\sigma) \end{cases} \tag{24}$$

Finally, with taking into account the sliding mode MPC part (19) and the super-twisting term (24), the proposed control law is expressed as follows :

$$\tau_{mp-stsmc}(t) = \tau_{mp-smc}(t) + \tau_{st}(t) \tag{25}$$

The proposed control system of ASV is shown in Fig. 2.

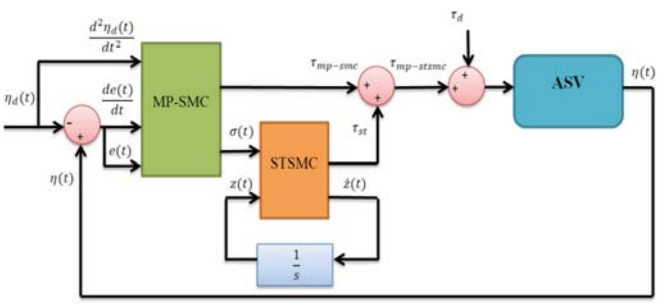


Fig. 2. Schematic diagram of the proposed Model Predictive Super-Twisting Sliding Mode Controller (MP-STSMC)

COMPUTER SIMULATION RESULTS

In this section, the results of three simulated controllers including Super-Twisting Sliding Mode Controller (STSMC), Model Predictive Controller (MPC) and proposed Model Predictive Super-Twisting Sliding Mode Controller (MP-STSMC) are presented. The comparative outputs are shown in Fig. 3, Fig. 4 and Fig. 5 for the path following, tracking errors and control inputs, respectively.

In the mathematical modeling of ASV, the nonlinear parts of the damping coefficients are also significant elements taken into account in these simulations. They are described as follows [15]:

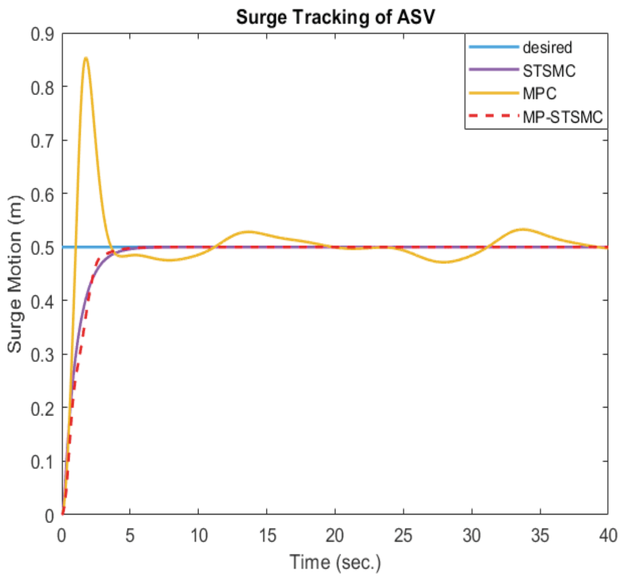
$$\begin{aligned} d_{11} &= 0.72 + 1.33|u| + 5.87u^2 \\ d_{22} &= 0.8896 + 36.5|v| + 0.805|r| \\ d_{23} &= 7.25 + 0.8451|v| + 3.45|r| \\ d_{32} &= 0.0313 + 3.96|v| + 0.13|r| \\ d_{33} &= 1.9 - 0.08|v| + 0.75|r| \end{aligned} \quad (26)$$

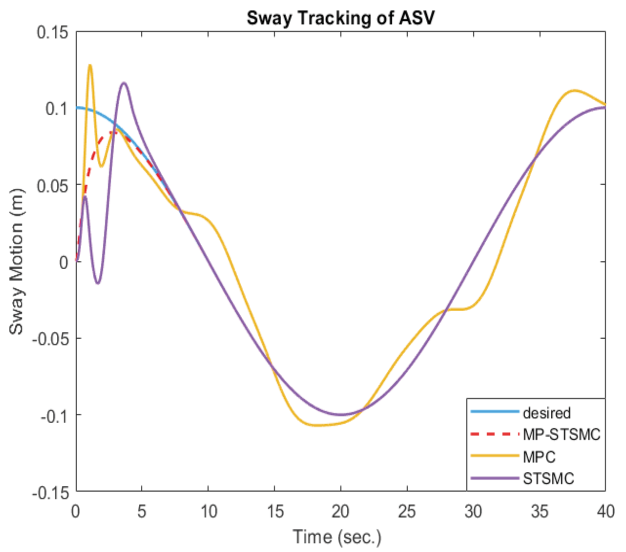
Other damping coefficients 3×3 in the damping matrix are assigned to zero. And, the constants in inertia matrix are assigned as follows [15]:

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} = \begin{bmatrix} 25.8 & 0 & 0 \\ 0 & 33.8 & 1.0115 \\ 0 & 1.0115 & 2.76 \end{bmatrix}$$

The equations of desired paths with the initial conditions $[0 \quad 0 \quad 0]^T$ and simulation time t = 40 sec. are as follows:

$$\eta_d(t) = \begin{cases} x_d = 0.5 \text{ m} \\ y_d = 0.1 \cos\left(\frac{\pi}{20}t\right) m \\ \psi_d = \pi \cos\left(\frac{\pi}{20}t\right) rad \end{cases} \quad (27)$$





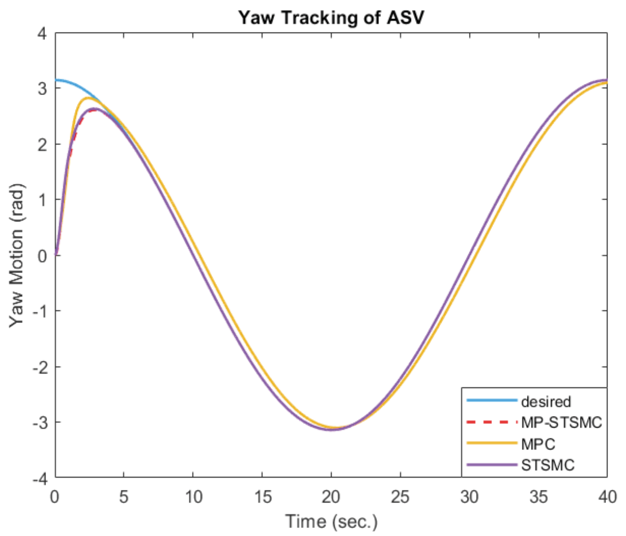


Fig. 3. Path Following

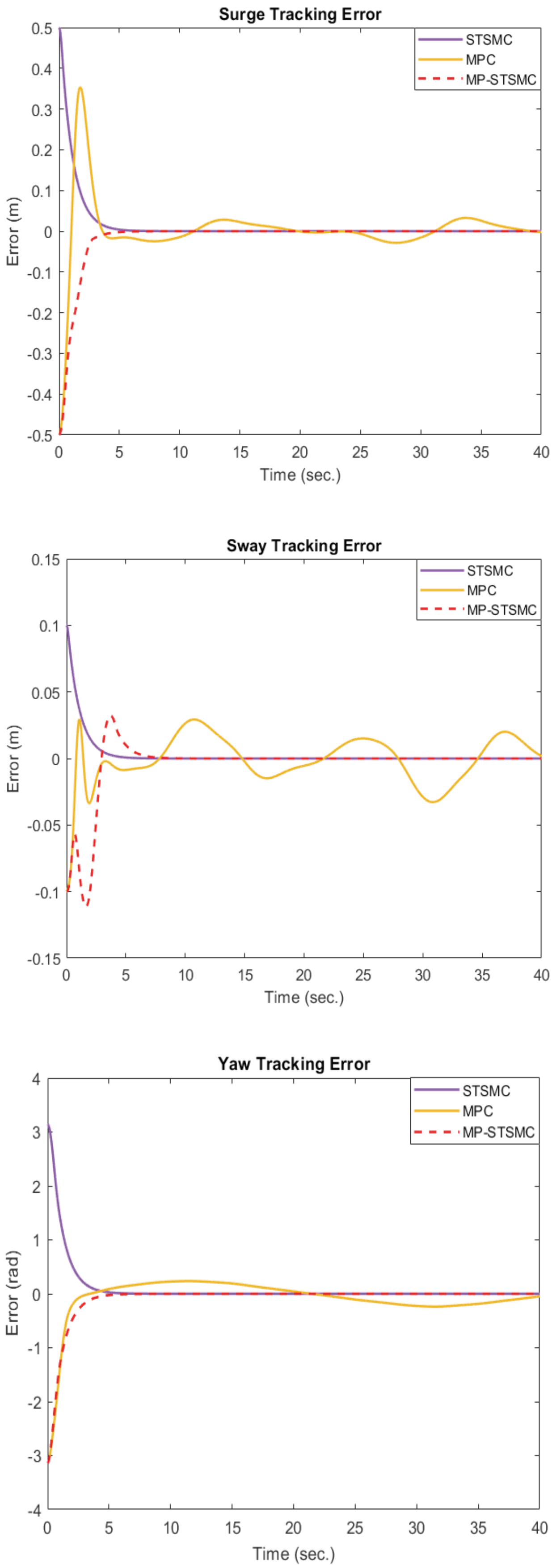


Fig. 4. Tracking Errors

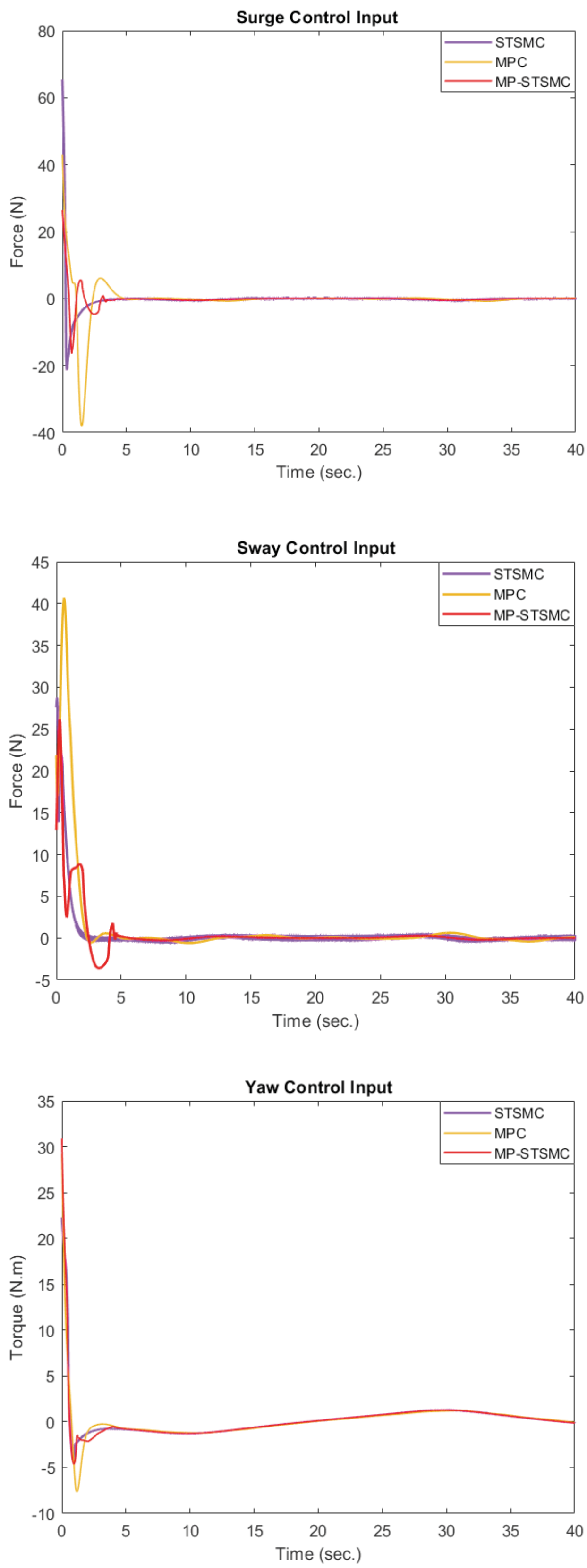
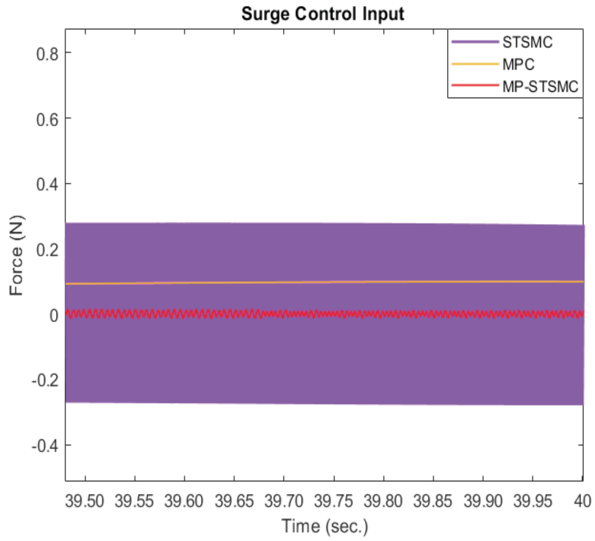
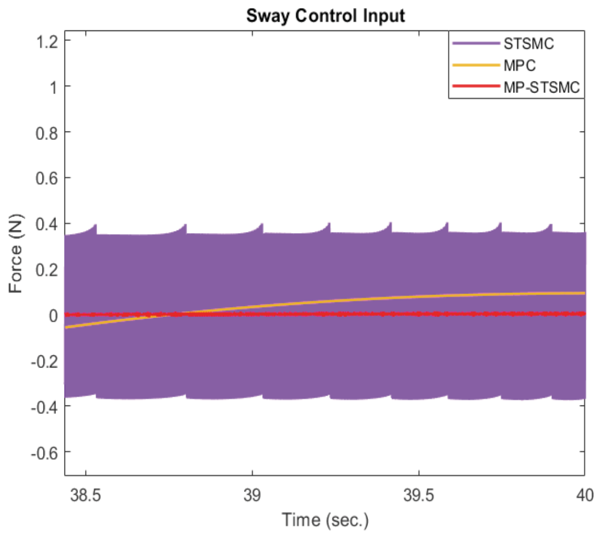


Fig. 5. Control Inputs

As to chattering attenuation in the proposed algorithm in comparison with the super-twisting method, we have provided Fig. 6 containing zoomed control inputs to compare the signals in terms of chattering effect.

The chattering is due to the assuming of the function in the switching term in a discontinuity in a super-twisting control law. The chattering phenomenon can be also induced by perturbations which compel ASV to leave the sliding mode in dynamic motion. For suppressing this phenomenon one solution is the using of a continuous term *s* with a boundary layer instead of discontinuous part sign(*s*) and, as another effective way, we can use the higher-order sliding mode controllers such as super-twisting algorithm. However, the chattering , particularly in steady-state response, is still present on control input as shown in Fig. 6, which let the tracking error to oscillate around the origin. In the proposed MP-STSMC, we can achieve the high robustness attribute of STSMC as well as drastically reduce steady-state chattering in finite time of tracking (see a chattering suppression scheme). Nevertheless, the chattering phenomenon, even with a very low amplitude in super-twisting SMC leads to the dissipation of a large quantity of fuel or energy in manoeuvring thrusters and propeller system , as well as to a rapid wear of mechanical actuators. Also, these high frequencies may excite unmodeled dynamics.





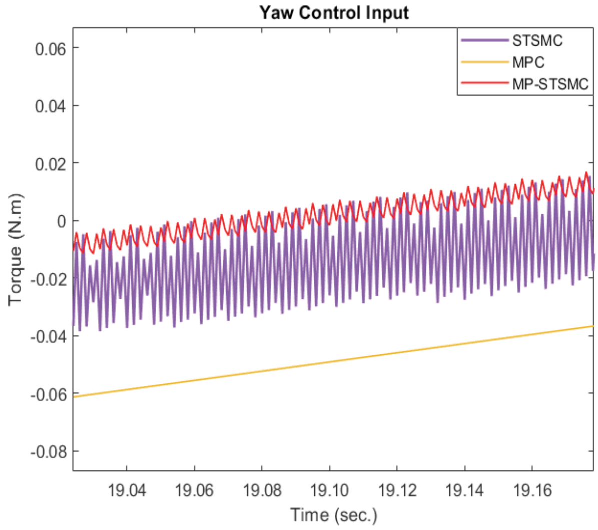


Fig. 6. Zoom in View of Control Inputs

ANALYSIS AND DISCUSSION OF RESULTS

The analyzing of outputs resulting from the three controllers can be done in most nonlinear control theories in terms of four common properties:

- *Transient response*
- *Steady-State response*
- *Robustness*
- *Chattering phenomenon*

Based on the tracking errors depicted in Fig. 4, an undesired overshoot is obviously observed in MPC algorithm during surge trajectory tracking. Indeed, this severe overshoot has been stemmed from the fast dynamic property of MPC approach. However, we can see a smooth transient response for the STSMC and proposed MP-STSMC. Also, due to a lack of robustness of a conventional MPC, an inaccurate trajectory tracking and an undesired steady state response are observed in Fig. 3 and Fig. 4, respectively. Concerning STSMC and MP-STSMC, an acceptable accuracy as well as high robustness has been observed in presence of time-varying external disturbances. As it is illustrated in Fig. 5, we have a reduction in control efforts of MP-STSMC in comparison with STSMC because of optimization feature present in MPC. Finally, it is easily to argue that both proposed and STSMC algorithms bring about an accurate trajectory tracking, however there are two additional advantages of the proposed MP-STSMC in contrast to STSMC. The extra advantages include optimal control efforts and chattering attenuation, shown in Fig. 6.

CONCLUSION AND FUTURE OUTLOOK

Regarding suitable control system in terms of real-time implementation for marine robotics platforms, particularly autonomous surface vehicles and unmanned ships, MPC algorithm can be an interesting choice. To model predictive controllers fast dynamic response and simplicity in their implementation into autonomous systems can be attributed. However, a paramount challenge for applying the MPC is its robustness against external disturbances and model uncertainties. In this research, the authors considered the weaknesses of MPC and developed an improved robust MPC to remove the lack of robustness in conventional MPC.

The new hybrid strategy consists of two main parts. The first part is a sliding mode-based MPC law, in which a Proportional Derivative (PD) sliding surface is considered a function which to be optimized by MPC. The second part is the super-twisting term which has been regarded to deal with the robustness of MPC. In the meanwhile, by using this robust strategy, the transient and steady-state responses of conventional MPC have been also enhanced. Super-twisting sliding mode control algorithm is an effective control method in the robust control category. However, due to switching structure of sliding mode algorithms, including first-order and higher-order sliding mode controllers, they have been associated with generating of chattering in their control inputs. In general, super-twisting method can be considered a chattering attenuation strategy among sliding mode controllers. However, for some applications with high external disturbances and complex cases such as control of autonomous surface vehicles in disturbed environment, the super-twisting algorithm might not be able to attenuate the chattering effectively. Therefore, the proposed algorithm MP-STSMC has drastically eliminated the chattering from STSMC algorithm.

Briefly, the presented robust MPC strategy offers a trade-off between a fast real-time controller and a robust controller. In the proposed approach, a high performance controller was developed in terms of transient response, robustness, optimal control efforts and steady-state response. As to future work, these authors intend to find a perfect mathematical proof procedure for stability analysis of the proposed control algorithm by using an approach based on Lyapunov theory.

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