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Thrust allocation with power management functionality on dynamically positioned vessels

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Abstract—**A thrust allocation method with capabilities to assist the power management system on dynamically positioned ships is proposed in this paper. Its main benefits are reduction in frequency and/or load variations on the electric network, and a formulation of thruster bias which can be released when required by the power management system. To reduce load variations without increasing overall power consumption it is necessary to deviate from the thrust command given by the dynamic positioning system or joystick. The resulting deviation in position and velocity of the vessel is tightly controlled, and results show that small deviations are sufficient to fulfill the objective. For simplicity, the study has been limited to thrusters with fixed direction, having in mind that generalizations are fairly straightforward.**

Index Terms—**Thrust Allocation, Surface Vessels, Power Management**

I. INTRODUCTION

DIESEL-ELECTRIC propulsion on offshore vessels has been used extensively in the high-end market in the North Sea since the early 90s. The development in the recent years has been that diesel-electric propulsion has increased its marked share, to the point that it has become standard in the offshore industry world-wide. The main benefits of diesel-electric propulsion and thrusters are reduced power consumption under operational conditions typical for certain vessel types, resilience to equipment failures, lighter engines, and less noise [6]. Ensuring fuel-optimal operation during normal conditions as well as continued fulfillment of the operational requirements despite equipment failures introduces new challenges for the control system.

Consumers on a ship may include hotel loads, drilling units, heave compensators, cranes, pumps, winches and many more, but the thrusters and the propulsion system remain the largest consumer on most ships. The issue of power-optimal thrust allocation is discussed in [11]. That paper proposes a power limit as part of the optimization algorithm in thrust allocation. It also addresses the issue of wear-and-tear in generators by making the load on the switchboards as evenly distributed as possible. In [10], typical causes of failure in power generation are described and systematised.

Typical controller design of a dynamic positioning system separately considers the task of thrust allocation, that is calculating what force the individual thrusters should produce so that the total force and angular moment on the ship will be as commanded. This command may be produced by a dynamic positioning system or a joystick. A survey of the state of the art thrust allocation technology is available in [9], with [3] being one of the first academic publications that considered non-quadratic cost function for power consumption.

The main benefit of the proposed thrust allocation algorithm is that it controls thrusters in a way that makes it possible to introduce controlled variations of power consumption into the electric network. Two ways to exploit these variations are proposed. One is to compensate for the load variations from consumers elsewhere on the ship. This will reduce wear-and-tear on the power generating units, as well as the NO_X emissions. Large and rapid load variations could be produced by for example a drilling system, fire fighting pumps, heave compensators or the anchor winches. The other use is to reduce frequency variations on the electric network, improving its stability and reducing the likelihood of a blackout event. Both practices may significantly contribute to decreased likelihood of DP position loss events, which were caused by failure in power generation systems in 10-24% of incidences during the period of 2000-2004 [10]. Increased reliability leads to reduced need for safety margins, which means that the power plant may be operated closer to its peak efficiency and thus generate less waste products and emissions into the environment.

For any feasible thrust command given to the thrust allocation there exists a minimal value for the power consumption needed to achieve this command. This gives two ways to control variations in power consumption. The first option is to maintain a thruster bias as a reserve. This way, when a reduction in power consumption is requested to compensate for an increase elsewhere, the thrust allocation algorithm can release some or all of this bias. The second option is to let power consumption go below this minimal value, allowing a temporary deviation between commanded and generated thrust.

Using bias inevitably increases the power consumption. Be-

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cause of that, the only suggested use for thruster bias is to assist Fast Load Reduction (FLR). This will be discussed later in this section. The proposed algorithm explores only the second option, allowing a deviation between commanded and generated thrust. It then takes measures to ensure that the resulting deviations in position and velocity of the vessel are confined within a specified range that does not exceed the requirements of the dynamic positioning system.

The proposed thrust allocation algorithm formalizes the notion of using thruster bias to assist FLR. For any given azimuth and rudder angles, the combined force vector and angular momentum produced by the thrusters is

$$\tau = B(\alpha)Kf \tag{1}$$

and is a linear combination of the forces f generated by the individual thrusters. If there are four or more thrusters onboard the ship, then the matrix $B(\alpha)K$ is guaranteed to have a non-trivial null space F_0 so that for any $f_0 \in F_0$, $B(\alpha)Kf_0 = 0$. This means that it is always possible to bias the thrusters, since adding some $f_0 \in F_0$ to the thruster command f will not change the combined thrust. The power consumption will change, and, if f minimizes power consumption, then the power consumption will increase by changing f.

The addition of f_0 can serve two purposes. One is to ensure that the thrust allocation can instantly reduce its power consumption by returning back to thrust allocation f without significantly deviating from the desired thrust command τ_d, thus increasing the capacity of the the Fast Load Reduction. Classification societies require that vessels performing certain operations must be able to keep their position even if some of the generators fail to deliver power to the network due to a single-point failure. This means that the generators must at all times be prepared to take over the load of a failing generator. After a single generator fails in a system of N generators the total transferred load step the remaining generators must be able to accept will be $\Delta P_{tran,g} = max\,(P_{gi}) - \Delta P_{FLR}^{max}$ [2, page 12], where P_{gi} is the power produced by generator number i, making $max\,(P_{gi})$ the load of the heaviest loaded generator, and ΔP_{FLR}^{max} the maximal load reduction FLR is able to make[3]. A typical diesel generator is unable to accept a load step of more than 25 to 30 percent of its rated power; if the generators currently online are unable to accept $\Delta P_{tran,g}$ in the instance of a generator failure, additional generators must be started as a spinning reserve.

This means that although biasing thrusters seemingly wastes power and thus fuel, under certain circumstances it may allow the power management system to avoid starting additional generators. This may result in a net saving of fuel, since the additional generators would operate at lower efficiency.

An outline of the proposed algorithm is given in Section III. Optimization problems in Section III contain continuous terms, which must be discretized before being solved with standard solvers. This is done in Section IV. Results are presented in Section V, and the conclusion in Section VII.

II. Nomenclature

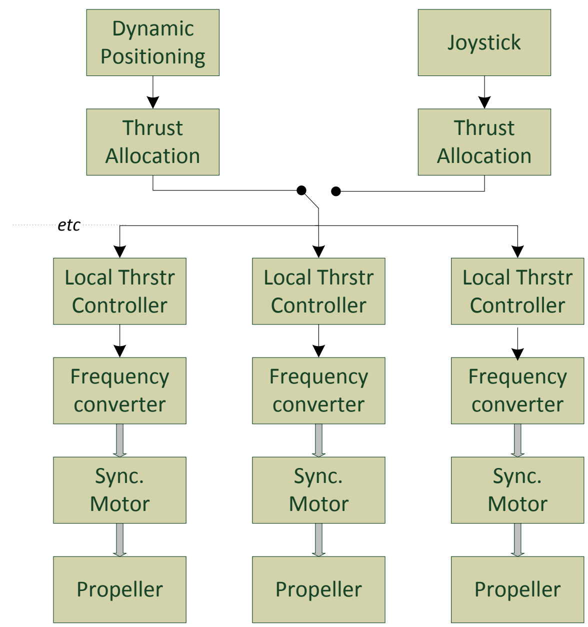

Figure 1. Control hierarchy of a vessel in dynamic positioning mode. DP and joystick could in principle share the thrust allocation algorithm, but in practical applications they usually do not.

Terms

- *Power Management System, PMS* - A system that controls the power generation, distribution and consumption, by commanding the speed governors, AVRs, circuit breakers and variable speed drive consumer (VSDs).
- *Dynamic Positioning System, DP* - A system that maintains position of a maritime vessel using its thrusters, in presence of disturbances such as wind, waves and current. In the context of control algorithm design, the DP is an algorithm which assesses position of the vessel based on various instruments, calculates how far it is from a desired position selected by operator, and based on that decides the thruster force needed to get to the desired position.
- *Thrust Allocation, TA* - An algorithm that takes as input the desired total force and moment that the thrusters need to produce, and calculates what forces the individual thrusters need to produce so that total force and moment on the vessel will be as desired.

[3]This situation is further complicated by the fact that it takes some time, typically in range of 100-200 milliseconds [11], for the FLR system to reduce the load, while the diesel generators are able to accept very high loads for very short periods of time at the expense of a fall in frequency. This must be handled by the power management system, and falls out of scope for the present work.

- *Thruster* - Any unit capable of producing controlled thrust on the vessel. For some thrusters, the direction in which they produce thrust may be controlled, while others may only produce thrust in a fixed direction.
- *Fast Load Reduction system, FLR* - A function of the PMS. In situations of critical overload of one or more generators, this function will attempt to prevent blackout by rapidly reducing the loads of the consumers, primarily by reducing the power consumption by the VSDs, and secondarily by shedding groups of nonessential consumers from the electric grid.
- *Thruster bias* - A situation where thrusters on a ship are acting against each other, using more power than is necessary to generate the commanded thrust. The thrust allocation algorithm presented in this paper may be ordered to bias thrusters to consume a specific amount of surplus power. This surplus power can be released instantly at request, making it easier to prevent blackout when the power generating capacity is reduced due to faults.
- *AVR, Automatic Voltage Regulator* - a controller in electrical generators that maintains a desired voltage on the output terminals by controlling magnetization of the coils in the rotor.

Non-standard expressions

For $x \in R^N$, $Q = Q^T \in R^{N \times N} \succ 0$, $Q = LL^T$

$$|x|^p \triangleq [|x_1|^p, |x_2|^p, \dots |x_N|^p]^T \tag{2}$$

$$|x|^p\, sign(f) \triangleq \begin{bmatrix} |x_1|^p\, sign(f_1) \\ |x_2|^p\, sign(f_2) \\ \vdots \\ |x_N|^p\, sign(f_N) \end{bmatrix} \tag{3}$$

Notice that $|x|^p \in \mathbb{R}^N$, and is not a vector norm.

$$\|x\|_Q^2 \triangleq x^T Q x = \|Lx\|_2^2 \tag{4}$$

Common abbreviations

Description	*Letter*
Current time, i.e. time when the thrust allocation problem is solved.	T
Deviation in respectively velocity and position of the vessel from what they would have been if thrust command was allocated exactly, as functions of time. $v_{err}(t)$, $x_{err}(t) \in \mathbb{R}^3$ contain longitudinal, lateral and heading components; $v_{err,\,T} \triangleq v_{err}(t = T)$, $x_{err,\,T} \triangleq x_{err}(t = T)$	$v_{err}(t)$, $x_{err}(t)$, $v_{err,\,T}$, $x_{err,\,T}$
Maximal allowed values for $v_{err}(t)$ and $x_{err}(t)$	$v_{err,\,max}$, $x_{err,\,max}$
Lower and upper limits for the integrals in (10), (11) which calculate deviations in velocity and position at time T_e.	T_s, T_e
Respectively actual and desired angular frequency of the voltage on the electrical network. Typically, $\omega_{0g} = 2\pi \cdot 60$.	ω_g, ω_{0g}
Thruster configuration matrix. It is a function of the vector α consisting of orientations of the individual thrusters. In this paper, α is assumed to be constant.	$B(\alpha)$
Number of thrusters installed on the ship.	N
$f \in \mathbb{R}^N$, the force produced by individual thrusters. The elements of f are normalized into range $[-1, 1]$.	f
$K \in \mathbb{R}^{N \times N}$ such that Kf is the vector of forces in Newtons.	K
$P_c \in \mathbb{R}^{1 \times N}$ such that (8) holds.	P_c
$\Psi \succ 0$, quadratic cost matrix of variation in force produced by individual thrusters.	Ψ
$\Theta \in \mathbb{R}^+$ is the cost of variation in total power consumption.	Θ
The total power consumed by the thrusters per (8)	P_{th}
The desired rate of change of power consumption by the thrusters. This signal can be used to reduce either frequency or load variations on the electrical network.	$\dot{P}_{ff}$
Minimal power consumption by the thrusters needed to produce commanded thrust.	P_{min}
Actual and desired generalized force produced by all thrusters. τ, $\tau_d \in \mathbb{R}^3$ contain surge and sway forces, and yaw moment.	τ, τ_d

III. Method

This section presents the proposed method, with some implementational details left for later sections.

As the first step, the thrust allocation problem is solved for minimal power consumption without regard to variation in

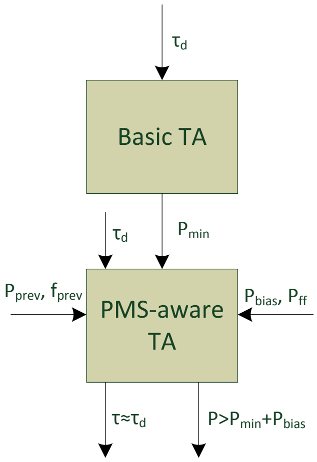

Figure 2. Steps in the proposed thrust allocation algorithm. First, a basic thrust allocation algorithm computes the minimal power necessary to allocate commanded thrust. Then, a PMS-aware thrust allocation allocates thrust with a bias so that total power consumption is at least this minimal possible value plus a bias.

the power consumption. This method is well-documented in the literature - although usually with quadratic power cost function; see [5].

$$P_{min} = \min_{f,s} P_c K \left|f\right|^{3/2} + \left\|s\right\|^2_{Q_1} \tag{5}$$

subject to

$$B(\alpha)Kf = \tau_d + s \tag{6}$$

$$\underline{f} \leq f \leq \overline{f} \tag{7}$$

Ideally, the thrust allocation algorithm should fulfill the thrust command τ_d exactly, which would imply $s \equiv 0$. This may not be possible without violating the constraint (7). Therefore, s must be allowed to be non-zero, with the cost matrix Q_1 being large enough to ensure that s is significantly larger than zero only when constraints (6)-(7) would otherwise be infeasible. The constraint (6) therefore ensures that the produced generalized force τ for practical purposes is equal to the commanded force τ_d unless the commanded force is infeasible, while (7) ensures that thrusters are not commanded to produce more thrust than their maximal capacity. The solution to this optimization problem provides a minimum P_{min} to which the power consumption can be reduced while delivering the requested thrust τ_d, at least as long as the condition $s \approx 0$ holds. Power consumption in thrusters is estimated by the nonlinear relationship

$$P_{th} = P_c K \left|f\right|^{3/2} \tag{8}$$

which is similar to what was used in [3].

In this paper we propose the following thrust allocation optimization problem for normal operational conditions:

$$\begin{gathered}\min_{f,\tau_e,s_1,s_2} P_c K \left|f\right|^{3/2} + \left\|K\dot{f}\right\|^2_{\Psi} + \Theta\left(\dot{P}_{th} - \dot{P}_{ff}\right)^2 + \\ \left\|\tau_e\right\|^2_{Q_2} + \left\|s_1\right\|^2_{Q_3} + \left\|s_2\right\|^2_{Q_4}\end{gathered} \tag{9}$$

subject to

$$-v_{err,max} \leq M^{-1}\int_{T_s}^{T_e} B(\alpha)Kf(t) - \tau_d dt + s_1 \leq v_{err,max} \tag{10}$$

$$-x_{err,max} \leq \int_{T_s}^{T_e} v_{err}(t)dt + s_2 \leq x_{err,max} \tag{11}$$

$$B(\alpha)Kf = \tau_d + \tau_e \tag{12}$$

$$P_{max} \geq P_c K \left|f\right|^{3/2} \geq P_{min} + P_{bias} \tag{13}$$

$$\underline{f} \leq f \leq \overline{f} \tag{14}$$

This optimization problem includes cost for variations in power consumption and in force produced by individual thrusters. It uses a smaller cost Q_2 on deviation from thrust allocation command τ_d, that is $Q_2 \ll Q_1$. This is to allow the produced generalized force τ to deviate from τ_d whenever this is beneficial. Use of τ_e instead of s for this deviation is meant to emphasize that significant deviations are to be expected. The relationship between the optimization variable f and the derivatives $\dot{f}$ and $\dot{P}_{th}$ can be derived using a discretization scheme e.g. forward Euler.

In a practical system a limit on maximal power consumption has to be imposed. It is introduced as P_{max} in (13). This limit necessitates the slack variables s_1 and s_2 in the constraints (10) and (11), with cost matrices Q_3 and Q_4 large enough to ensure that s_1 and s_2 will significantly deviate from zero only if the constraints (10) and (11) would otherwise be infeasible.

Allowing this deviation means that the ship can accelerate differently than commanded. Quantitatively, the difference in acceleration is $M^{-1}\left(B(\alpha)Kf - \tau_d\right)$, expressed in the body frame. If the orientation of the vessel remains constant, the resulting velocity error v_{err} can be calculated by integrating the error in acceleration. It is also possible to perform integration in an inertial frame of reference, but doing so would require thrust allocation to know the vessel's orientation and would complicate the calculations.

In the algorithm it is assumed that the orientation remains *approximately* constant. This allows velocity to be constrained within a pre-defined range by imposing (10). The error in position is calculated by integrating the velocity error - again assuming approximately constant orientation. The error in position is constrained by (11).

The middle terms of equations (10) and (11) represent deviations in the ship's velocity and position, at time T_e, from what they would have been if the thrust allocation command were to be executed exactly. In exact physical interpretation T_s must be the time when thrust allocation started running[4].

[4]Strictly speaking, any time when those deviations happened to be zero.

In practice it is desired to let the thrust allocation operate on a shorter time scale than dynamic positioning, since the dynamic positioning system will also attempt to correct a deviation in position. In the implementation, the choice was made to let integration start five seconds in the past relative to when the thrust allocation is solved. The discussion of the end time of the integral is delayed until Section IV.

Without the $\dot{P}_{ff}$ signal the third term in (9) would be zero if thrust allocation consumed exactly same amount of power as in the previous iteration of the algorithm. The power feedforward term P_{ff} signals a "soft" requirement for thrust allocation to increase or decrease its power consumption compared to power consumption in the previous iteration. As mentioned in the introduction, there are two application for this signal. One use is in cases where the ship has other power consumers that rapidly vary their consumption in predictable patterns. Then $\dot{P}_{ff}$ can be used to reduce variations in total power consumption by setting

$$\dot{P}_{ff} = -\dot{P}_{others} \tag{15}$$

where P_{others} is the power consumption by other consumers on the vessel. The other use is to stabilize network frequency by setting it to

$$\dot{P}_{ff} = -k_{gp}(\omega_g - \omega_{0g}) \tag{16}$$

where k_{gp} is a positive constant. A similar control strategy is employed in [1] on the level of local thruster controllers. Since a local thruster controller has no information about what other local controllers are doing, that strategy does not allow for guarantees regarding the ship's position or velocity.

The presence of a power bias is ensured with the constraint (13), where the addition of a vector from the null space of $B(\alpha)Kf$ is implicit in the optimization task.

IV. Discretization and constraint handling

Neither of the optimization problems used so far attempt to predict the trajectory of the system based on any kind of model. However, a solution of a thrust allocation problem is applied on the vessel for some time δt, until a new solution is calculated. This implicitly assumes that the system state will be approximately constant during δt, otherwise the output would become sub-optimal during this period. For constraints (10), (11) the only part of the signal f in the integrals that is under control in any optimization step is f in the future from the current time. It is therefore natural to evaluate constraints (10), (11) at the end of the period during which the solution is to be applied on the vessel. This choice admits the possibility that constraints would be violated during the allocation period. Since (10) integrates over a constant term, this problem only applies to (11) and in any case is not large enough to be practically significant.

Separating the continuous integrals in (10) into past, and the time from present until the next thrust allocation is calculated,

$$\begin{aligned} -v_{err,\,max} \leq\ & \underbrace{M^{-1}\int_{T_s}^{T} T(\alpha)Kf(t) - \tau_d(t)dt}_{v_{err,\,T}} + \\ & M^{-1}\int_{T}^{T+\delta t} \underbrace{T(\alpha)Kf_T - \tau_{d,T}}_{\tau_{err,\,T}} dt \\ \leq\ & v_{err,\,max} \end{aligned} \tag{17}$$

Figure 3. Time horizon of integration

The value of the first integral, $v_{err,\,T}$, is given each time the thrust allocation is solved. The second integral is over a constant term, and can be solved exactly.

Solving the second integral of (17),

$$M^{-1}T(\alpha)Kf\delta t \leq v_{err,\,max} + M^{-1}\tau_{d,T}\delta t - v_{err,\,T} \tag{18}$$

$$-M^{-1}T(\alpha)Kf\delta t \leq v_{err,\,max} - M^{-1}\tau_{d,T}\delta t + v_{err,\,T} \tag{19}$$

Similarly, for (11),

$$x_{err,\,T+\delta t} = \underbrace{\int_{T_s}^{T} v_{err,\,T}dt}_{x_{err,\,T}} + v_{err,\,T}\delta t + M^{-1}\tau_{err,\,T}\frac{(\delta t)^2}{2} \tag{20}$$

Resulting in following inequalities:

$$M\tau_{err,\,T}\frac{(\delta t)^2}{2} \leq x_{err,max} - x_{err,T} - v_{err,T}\delta t \tag{21}$$

$$-M^{-1}\tau_{err,\,T}\frac{(\delta t)^2}{2} \leq x_{err\,max} + x_{err,T} + v_{err,T}\delta t \tag{22}$$

If the ship has a significant momentum in the direction that would violate constraints (21)-(22) during δt, it would require a large force over this time period to stop it. Also, when constraints (18)-(19) are approached, thrust allocation may have to start delivering thrust exactly as commanded, without any further possibility to assist the power management system. It is therefore desirable to soften the constraints, so that the thrust allocation algorithm starts taking action some time before the constraints are reached. This can be achieved by adding a term in the cost function that would increase as the state of the system approaches the constraints. A quadratic function has proved to provide excellent results:

$$z_{v,x} = \|v_{err,\,T+\delta t}\|^2_{Q_v} + \|x_{err,\,T+\delta t}\|^2_{Q_x} \tag{23}$$

where $v_{err,T+\delta T} = v_{err,T} + M^{-1}\tau_{err,T}\delta t$ and $x_{err,T+\delta t}$ is defined in (20). The diagonal matrices Q_v and Q_x are selected such that if one of the values in the error vectors $x_{err,\,T+\delta t}$ or $v_{err,\,T+\delta t}$ reaches its constraint while all other states are held to zero, the following will approximately hold:

$$z_{v,x} \approx \max_i P_{ci} K_{i,i} \tag{24}$$

where P_{ci} is the element i in the vector P_c, and $K_{i,i}$ is the diagonal element number i of the matrix K. This would imply a cost for violating the constraints equal to the cost of the most powerful thruster running at full power.

V. Results

The algorithm was tested in simulation, on SV Northern Clipper, featured in [5]. The simulated vessel is 76.2 meters long, has four thrusters, with two tunnel thrusters near the bow and two azimuth thrusters at the stern. Since the presented algorithm does not handle thrusters with variable thrust angle, the azimuth thrusters were locked in position 45° towards the center line. All the thrusters are assumed to be symmetric, each capable of producing a thrust equivalent to 1/40 of the ship's weight. The simulated ship is in dynamic positioning mode, dynamic positioning being implemented with three independent PID controllers, one in each degree of freedom. The following limits on velocity and position errors were selected: $v_{err,\,max} = \begin{bmatrix} 0.1 & 0.1 & 0.1 \cdot \pi/180 \end{bmatrix}^T$, $x_{err,\,max} = \begin{bmatrix} 0.5 & 0.5 & 0.5 \cdot \pi/180 \end{bmatrix}^T$.

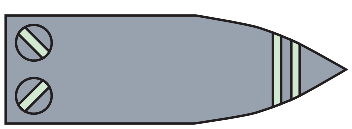

Figure 4. Thruster layout of the simulated vessel

In the simulation, the vessel started two meters away from the setpoint, in the longitudinal direction. Then, 30 seconds into the simulation, a steady external disturbance (i.e. wind, wave, current) of 1% of the ship's weight is applied.

The load from the other consumers on the ship was modelled as the sum of a constant component of 100 kW, and periodic spikes of 200 kW. The feedforwad term $\dot{P}_{ff}$ in (9) was set to the reverse of the load variation by other consumers, $\dot{P}_{ff} = -\dot{P}_{others}$. This way, the thrust allocation attempts to compensate for load variations elsewhere when this is feasible and does not incur too large costs in the other terms of (9).

Two experiments were run. In Experiment A the thrust allocation was required by PMS to bias the thrusters so that they could reduce their power consumption by 500 kW instantaneously at request by PMS, and immediately after this request be able to allocate the thrust command exactly. The reserve was released 60 seconds into the simulation. The TA considers this an emergency event, and reverts to simple thrust allocation by (5)-(7). In Experiment B, no such reserve needed to be kept and constraint (13) was disabled.

Since the power consumption in Experiment A always has to be higher than P_{min}, there is little motivation to deviate from the requested thrust. Also, since the thrusters must consume at least $P_{min}+P_{bias}$, they are unable to compensate for consumption increases elsewhere unless they happen to consume more than this minimum at the time of consumption increase - which they in general do not. The thrusters are, however, able to compensate for rapid decreases in power consumption. This obviously wastes fuel, so the value of power variation weight Θ should be selected carefully so that the reductions in wear-and-tear and frequency variations justify the increased fuel consumption.

In Experiment B, the thrust allocation was not required to keep a power reserve. As can be seen from Figure 10, upon sudden increases in demand from other consumers the algorithm was able to momentarily decrease power consumption in the thrusters. The cost of this was a deviation between commanded and produced thrust. The resulting deviation in the vessel's velocity was small, as expected. There was a significant stationary part in the deviation in position, which was easily corrected by the DP. Figures 7, 8 and 12 show the middle terms in constraints (10) and (11), which represent deviations in the position and velocity of the ship from what those states would have been with the simple thrust allocation algorithm described by equations (5)-(7) with the same thrust order from the DP. The power consumption in the thrusters was close to zero from approximately 15 to 30 seconds into the simulation. This of course made further decreases impossible, resulting in some load spikes getting through to the power generation system.

VI. Future work

The most immediate continuation of this work is to demonstrate effects of the proposed thrust allocation algorithm on the power system by simulating the electric power system with variations in bus frequency, fuel consumption and emissions. Also, in order to be implemented on a practical vessel, the algorithm needs to be able to control thrusters with variable force direction, such as azimuth thrusters and rudder-propeller pairs.

Dynamics due to local controllers in the propulsion units are not covered in this work. Practical implementations should consider that local controllers may have load-up curves and other functionality.

This algorithm only considers the case where all power generation is on a single electrical power network. Functionality

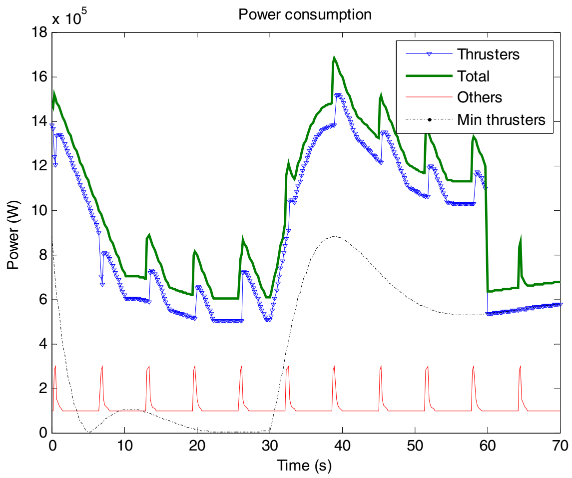

Figure 5. Experiment A; the total power consumption.

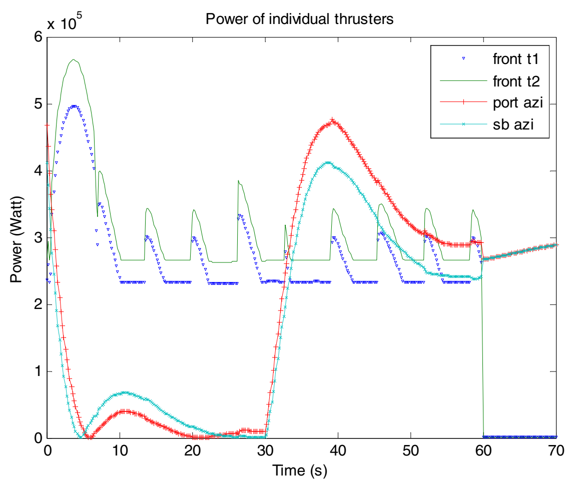

Figure 6. Experiment A; power consumption in individual thrusters.

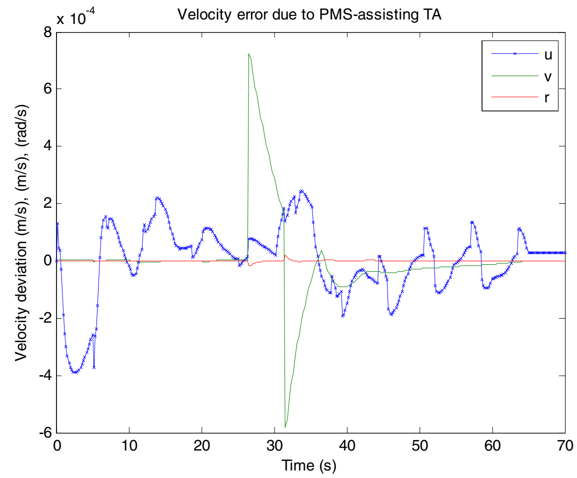

Figure 7. Experiment A; velocity error due to new features.

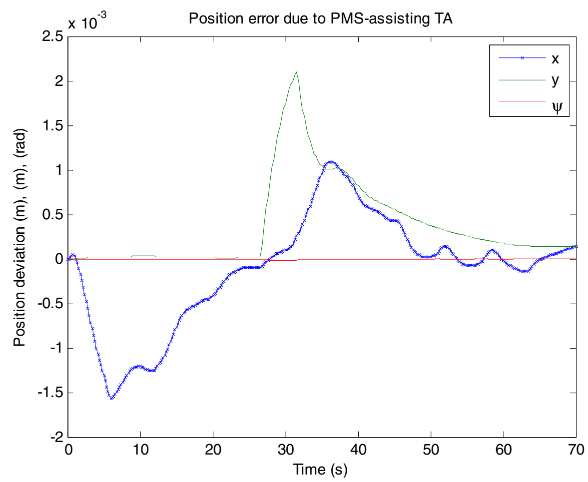

Figure 8. Experiment A; position error due to new features.

for split network operation should also be considered. Even in cases with connected network, effort should be made to even out the load on switchboards to minimalize the current flow through the circuit breakers.

VII. Conclusion

The proposed thrust allocation algorithm successfully reduces load variations on the power generation system, at the cost of increased variations in the propulsion units and deviations from the thrust command. These deviations are successfully constrained within an acceptable range in terms of deviation velocity and position of the vessel. The algorithm reduces the power variations most effectively when thrust allocation is not required to bias thrusters by the PMS.

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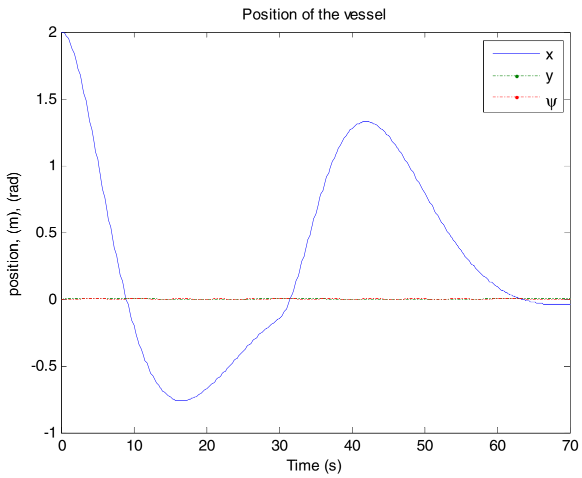

Figure 9. Experiment A; position of the vessel.

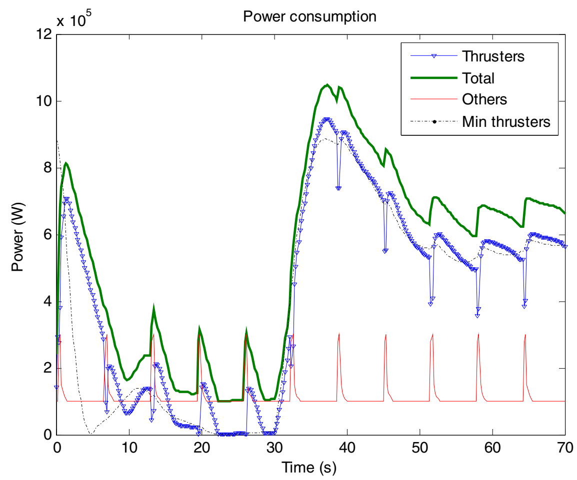

Figure 10. Experiment B; total power consumption.

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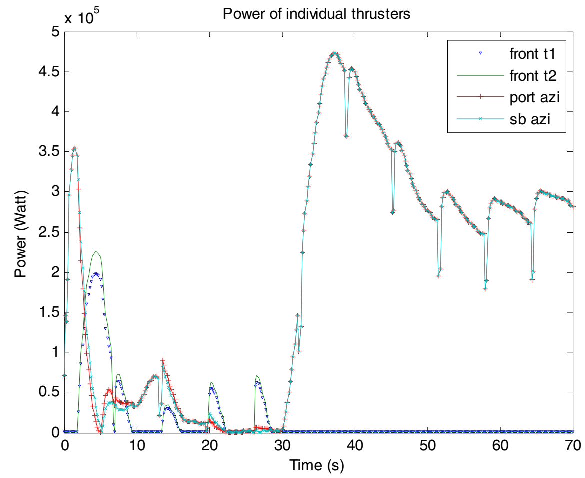

Figure 11. Experiment B; Power consumption in individual thrusters.

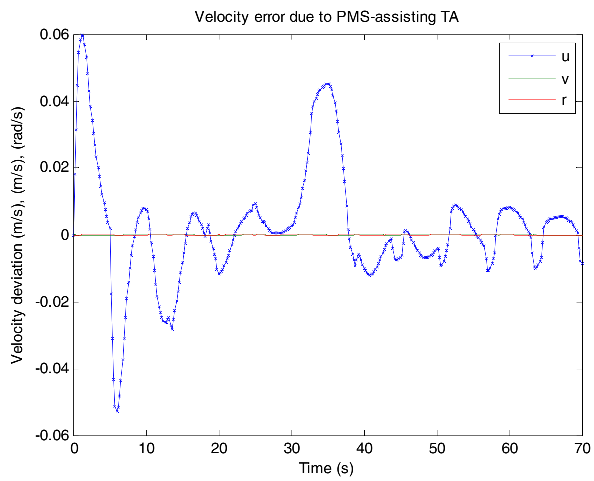

Figure 12. Experiment B; velocity error due to additional features.

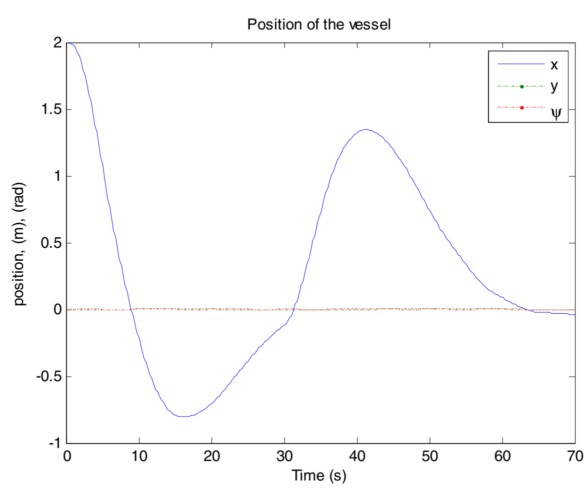

Figure 13. Experiment B; Position of the vessel.