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Thrusters

Comparative Investigation on Influence of the Positioning Time of Azimuth Thrusters on the Accuracy of DP

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1. Introduction

The Voith Schneider Propeller (VSP) allows extremely fast thrust variation [1]. Contrary to all other types of azimuth thrusters (thrust changes accordingly to polar coordinates), the thrust is varied on the basis of X/Y logic. Fig. 1 shows both thruster types; the Voith Radial Propeller (VRP) is an azimuth thruster developed by Voith Turbo Marine. As a result, ships with VSP can be kept stable in dynamic positioning (DP) mode, while the rolling motion of the vessel can also be reduced. DP capabilities and good sea handling are very important for the offshore industry.

Fig. 1 Voith Schneider Propeller (VSP) and Voith Azimuth Thruster (VRP)

In 2003, Voith Turbo Schneider Propulsion started to carry out intensive research programs aimed at making the VSP available to the offshore industry as an efficient propulsion system. These R & D activities focused primarily on the development of the Voith Roll Stabilization (VRS), model tests and CFD calculations on the interaction between the ship's hull and the propulsor ([2], [3] and [4]).

The first VSP-driven platform supply vessel is the Edda Fram (Fig. 2.) of Ostensjö Rederi AS. In the meantime, the vessel has demonstrated the successful application of VSPs in offshore service in over 35 000 operating hours. The Voith Schneider Propeller enables the ship to perform very safe DP operations, lowers fuel consumption and ensures excellent sea behavior - the latter especially because of the Voith Roll Stabilization (VRS).

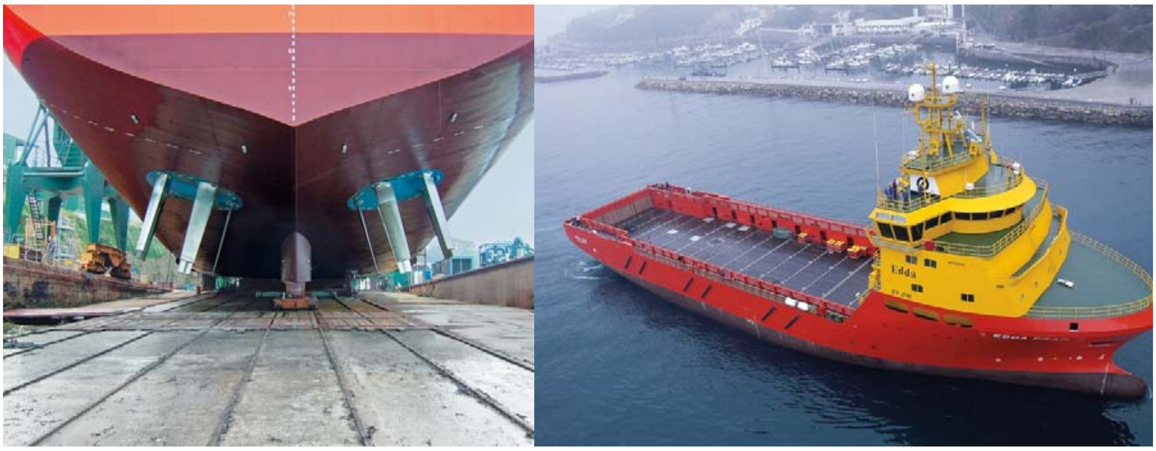

Fig. 2 Platform Support Vessel EDDA FRAM (Shipbuilder Astilleros Gondan), in successful operation since 2007.

In the meantime, numerous Offshore Supply Vessels (OSV) are in regular service with Voith Schneider Propellers. A few examples are listed below.

2. Offshore Support Vessels with Voith Schneider Propulsion

At present, the North Sea Giant (Fig. 3) is the most high-powered Offshore Support Vessel with Voith Schneider Propellers. The ship is fitted with 5 Voith Schneider Propellers, each with an input power of 3800 kW.

Fig. 3 North Sea GIANT (Shipbuilder Astilleros Metalship), driven by 5 Voith Schneider Propellers VSP 36R6 ECS

Operating under extreme conditions, the ship has proven its excellent DP capabilities. It has been used successfully for the installation of tidal turbines near the Orkney Islands, where the speeds of the tide currents can reach up to 4.5 kn.

Another example is a Voith Water Tractor with DP 2 system and Voith Roll Stabilization operated by Edison Chouest Offshore (Fig. 4.).

 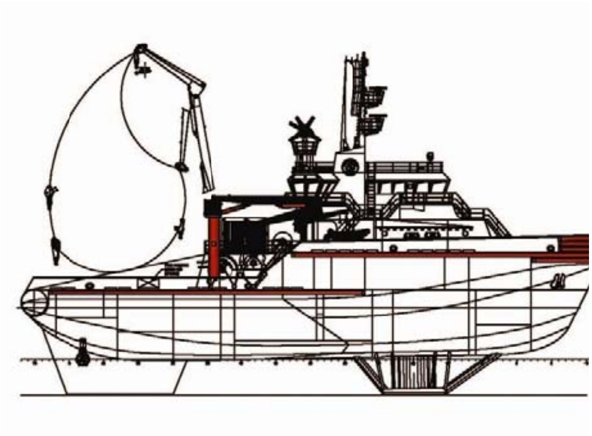

Fig. 4 Voith Water Tractor for offshore applications, LWL 49.38 m, 2 x VSP 36R6 ECR/285-2, input power 2x 3970 kW ; shipbuilder: North American Shipbuilders

Especially within the scope of the SAFETUG project [5] of the Netherlands test laboratory MARIN it has been possible to demonstrate that the Voith Water Tractor does not lose its escorting properties even if conditions at sea are extremely rough, and that its loss of thrust caused by the impact of strong waves is very low. Within the SAFETUG project it was possible to prove that the rolling motions of a Voith Water Tractor can be reduced by approximately 70% though the active utilization of the Voith Roll Stabilization.

Supplying offshore wind turbines with service personnel and materials will become an important task in the future. The 34-meter workboat shown in Fig. 5 is driven by two Voith Schneider Propellers and used for supplying lighthouses and navigational aids. The German authority operating the ship has gained excellent experiences with the vessel. Personnel transitions can be carried out very safely, because the ship is able to hold its position thanks to the VSP.

 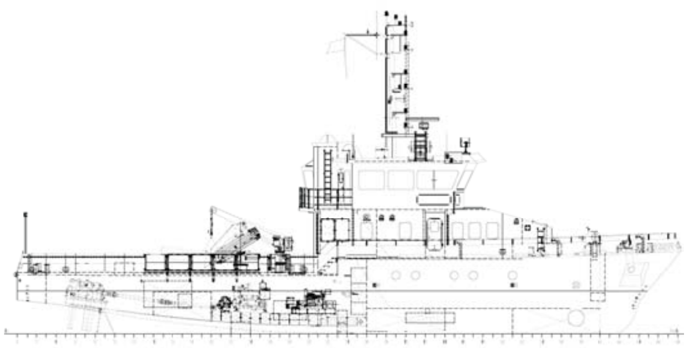

Fig. 5 Workboat of WSA Bremerhaven with excellent maneuvering capabilities for supplying lighthouses and navigational aids with technicians and materials; Shipbuilder Fassmer yards

3. Technical and physical reasons for the advantages of VSPs in offshore service

In offshore service, the following demands on thrusters are of utmost relevance:

- High availability,
- DP capabilities (DP mode is decisive for the successful operation of OSVs),
- Low fuel consumption and
- Positive impact on sea handling.

The Voith Schneider Propeller is fundamentally different from other azimuth thrusters. Fig. 6 shows the Voith Schneider Propeller and its kinematics, as well as the installation position in the ship.

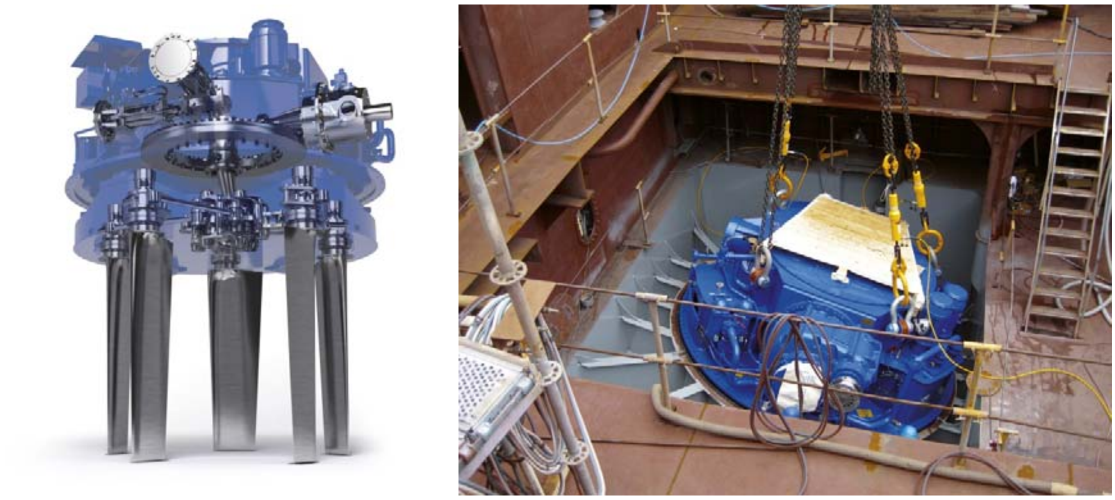

Fig. 6 Voith Schneider kinematics and installation of VSP into a vessel

The Voith Schneider Propeller varies its thrust following a X/Y logic. This allows setting the required thrust level very quickly. Fig. 7 explains how quickly the thrust of the Voith Schneider Propellers can be changed between two positions. This highlights the difference between the VSP and other azimuth propellers.

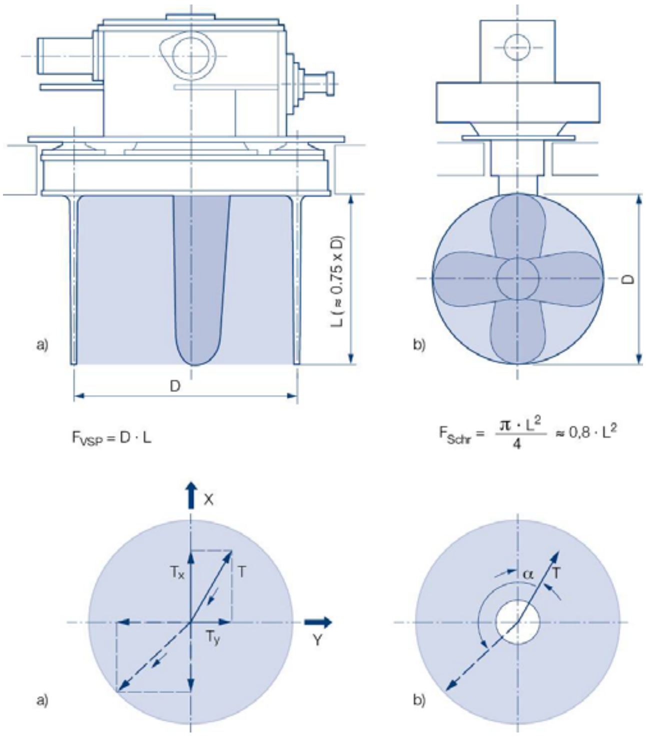

Fig. 7 Thrust variation a) Voith Schneider Propeller based on X/Y logic and b) Azimuth thruster based on polar coordinates

3. Hydrodynamic effects of the Voith Schneider Propeller

The Voith Schneider Propeller is advantageous for offshore applications, because it differs significantly from conventional thrusters. This applies specifically to:

- Accuracy in DP mode,
- Behavior towards ventilation,
- Reduction of loads due to slamming,
- Degree of propulsion quality in transit,
- Power uptake during dynamic positioning and
- Capability of reducing rolling motions of OSVs.

The accuracy of DP mode is well known in practical operation. A possibility to assess it also quantitatively is offered through simulation.

4. Dynamic Positioning

In DP operation, the vessel maintains its position and direction by the drives which are steered by a control system and act against external disruptive forces, such as wind, waves and currents [6]. In the following, two drives are examined - the Voith-Schneider-Propeller (VSP) as well as an azimuth propeller. A comparison will be made how fast they can react to external disturbances and how much energy is needed for this process.

4.1. DP System

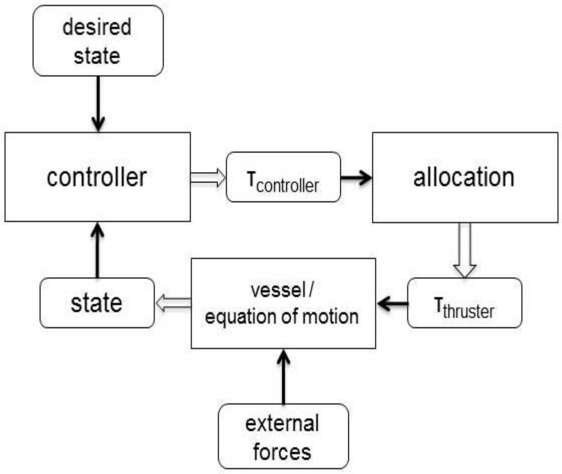

Figure 8: DP system consisting of regulator, allocation and motion compensation

Figure 8 depicts a simplified DP system in its individual steps.
The given situation comprises a desired position $\hat{\eta} \in \mathbb{R}^3$, the current position $\eta(t) \in \mathbb{R}^3$, as well as the current speed $\nu(t) \in \mathbb{R}^3$. Position and speed consist of the components surge, sway und yaw.
Using the deviation

$$e(t) = \eta(t) - \hat{\eta}$$

and its derivation

$$\dot{e}(t) = \nu(t)$$

the control system calculates a force τ, which is to allow the ship to sail closer to the desired position $\hat{\eta}$.
In the next step, the allocation, the control settings of the propellers are determined in such a way that the force τ required by the control system is, as far as possible, generated by the propellers, requiring as little energy as possible. Which forces τ_{thr} can be generated by the propellers, and/or which control settings, such as rpm n, control stick position x, y, are possible for a VSP, or which azimuth angles are possible for an azimuth propeller, depends on the prevailing control settings as well as the control times of the propellers.
In order to calculate the force τ_{thr}, an constrained optimization problem, for example the SQP process (sequential quadratic programming), has to be solved.
For VSP-driven ships, the formula is

$$J(\tau_{thr}, x, y, n) := w \cdot power(x, y, n) + \|\tau_{PID} - \tau_{thr}(x, y, n)\|_2^2) \rightarrow Min,$$

subject to

$$x_{min} \leq x \leq x_{max}$$
$$y_{min} \leq y \leq y_{max}$$
$$n_{min} \leq n \leq n_{max}$$

For azimuth-driven ships, it is

$$J(\tau_{thr}, \alpha, n) := w \cdot power(\alpha, n) + \|\tau_{PID} - \tau_{thr}(\alpha, n)\|_2^2) \rightarrow Min,$$

subject to

$$\alpha_{min} \leq \alpha \leq \alpha_{max}$$
$$n_{min} \leq n \leq n_{max}$$

The parameter $w \in \mathbb{R}$ to be chosen weights the proportion of power in the objective function. The variables x, y, α and n are vectors of the length m, with m representing the number of propellers. The position $\eta(t + \Delta t)$ and speed $\nu(t + \Delta t)$ is established by the equation of motion (see [7]), depicted in simplified form as follows:

$$M\dot{\nu} + D\nu = \tau_{thr} + \tau_{ext}$$

In the following calculations, the external disruptive forces τ_{ext} were assumed to be constant or sinusoidal.

4.2. PID Controller

A possibility for calculating the desired force τ_{PID} is the widely known PID controller. The PID controller consists of three components: the proportional term P, the integral term I and the differential term D. The constants P, I and D weight the control deviation $e(t)$, the integral via $e(t)$ as well as the deviation. The force τ_{PID} is presented by (see. [8])

$$\tau_{PID}(t) = Pe(t) + D\dot{e}(t) + I\int_0^t e(s)ds.$$

The constants P, I and D can be determined via an optimal control problem. The objective is the minimization of the objective function J (see [7], [9])

$$J(\tau) = \frac{1}{2}\int_0^\infty e(t)^T Q e(t) + \tau(t)^T R \tau(t) dt,$$

in which $Q,\ R \in \mathbb{R}^{3\times3}$ are selected like this, so that the control deviation and the control τ are weighted accordingly. The matrix R has to be the positive definite, while the matrix Q must be positive semidefinite. For the reference point $\hat{\eta} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$ the objective function can be formulated as follows:

$$J(\tau) = \frac{1}{2}\int_0^\infty \eta(t)^T Q \eta(t) + \tau(t)^T R \tau(t) dt.$$

This objective function is minimized under the precondition that the following equation of state is being met:

$$\underbrace{\begin{pmatrix}\dot{z}\\ \dot{\eta}\\ \dot{\nu}\end{pmatrix}}_{\dot{x}} = \underbrace{\begin{pmatrix}0 & I & 0\\ 0 & 0 & I\\ 0 & 0 & -M^{-1}D\end{pmatrix}}_{A}\underbrace{\begin{pmatrix}z\\ \eta\\ \nu\end{pmatrix}}_{x} + \underbrace{\begin{pmatrix}0\\ 0\\ M^{-1}\end{pmatrix}}_{B}\tau,$$

which means: $\dot{x} = Ax + B\tau$.

According to Pontryagin's minimum principle, the minimum condition

$$H(t, x^*, \lambda, \tau^*) = \min_{\tau} H(t, x^*, \lambda, \tau)$$

for the force τ results in

$$\tau = -R^{-1}B^T\lambda.$$

The function $H(t, x, \lambda, \tau)$ depicts the Hamilton function

$$H(t, x, \lambda, \tau) = \frac{1}{2}(x^T C^T QCx + \tau^T R\tau) + \lambda^T(Ax + B\tau),$$

with $C = (\mathbf{0}_{3\times3}, I_{3\times3}, \mathbf{0}_{3\times3})$.

The adjoint equation

$$\dot{\lambda} = -H_x(t, x, \lambda, \tau)$$

together with the state equation results in the Hamilton system

$$\begin{pmatrix}\dot{x}\\ \dot{\lambda}\end{pmatrix} = \begin{pmatrix}A & -R^{-1}B^T\\ -C^T QC & -A^T\end{pmatrix}\begin{pmatrix}x\\ \lambda\end{pmatrix}$$

which can be solved through the Algebraic Riccati Equation (ARE)

$$PA + A^T P - PBR^{-1}B^T P + C^T QC = \mathbf{0},$$
with $Px = \lambda$

Further details are provided in [9].
With $\lambda = Px$ applying, the force τ linearly depends on x, which implies:

$$\begin{aligned}\tau(t) &= -R^{-1}B^T\lambda(t)\\ &= \underbrace{-R^{-1}B^T P}_{:= G = (G_1, G_2, G_3)}\ x(t)\\ &= G_1 \cdot z(t) + G_2 \cdot \eta(t) + G_3 \cdot \nu(t)\\ &= I \cdot \int_0^t \eta(s)ds + P \cdot \eta(t) + D \cdot \nu(t)\end{aligned}$$

4.3. Results

The following calculations are based on the supply vessel of Matlab Toolbox MSS GNC/Hydro [10] .

Data of Supply Vessel:
Lpp: $82m$
T: $6\ m$
B: $19\ m$
m: $6362\ t$

The external forces affected the vessel in x-direction with an amplitude of $500\ kN$ and a frequency of $\frac{1}{60}\ Hz$. The required output and the accuracy of a VSP-driven vessel and an azimuth propeller-driven vessel were compared. In both cases, the vessel had two stern-mounted drive systems, each with a maximum rating of $3600\ kW$.
For the control times, the following values were assumed:
Propeller revolution n: $0\ \rightarrow 100\%$ in $30\ sec$.
Pitch (VSP): $-100\%\ \rightarrow 100\%$ in $5\ sec$.
Azimuth angle α: $0° \rightarrow 180°$ in $15\ sec$.

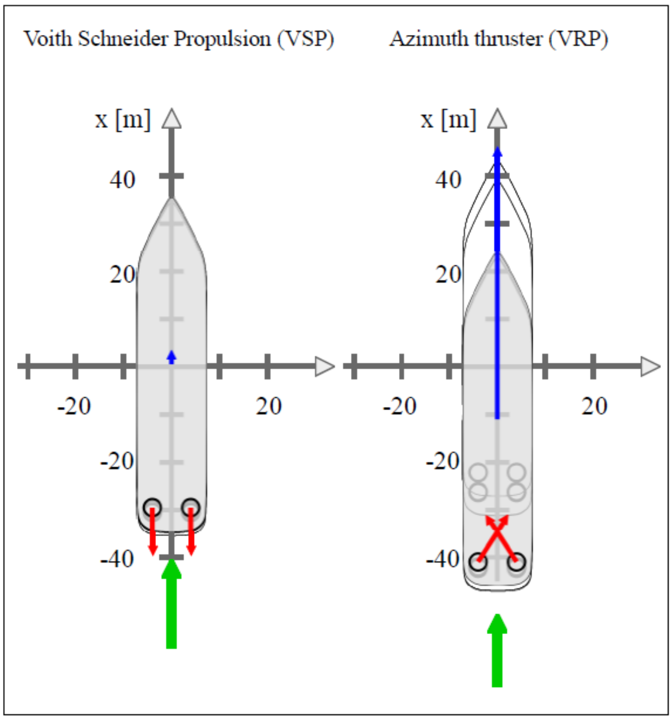

Figure 9: periodic external force (amplitude: 500kN, frequency: 1/60Hz) affecting the vessel

maximum deviation: VSP (left): 0.5m, azimuth (right): 12.5m

Due to the advantageous control times, the VSP can react significantly faster and more efficiently to the external disruptive forces. Figure 9 shows the position of the vessels after about one period

$(60\ sec.)$. The VSP already acts against the external force, while the azimuth still needs to rotate in order to do so. For this reason, the azimuth still generates thrust in the same direction as the external force for several seconds. This also affects the accuracy. While the VSP-driven vessel moves away from the desired position by a maximum of 0.5 m, the vessel with the azimuth propellers deviates by 12.5 m.

A further advantage of the VSP is depicted in figure 10, which illustrates the total power required by the propellers. Unlike the two azimuth propellers, which require a total of ~ 121 MJ over one period, the VSPs only need ~ 98 MJ.

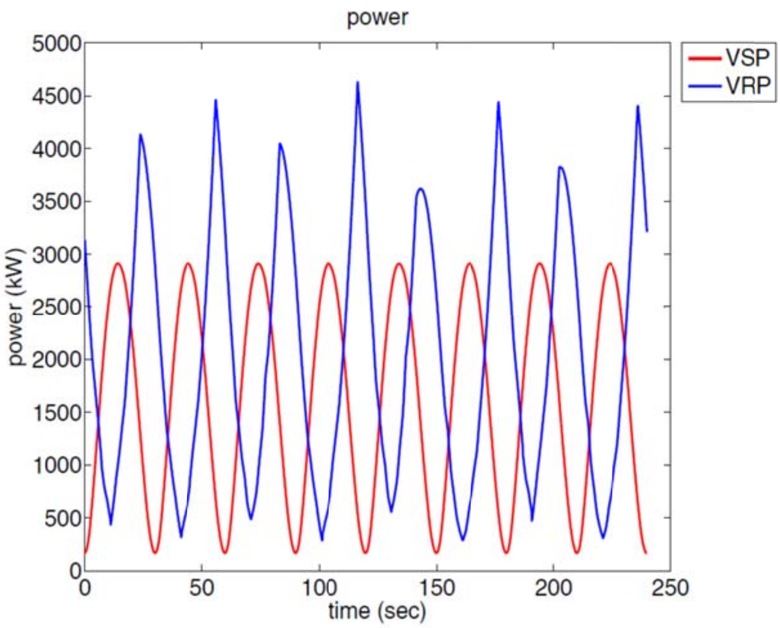

Figure 10: Required propeller output (kW): (VSP / red, Azimuth / blue).

The vessel with the VSP propulsion system also benefited from the short control times in further calculations. After doubling the frequency of the disruptive forces of $\frac{1}{60}Hz$ to $\frac{1}{30}Hz$. the disruption was still evened out by the VSP, while the azimuth drives did no longer cope.

In the event of suddenly occurring disturbances, the azimuth drives were also not able to achieve the desired position as quickly as the VSP drives.

5. Summary and Outlook

Voith Turbo Schneider Propulsion will focus on the enhanced integration of Voith Roll Stabilization into the DP. The target is an excellent DP behaviour with a minimum of platform motions. There are planned model tests and calculations in time domain for different types of OSV and new ways to allocate the thruster forces of the Voith Schneider Propeller accordingly.

In future, the PID control is to be replaced by a predictive control system. The PID-control determines the force τ_{PID} only via the current position and speed. Predictive control, on the other hand, also considers the position via a period $\tilde{T}$. As a general rule, the force τ is determined over this period in such a way that the integral is minimized via the squared control deviation or via the weighted sum of the squared control deviation and the squared force τ [11] .

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