DISTRIBUTED SCHEME FOR MAIN ENGINE POWER CONTROL SYSTEMS OF SMALL AND MEDIUM SIZED CONTAINER SHIPS BASED ON NASH EQUILIBRIUM

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SUMMARY

As a main force of ocean shipping, the energy consumption of container ships is considerably high due to the frequent load shifts of the main engines and other disturbances. In this study, for main engine power control systems consisted of several subsystems in small and medium sized container ships, a distributed scheme is proposed to relief input and output fluctuations caused by disturbances. First, a simplified interconnected model considering couplings among subsystems is established in a state space form. Second, a distributed model predictive control scheme based on Nash equilibrium is proposed to reduce influences from unknown and bounded disturbances by optimising in a negotiated manner. Finally, a contrast simulation is carried out between the proposed method and the decentralised model predictive control. The result shows that the proposed method works better than the decentralised one with less fluctuations. This study provides a theoretical basis for designs and reformations of main engine power control systems in small and medium sized container ships.

KEYWORDS

distributed control; small and medium sized container ship; main engine power control system; interconnected models

NOMENCLATURE

IMO	International Maritime Organisation
MPC	Model Predictive Control
DMPC	Distributed Model Predictive Control
NE-DMPC	DMPC based on Nash equilibrium
PID	Proportion Integral Derivative
KKT	Karush-Kuhn-Tucker
S_1	cooling water temperature control subsystem
S_2	main engine control subsystem
S_3	fuel oil viscosity control subsystem
S_i	Subsystem i
x_i	state of S_i
u_i	control input of S_i
z_i	interconnected input of S_i
y_i	output of S_i
v_i	disturbance of S_i
x_{is}	steady value of x_i
u_{is}	steady value of u_i
z_{is}	steady value of z_i
y_{is}	steady value of y_i
Δx_i	$\Delta x_i(k) = x_i(k) - x_{is}$
Δu_i	$\Delta u_i(k) = u_i(k) - u_{is}$
Δz_i	$\Delta z_i(k) = z_i(k) - z_{is}$
Δy_i	$\Delta y_i(k) = y_i(k) - y_{is}$
Q_i	weight matrix of error
R_i	weight matrix of control input
$J_{i,k}$	objective function of S_i at time $t=k$
A_i	system matrix of S_i
B_{iu}	control input matrix of S_i
B_{iz}	interconnected input matrix of S_i
C_i	output matrix of S_i

1. INTRODUCTION

Characterized by high efficiency, multiple collaboration, and low cargo loss rate, container ships play an important part in merchandise waterway transportation (Meng, Zhao, & Wang, 2019). In the latest research of Clarksons, container ships account for 58% in the new shipbuilding market in the first quarter of 2021 (http://www.eworldship.com/html/2021/ship_market_observation_0709/172706.html (Accessed 9th July 2021)). With the wide application of core technologies such as intelligent control (Wu, Jin, Liu, *et al*, 2021), internet of things (Philip, *et al*, 2021), artificial intelligence (Liu, *et al*, 2018), and cloud computing (Ogbole, Ogbole, & Olagesin, 2021), intelligent ships (e.g. autonomous underwater vehicles (Cai, Zhang, & Zheng, 2017) (Li & Yan, 2017), unmanned surface vessels (Peng, Liu, & Wang, 2020) (Hao, *et al.*, 2021), ships with intelligent navigation system (Zhang, *et al.*, 2021) (Zhang, *et al.*, 2020), etc.) have received increasing attention of researchers both at home and abroad. Therefore, the technical upgrading and systematic transformation of small and medium sized container ships are extremely urgent. As an essential part of a small and medium sized container ship, a main engine power control system provides propulsion for the ship, to ensure its normal navigation and safe operation on water. Consisted of several subsystems such as a main engine control subsystem, a cooling water temperature control subsystem, and a fuel oil viscosity control subsystem, the main engine power control system is an interconnected system involving many process variables and complicated couplings. The fuel oil viscosity control subsystem provides fuel oil for the main engine control subsystem, and the cooling water temperature control subsystem takes off excessive heat from burning oil in the main engine control subsystem.

Due to operational facility and positional dispersion, traditional controls (e.g. PID control, robust control, model predictive control (MPC), etc.) of the subsystems in the main engine power control system are always decentralised. Each subsystem optimises according to its own objective without information exchanged. The commonest control approach is PID. It is widely used in main engine power control systems due to its simplicity. But it is difficult for researchers to find an optimal set of PID parameters, especially in the complex and changeable working environment at sea. To solve the problem, studies on PID approach mainly focus on parameter tuning (Farouk & Sheng, 2011) (Shi, *et al.*, 2013) (Xiros, 2004) (Lan, 2020) and intelligent control methods combination (Li, Zhao, & Zhang, 2007) (Shen & Su, 2012). Another approach is robust control (Huang & Wang, 2007) (Wang & Wang, 2019) (Kim, 2012) (Hua, *et al.*, 2013) (Hirata, Ishizuki, & Suzuki, 2017). Designed offline at the worst case, the robust controller needs little manual intervention after the designing process. However, since the robust controller is not working at the optimal point, its control accuracy is comparably poor. As an advanced control algorithm, MPC can cope with constraints explicitly, and is able to compensate the system uncertainty caused by model mismatch, distortion, and interference in time (Qian & Zhao, 2007). According to whether the coupling information is exchanged among coupling subsystems or not, MPC methods can be divided as distributed MPC and decentralised MPC. To the best of our knowledge, the existed MPC studies of marine main engine power systems are all decentralised. For diesel engine timing control systems, Wang proposed a predictive function controller based on Morlet function (Wang, Wu, & Zhu, 2010), Emekli proposed an explicit model control algorithm (Emekli & Guvenc, 2017), and Wang proposed a predictive function control scheme based on multi models (Wang, *et al.*, 2018).

The above researchers have achieved good results in their concerned aspects using corresponding methods, but they did not consider the effect of interconnections among subsystems in the main engine power control system. Unknown about the latest change of the interconnected subsystem, the controller of the main engine power control subsystem uses a constant as its interconnected variable value. Thus, the variation of the interconnected variable is treated as a disturbance, and the control input changes accordingly. Particularly, when the system is subject to external disturbances such as load changes of main engine, fuel oil shifts of different origins or kinds, and so on, the control input will probably have a large fluctuation, which will lead to the waste of fuel oil and excessive emissions of exhaust gas. During normal ship navigation processes such as cruising, it is desirable for the main engine power control system to keep in a smooth operation mode to reduce oil consumption and exhaust emission, improve comfortableness of travelling experience, and prolong service lives of actuators.

As an alternative, distributed MPC can deal with system interconnection effectively by iterative computation and information exchange (Christofides, *et al*., 2013). Most widely used in power systems (Liu, *et al*., 2016) (Mroadzadeh, *et al*., 2012) (MA, *et al*., 2016), distributed MPC approaches can be divided into different categories according to different standards. For example, they can be divided as deterministic systems (Zhu, Guo, & Xie, 2018) (Xu, *et al*., 2009) and nondeterministic systems (Han, Zhang, & Zhang, 2016) according to system randomness, and can be divided as linear systems (Zanini, *et al*. 2011) (Wang & Ong, 2017), nonlinear system (Rosiane & Luís, 2016) (Liu, *et al*., 2012), and hybrid system (Zhang, Yue, & Xie, 2017) when classified by process type. With the advantage of simple structure and easy realization, the distributed model predictive control (DMPC) method based on Nash equilibrium (Dong & Krogh, 2001) (Du, Xi, & Li, 2002) utilizes local controllers to solve local optimisation problems, obtains interconnected variables of coupling subsystem through information exchange, and achieves a Nash equilibrium solution by multiple iterative calculations. With the development of Internet technology, it is possible to network the three subsystems of the main engine power control system through ship local area network, thereby constructing a distributed control structure of the whole system. Optimised in an overall perspective, the results will probably be more close to the global optimal solution, and the problems brought by information blocking can be solved. Having more information about its coupling subsystem, the main engine power subsystem can make a series of adjustments in advance to reduce frequent fluctuations in control inputs and outputs and finally control the corresponding energy consumption.

Giving full considerations to the couplings, this article sets an interconnected model of the main engine power control system of a small and medium-sized container ship, and proposes a distributed MPC method based on Nash equilibrium in the presence of unknown bounded disturbances. In Section 2, for the main engine power control system of small and medium sized container ships, an interconnected model is established and an optimisation problem is formulated with to ensure the smooth operation of the system. In Section 3, a distributed model predictive control scheme via Nash equilibrium is designed to solve the above optimisation problem. In Section 4, a contrast simulation is carried out to verify the effectiveness of the proposed scheme.

2. PROBLEM FORMULATION

For a small and medium sized container ship with a tonnage of 3000t to 10000t, a typical schematic diagram of the main engine power system is shown in Figure 1, and interconnections among subsystems of the main engine power control system are shown in Figure 2. The cooling water temperature control subsystem, the main engine control subsystem, and the fuel oil viscosity control subsystem (denoted as S_1, S_2, and S_3 for simplicity, respectively) have their own local controllers, but keep interconnected according to the dark blue lines with arrows shown in Figure 2. Take S_2 for example. On the one hand, it is obvious that the cooling water temperature from S_1 and the fuel oil viscosity from S_3 influence the operation status of the main engine in S_2. On the other hand, the heat produced by burning fuel oil in the cylinder is changed into mechanical energy, mostly used to provide propulsion for ship navigation and partly used to drive the fresh water pump. In other words, the speed of the fresh water pump from S_1 is in proportion to the speed of the main engine in S_2. Thus, the speed of the main engine affects the cooling water temperature of S_1 indirectly. Similarly, the exhaust gas produced by S_2 is used to heat the steam in S_3, whose flow is the control input of S_3, the higher the exhaust temperature is, the more the heat transfers to the fuel oil by steam. In a word, in the above main engine power control system, the outputs of the subsystems are not only dependent on their own states and control inputs, but also related to those of other subsystems. Since the decentralised control scheme neglects the coupling information, it may not be the first choice in the control of main engine power systems in small and medium sized container ships.

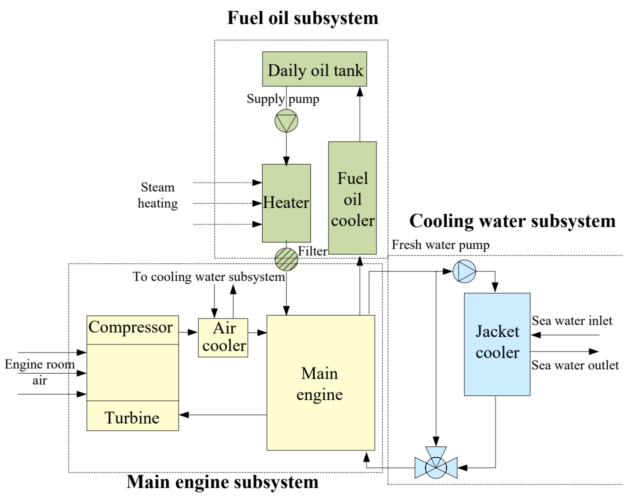

Figure 1: The typical schematic diagram of a main engine power system in a small and medium sized container ship

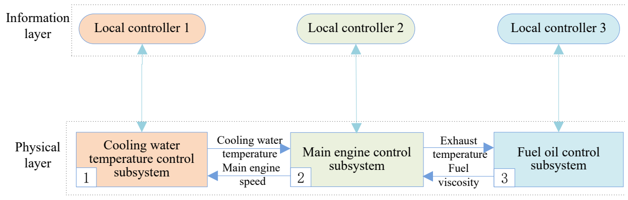

Figure 2: The interconnection diagram of a main engine power system in a small and medium sized container ship

To establish a distributed control scheme, an optimisation problem should be formulated first. For a given steady point $P_i(x_{is}, u_{is}, z_{is}, y_{is})$ of S_i, define $\Delta x_i(k) = x_i(k) - x_{is}$ $\Delta u_i(k) = u_i(k) - u_{is}$, $\Delta z_i(k) = z_i(k) - z_{is}$, $\Delta y_i(k) = y_i(k) - y_{is}$, where x_i is an n_i dimensional state variable, u_i is an m_i dimensional control input, z_i is a q_i dimensional interconnected input, and y_i is a r_i dimensional output, respectively. x_{is}, u_{is}, z_{is}, and y_{is} are the corresponding steady values at P_i, which are the values of states, outputs, control inputs and interconnected inputs of the main engine power control system during the cruising period of the ship in a normal operation. The optimisation problem is to find an optimal control vector $u_i^*(k)$ in a constraint condition of the system state space model so that the deviation values between the actual outputs and control inputs and the steady ones are minimum. Thus, we formulate it as a quadratic problem below:

$$\min_{\Delta u_i(k), \Delta u_i(k+1), \dots, \Delta u_i(k+M-1)} J_{i,k} = \frac{1}{2}\sum_{m=1}^{P}\left\|\Delta y_i(k+m)\right\|_{Q_i}^2 + \frac{1}{2}\sum_{m=0}^{M-1}\left\|\Delta u_i(k+m)\right\|_{R_i}^2, \ i = 1,2,3$$

s.t.

$$\begin{cases} \Delta x_i(k+1) = A_i \Delta x_i(k) + B_{iu}\Delta u_i(k) + B_{iz}\Delta z_i(k) + v_i(k) \\ \Delta y_i(k) = C_i \Delta x_i(k) \\ \Delta z_i = \sum_{j=1}^{n} L_{ij}\Delta x_j \end{cases}$$

where Q_i and R_i are the weight matrices of error and control input, and v_i(k) denotes an unknown bounded disturbance to S_i, $v_i(k) \in \Omega_i$, where Ω_i is an n_i dimensional vector set.

According to the relationship shown in Figure 2, an interconnected simplified model is set up by using similar methods in (Xu, 2000) (Chen, & Deng, 2011) (Liu, 2002) with coefficient matrices as

$$A_1 = \begin{bmatrix} 0.0012 & 0.0087 \\ 0.01 & 0.8501 \end{bmatrix},$$

$$A_2 = \begin{bmatrix} 0.9 & 0 & 0 & 0 \\ -0.2 & 0.9 & 0 & 0 \\ 0 & 0 & 0.85 & 0 \\ 0.06 & 0 & 0 & 1 \end{bmatrix}, \quad A_3 = \begin{bmatrix} 0.8 & -0.022 \\ -1.25 & 0.53 \end{bmatrix},$$

$B_{1u} = \begin{bmatrix} 0.25 & -0.001 \\ 0.04 & -0.002 \end{bmatrix}$,

$B_{2u} = \begin{bmatrix} 0.003 & 0.001 & 0.0005 & 0.02 \end{bmatrix}^T$,

$B_{3u} = \begin{bmatrix} -0.002 \\ 0.004 \end{bmatrix}$, $B_{1z} = \begin{bmatrix} -0.014 \\ 0.03 \end{bmatrix}$,

$B_{2z} = \begin{bmatrix} -0.15 & 0.0012 & 0.0006 & -0.15 \\ -0.03 & 0.0025 & 0.0006 & -0.03 \end{bmatrix}^T$,

$B_{3z} = \begin{bmatrix} -0.006 \\ 0.010 \end{bmatrix}$, $C_1 = \begin{bmatrix} 0 & 1 \end{bmatrix}$, $C_2 = \begin{bmatrix} 1 & 0 & 0 & 1 \end{bmatrix}$,

$C_3 = \begin{bmatrix} 1 & 0 \end{bmatrix}$. The corresponding variable list is shown in Table 1 coming from an underway small and medium sized container ship of Ningbo Marine Co., Ltd.

Remark 1: Since the interconnected system model considers the couplings among the three subsystems, it can be used in the distributed control scheme to relief frequent and violent fluctuations of system control inputs such as fuel oil injection amounts when load shifts of main engine or other disturbances occur. Thus, the high energy consumption and excessive emissions of exhaust gas can be controlled in some extent.

Table 1: Variable list of three subsystems in small and medium sized container ships

Sys.	Var.	Physical meaning	Steady Value
S_1	x_{11}	Inlet temperature of fresh water cooler	86°C
	x_{12}	Outlet temperature of fresh water cooler	75°C
	u_{11}	Valve lift of three-way valve	56%
	u_{12}	Flow of fresh water	0.78m^3/min
	z_1	Main engine speed	400r/min
	y_1	Outlet temperature of fresh water cooler	75°C
S_2	x_{21}	Main engine speed	400r/min
	x_{22}	Scavenging pressure	182kPa
	x_{23}	Discharge pressure	146kPa
	x_{24}	Exhaust temperature after turbine	228°C
	u_2	Fuel injection quantity per cylinder per cycle	1.63kg
	z_{21}	Outlet temperature of fresh water cooler	75°C
	z_{22}	Fuel viscosity	14cst
	y_{21}	Main engine speed	400r/min
	y_{22}	Exhaust temperature after turbine	228°C
S_3	x_{31}	Fuel viscosity	14cst
	x_{32}	Fuel temperature	125°C
	u_3	Steam flow	208kg/h
	z_3	Exhaust temperature after turbine	228°C
	y_3	Fuel viscosity	14cst

3. DISTRIBUTED MPC BASED ON NASH EQUILIBRIUM

For the interconnected model obtained in Section 2, centralized control is not applicable due to the dispersed geographical locations and high computation burdens. Distributed MPC has the great ability to deal with the couplings between subsystems effectively by information exchange and iterative computation. In this section, a DMPC control scheme based on Nash equilibrium in the presence of unknown bounded disturbances is proposed for the main engine power system of small and medium sized container ships.

For the optimisation problem in Section 2, we consider the nominal model in the formulation of the DMPC approach based on Nash equilibrium. Thus, the state deviation at time *k*+*m* can be represented as

$$\Delta x_i(k+m) = A_i^m \Delta x_i(k) + \sum_{s=0}^{m-1} A_i^s \left(B_{iu}\Delta u_i(k+m-1-s), + B_{iz}\Delta z_i(k+m-1-s)\right)$$

and the corresponding output is $\Delta y_i(k+m) = C_i A_i^m \Delta x_i(k)$

$$+C_i\left[\sum_{s=0}^{m-1} A_i^s \left(B_{iu}\Delta u_i(k+m-1-s) + B_{iz}\Delta z_i(k+m-1-s)\right)\right],$$

where $\Delta u_i(k+m)$
$=\Delta u_i(k+M-1), m > M-1$.

Define $\tilde{A}_{i,l} = \begin{bmatrix} A_i^0 & \cdots & A_i^{m-1} & \mathbf{0} & \cdots & \mathbf{0} \end{bmatrix}$,

$$\tilde{B}_{iu,m} = diag\Big\{\underbrace{B_{iu} \ \cdots \ B_{iu}}_{m} \ \underbrace{\mathbf{0} \ \cdots \ \mathbf{0}}_{M-m}\Big\},$$

$$\tilde{B}_{iz,m} = diag\Big\{\underbrace{B_{iz} \ \cdots \ B_{iz}}_{m} \ \underbrace{\mathbf{0} \ \cdots \ \mathbf{0}}_{P-m}\Big\},$$

$\Delta\tilde{u}_{i,m}(k) = \begin{bmatrix} \Delta u_i^T(k+m-1) & \cdots & \Delta u_i^T(k) & \mathbf{0} & \cdots & \mathbf{0} \end{bmatrix}^T$,

and

$\Delta\tilde{z}_{i,m}(k) = \begin{bmatrix} \Delta z_i^T(k+m-1) & \cdots & \Delta z_i^T(k) & \mathbf{0} & \cdots & \mathbf{0} \end{bmatrix}^T$.

Then, the deviation state and output changes to

$$\Delta x_i(k+m) = A_i^m \Delta x_i(k) + \tilde{A}_{i,m}\left(\tilde{B}_{iu,m}\Delta\tilde{u}_{i,m}(k) + \tilde{B}_{iz,m}\Delta\tilde{z}_{i,m}(k)\right)$$

and $\Delta y_i(k+m)=C_i\left[A_i^m\Delta x_i(k)+\tilde{A}_{i,m}\left(\tilde{B}_{iu,m}\Delta\tilde{u}_{i,m}(k).\right.\right.$

$\left.\left.+\tilde{B}_{iz,m}\Delta\tilde{z}_{i,m}(k)\right)\right]$ Defining

$$\Delta X_i(k)=\left[\Delta x_i^T(k+1)\ \cdots\ \Delta x_i^T(k+P)\right]^T,$$

$$\Delta Y_i(k)=\left[\Delta y_i^T(k+1)\ \cdots\ \Delta y_i^T(k+P)\right]^T,$$

$$\hat{A}_i=\left[\left(A_i\right)^T\ \cdots\ \left(A_i^P\right)^T\right]^T,$$

$$\overline{A}_i=\left[\left(C_iA_i\right)^T\ \cdots\ \left(C_iA_i^P\right)^T\right]^T,$$

$$\hat{\tilde{B}}_{iu}=diag\left\{\tilde{A}_{i,1}\tilde{B}_{iu,1}\ \cdots\ \tilde{A}_{i,P}\tilde{B}_{iu,P}\right\},$$

$$\overline{\tilde{B}}_{iu}=diag\left\{C_i\tilde{A}_{i,1}\tilde{B}_{iu,1}\ \cdots\ C_i\tilde{A}_{i,P}\tilde{B}_{iu,P}\right\},$$

$$\Delta\overline{\tilde{u}}_i(k)=\left[\Delta\tilde{u}_{i,1}^T(k)\ \cdots\ \Delta\tilde{u}_{i,M}^T(k)\right]^T,$$

$$\hat{\tilde{B}}_{iz}=diag\left\{\tilde{A}_{i,1}\tilde{B}_{iz,1}\ \cdots\ \tilde{A}_{i,P}\tilde{B}_{iz,P}\right\},$$

$$\overline{\tilde{B}}_{iz}=diag\left\{C_i\tilde{A}_{i,1}\tilde{B}_{iz,1}\ \cdots\ C_i\tilde{A}_{i,P}\tilde{B}_{iz,P}\right\},$$

$$\Delta\overline{\tilde{z}}_i(k)=\left[\Delta\tilde{z}_{i,1}^T(k)\ \cdots\ \Delta\tilde{z}_{i,P}^T(k)\right]^T,$$

we can derive a state space model in an augmented form as follows:

$$\begin{cases}\Delta X_i(k)=\hat{A}_i\Delta x_i(k)+\hat{\tilde{B}}_{iu}\Delta\overline{\tilde{u}}_i(k)+\hat{\tilde{B}}_{iz}\Delta\overline{\tilde{z}}_i(k)\\ \Delta Y_i(k)=\overline{A}_i\Delta x_i(k)+\overline{\tilde{B}}_{iu}\Delta\overline{\tilde{u}}_i(k)+\overline{\tilde{B}}_{iz}\Delta\overline{\tilde{z}}_i(k)\end{cases}$$

Define $\Delta U_i(k)=\left[\Delta u_i^T(k)\ \cdots\ \Delta u_i^T(k+M-1)\right]^T$,

$$\tilde{Q}_i(k)=diag\left\{\underbrace{Q_i(k),\cdots,Q_i(k)}_{P}\right\},$$

$$\tilde{R}_i(k)=diag\left\{\underbrace{R_i(k),\cdots,R_i(k)}_{M}\right\}.$$

Then, the objective function can be transferred into the following form:

$$\min_{\Delta u_i(k),\ldots,\Delta u_i(k+M-1)} J_{i,k}=$$
$$\frac{1}{2}\left(\overline{A}_i\Delta x_i(k)+\overline{\tilde{B}}_{iu}\Delta\overline{\tilde{u}}_i(k)+\overline{\tilde{B}}_{iz}\Delta\overline{\tilde{z}}_i(k)\right)^T\tilde{Q}_i\left(\overline{A}_i\Delta x_i(k)\right.$$
$$\left.+B_{iu}\Delta\tilde{u}_i(k)+B_{iz}\Delta\tilde{z}_i(k)\right)$$
$$+\frac{1}{2}\left(\Delta U_i(k)\right)'\tilde{R}_i\left(\Delta U_i(k)\right)$$

where $\overline{\tilde{u}}_i(k)=G_iU_i(k)$, $G_i=\left[G_{i1}^T\ \ G_{i2}^T\ \cdots\ G_{iP}^T\right]^T$,

$$G_{ij}=\left[\begin{array}{c|c}\begin{matrix}\mathbf{0} & \cdots & I\\ \vdots & \iddots & \vdots\\ I & \cdots & \mathbf{0}\end{matrix} & \mathbf{0}_{m_ij\times m_i(M-j)}\\ \hline \mathbf{0}_{m_i(M-j)\times m_ij} & \mathbf{0}_{m_i(M-j)\times m_i(M-j)}\end{array}\right],j=1,\ldots P.$$

According to KKT (Karush-Kuhn-Tucker) condition (Bazaraa, Sherali, Shetty, 2005), we can derive the optimal control input as follows:

$$\Delta U_i(k)=-\left(\left(\hat{\tilde{B}}_{iu}G_i\right)^T\tilde{Q}_i\hat{\tilde{B}}_{iu}G_i+\tilde{R}_i\right)^{-1}\left(\tilde{Q}_i\hat{\tilde{B}}_{iu}G_i\right)^T\psi_i(k)$$

where $\psi_i(k)=\overline{A}_i\Delta x_i(k)+\overline{\tilde{B}}_{iz}\Delta\overline{\tilde{z}}_i(k)$. In conclusion, for subsystem S_i at time $t=k$, the optimisation process of DMPC based on Nash equilibrium (NE-DMPC) is as follows:

Step 1 Initialize $\Delta x_i(k)$, and exchange coupling information to obtain $\Delta\tilde{z}_{i,l}(k)$.

Step 2 Solve the optimisation problem in Section 2 using NE-DMPC, and obtain $\Delta U_i^{(q)}(k)$ (q is an iteration number).

Step 3 If $\left\|\Delta U_i^{(q)}(k)-\Delta U_i^{(q-1)}(k)\right\|\geq\varepsilon$ (ε is a very small positive number), return Step 1.

Step 4 Implement the control input on the actual subsystem at time k, and obtain the actual state deviation $\Delta x_i(k)$.

Step 5 Update the correlation output deviation $\Delta z_i(k)$, and obtain the correlation input deviation $\Delta z_i(k)$.

Step 6 Let k=k+1, and return Step 1.

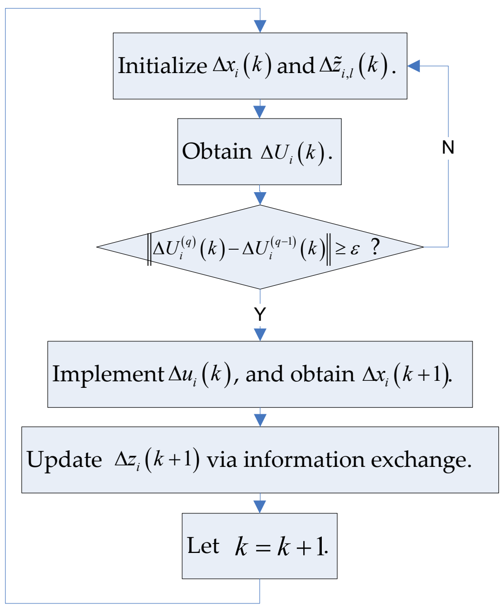

Figure 3: Flow chart of NE-DMPC

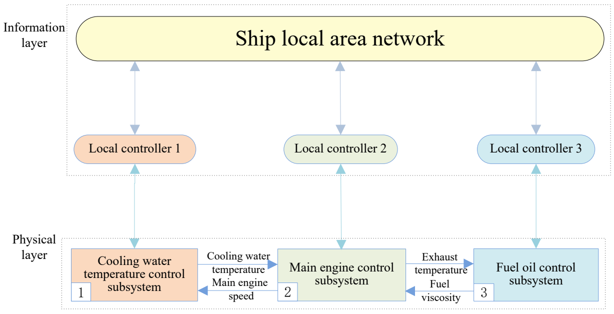

Figure 4: NE-DMPC structure of the main engine power control system of small and medium sized container ships

The flow chart and structure of NE-DMPC are shown in Figure 3 and Figure 4, respectively.

Remark 2: In practical applications, each subsystem has its own independent controller. Each controller obtains the optimal control signal according to its own optimisation goal and applies it to the actual subsystem. Due to the coupling effect between subsystems, each subsystem needs to exchange related information several times in each optimisation horizon, and then repeats the optimisation calculation until the convergence condition is satisfied.

4. SIMULATION

4.1 PARAMETER SELECTION

To evaluate the effectiveness of the proposed distributed control scheme (i.e. NE-DMPC) designed in Section 3, a contrast simulation between an NE-DMPC and a decentralised MPC is carried out using MATLAB in this section. As shown in Table 2, the main difference between the two methods is whether the system model considers system couplings or not.

The simulation is carried out in Matlab 2017b with simulation time $T = 200\,\text{min}$. Considering the priorities of system variables, the weight matrices are chosen as $Q_1 = 7$, $Q_2 = diag(5,5)$, $Q_3 = 3$, $R_1 = diag(0.3,0.2)$, $R_2 = 0.5$, $R_3 = 0.5$. The predictive and control horizon are chosen as $P = 6$ and $M = 4$. The actual data at the steady point P_i have been shown in Table 1.

For normal operation of the main engine power system of small and medium sized container ships, disturbances are inevitable such as temperature variance of sea water, type transformation of fuel oil, load shift of main engine, and so on. In this simulation, disturbances are applied to each subsystem by simulating practical applications. For S_1, the temperature disturbances change slowly and continuously, so we choose a sine wave signal. For S_2 and S_3, the load shift or type transformation is generally a change in sudden, so we choose rectangular waves. The specific settings of the disturbances are shown in Table 3.

Table 3: Disturbances setting

Disturbance variable	Application time	Value
v_1	6-25s	$0.005x_{s1}\sin\left(\frac{\pi}{10}(t-6)\right)$
	26-45s	$0.0025x_{s1}\sin\left(\frac{\pi}{20}(t-26)\right)$
v_2	6-20s	$-0.0025x_{s2}$
	21-35s	$0.001x_{s2}$
v_3	6-15s	$0.0025x_{s3}$
	16-25s	$-0.0015x_{s3}$

4.2 RESULTS ANALYSIS

Some comparative results between the NE-DMPC approach and the decentralised MPC method are presented in Figure 5, Figure 6, Table 4, and Table 5. Figure 5 and Figure 6 show the variances of control inputs and outputs of the three subsystems, respectively. Table 4 and Table 5 give the objective function values and the maximum variable deviations from steady values, respectively. The two figures and tables all indicate that the NE-DMPC approach works more effectively towards fluctuation suppressing compared with the decentralised method.

Table 2: The optimisation problem of the NE-DMPC and the decentralised MPC

Item	NE-DMPC	Decentralised MPC
Objective function	$\min\limits_{\Delta u_i(k),\ldots,\Delta u_i(k+M-1)} J_{i,k} = \frac{1}{2}\sum_{m=1}^{P}\left\|\Delta y_i(k+m)\right\|_{Q_i}^2 + \sum_{m=0}^{M-1}\left\|\Delta u_i(k+m)\right\|_{R_i}^2$	
System model	$\begin{cases}\Delta x_i(k+1) = A_i\Delta x_i(k) + B_{iu}\Delta u_i(k) + B_{iz}\sum_{j=1}^{n} L_{ij}\Delta x_j \\ \Delta y_i(k) = C_i\Delta x_i(k)\end{cases}$	$\begin{cases}\Delta x_i(k+1) = A_i\Delta x_i(k) + B_{iu}\Delta u_i(k) \\ \Delta y_i(k) = C_i\Delta x_i(k)\end{cases}$

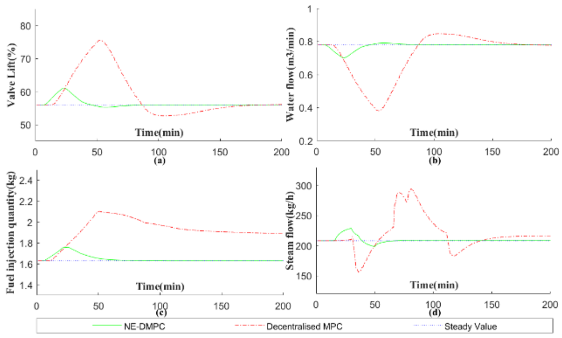

Figure 5: The control input variances of the three subsystems of small and medium sized container ships
(a) The variances of valve lift of S_1.
(b) The variances of water flow of S_1.
(c) The variances of fuel injection quantity of S_2.
(d) The variances of steam flow of S_3.

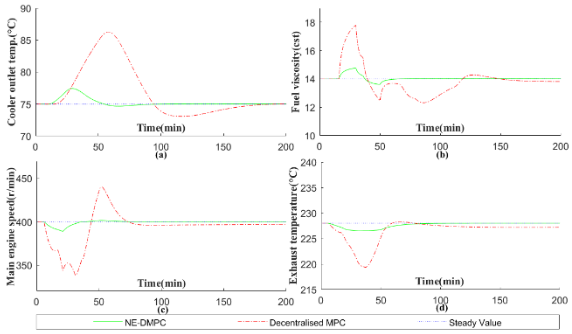

Figure 6: The output variances of the three subsystems of small and medium sized container ships
(a) The variances of cooler outlet temperature of S_1.
(b) The variances of main engine speed of S_2.
(c) The variances of exhaust temperature of S_2.
(d) The variances of fuel viscosity of S_3.

Table 4: Comparison of objective function values

Algorithm	Objection function value
NE-DMPC	5040
Decentralised MPC	270420

Table 5: Comparison of the maximum variable deviations from the steady values

Variables	NE-DMPC	Decentralised MPC	Fluctuation suppression rate
y_1	2.4°C	11.3°C	78.8%
y_{21}	11.16r/min	61.72r/min	81.9%
y_{22}	1.5°C	8.6°C	82.6%
y_3	0.77cst	3.80cst	79.7%
u_{11}	4.59%	19.55%	76.5%
u_{12}	0.079m^3/min	0.40m^3/min	80.3%
u_2	0.13kg	0.47kg	72.3%
u_3	20.74kg/h	86.67kg/h	76.1%

From Figure 5 and Figure 6, we can see that by using the NE-DMPC method, the control input and output variables have smaller fluctuations, faster reaction process, less oscillations, and no steady-state errors. Considering the interconnections among subsystems in advance, the NE-DMPC approach reduces over regulations and chain reactions of these subsystems, thus improving the overall performance. In Figure 5 (c), more fuel oil is wasted by using the decentralised MPC method due to the over regulation of fuel injection quantity, which goes against the national policy of energy conservation and emission reduction. To sum up, compared with the decentralised MPC, the NE-DMPC deals well with the influence from external disturbance, and keeps the system operating smoothly, which is extremely important to the main engine power systems of small and medium sized container ships to ensure safe and steady voyages.

5. CONCLUSIONS

With the increasing development of information technology, searching for new control styles of energy saving and exhaust reduction is extremely urgent for the main engine power system of small and medium sized container ships. This article established a novel control scheme by setting up an interconnected model and designing a distributed MPC method based on Nash equilibrium in the presence of unknown bounded disturbances. Compared with the traditional decentralised methods, the simulation results show that this scheme reduces the fluctuation of control and output effectively, and can ensure the smooth operation of the system in the existence of disturbances such as load changes, and reduce energy consumption. The result of this article lays a theoretical foundation for the designs and reformation of main engine power control systems in small and medium sized container ships, while the practical application needs more future studies.

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