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Optimal Control Allocation for AUVs with Through-body Thrusters

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Abstract. Developing multi-purpose AUV with through-body thrusters capable of undertaking both survey-style missions and low-speed interaction requires sophisticated thruster allocation algorithms. The paper presents the adaptive optimal allocation method. This method allows a smooth transition between different motion styles by exponentially decreasing through-body thrusters' involvement according to their hydrodynamic model. The proposed method is compared with the prioritized direct allocation method. The simulation result of the control allocation for the AUV "MMT-300" propulsion system model is provided.

1. Introduction

Modern multipurpose Autonomous Underwater Vehicles (AUVs) represent the next generation of robotic systems with new technological tasks faced by scientific researchers. One method of vehicle functionality extension is installing through-body (or tunnel) thrusters in addition to the stern propulsion system. Thereby the vehicle obtains the capability to undertaking both survey-style missions and low-speed interaction with the environment. But the efficiency of tunnel thruster depends strongly on vehicle velocity due to hydrodynamic aspects [1].

The design of control algorithm for underwater vehicles is often divided into several levels [2]. First, a high-level motion control algorithm is designed to compute a vector of virtual unbounded inputs to the vehicle $\boldsymbol{\nu}_c \in R^n$ from target and current vehicle state and control type, where n is controllable degrees of vehicle's freedom (DoF). Second, the control allocation algorithm is designed in order to map the vector of virtual input forces and torques $\boldsymbol{\nu}_c$ into individual thruster forces $\boldsymbol{u} \in \boldsymbol{R^p}$ (where p is the number of vehicle thrusters) such that the total forces and torques generated by all thrusters $\boldsymbol{\nu}$ amounts to the commanded virtual input $\boldsymbol{\nu}_c$. Third, there are separate high-frequency low-level controllers for each actuator that controls desired thrust u_i by a low-level control input.

This modularity allows the high-level motion control algorithm to be designed without detailed knowledge about the vehicle propulsion system. In addition to coordinating the effect of different thrusters in the system, issues such as thruster/fault tolerance, redundancy, and control constraints are typically handled within the control allocation module. In the case of an over-actuated propulsion system when the number of thrusters is more than the number of DOF controlled by the propulsion system ($p > n$), the control allocation module solves the optimization problem to archive minimal power consumption of the propulsion system.

In this paper, the problem of optimal thrust allocation in the case of over-actuated vehicles is only considered. This problem is well studied. There is an excellent survey devoted to this problem [2].

Different approaches to this problem, including linear iterative approach unsatisfying to optimal criteria and linear/quadratic programming approach, are contained in this paper. There are also interesting new papers published more recently [3-5].

The mentioning papers devoted to the control allocation problem focus on reducing the computing complicity of optimal thrust allocation. Still, there are no mentions that thruster constraints can be dynamically drifted due to thruster hydrodynamics. The presented approach is taking into account vehicle velocity. This approach allows motion control during survey-style missions and low-speed interactions with the vehicle equipped with tunnel thrusters. Moreover, it increases the quality of vehicle control during a complex motion path.

This article aims to an optimal control allocation problem for the underwater vehicle with through-body thrusters that strongly depends on incoming flow.

2. Problem statement

Let the vector of virtual inputs computed by high-level motion control or vehicle operator be denoted as the generalized force vector $\boldsymbol{v} \in R^n$. The NED (North, East, Down) coordinate frame [6] is used in this work. The x-axis is directed along the longitudinal vehicle axis from a vehicle stern to forward, the y-axis is directed along the latitudinal vehicle axis from the left side of vehicle to the right and the z-axis completes the frame to the right-handed coordinate system. Let assume that the system is equipped with p thrusters with control thrust $u_i (i = 1, \dots, p)$. This leads to the relationship between the vector of thrust $\boldsymbol{u} = [u_1, u_2, \dots, u_p] \in R^p$ and the vector of virtual inputs $\boldsymbol{v}$ [7] as follows:

$$\boldsymbol{v} = BK(v)\boldsymbol{u} \tag{1}$$

where $B = [B_m, B_t] \in R^{n\times p}$ is thrusters configuration matrix. It contains location and orientation of all thrusters in the vehicle body-fixed frame. $B_m \in R^{n\times m}$ and $\mathrm{B_t} \in R^{n\times \mathrm{q}}$ are submatrices that correspond to the main and through-body thrusters respectively, where m is the number of main thrusters and q is the number of through-body thrusters. $K(v) = [K_m(v), K_t(v)] \in R^{n\times p}$ is a diagonal matrix that represents efficiency drop of thrusters where v is incoming flow velocity. $K_m(v) \in R^{n\times m}$ and $K_t(v) \in R^{n\times q}$ are submatrices that correspond to the main and through-body thrusters respectively.

According to [8], the optimization statement of the control allocation problem for overactuated underwater vehicles can be written as:

$$\begin{gathered} \min\{(1-\epsilon)\boldsymbol{s}^T Q_v \boldsymbol{s} + \epsilon \boldsymbol{u}^T \mathrm{Q_u} \boldsymbol{u}\} \\ \text{subject to} \\ BK(v)\boldsymbol{u} - \boldsymbol{v} = \boldsymbol{s}, \boldsymbol{u} \in \boldsymbol{U} \end{gathered} \tag{2}$$

Here $\boldsymbol{s} = B\boldsymbol{u} - \boldsymbol{v}$ is the vector of slack variables used to penalize the allocation error, $\boldsymbol{U} \in \boldsymbol{R}$ is subset constraints thrust limits, Q_v and Q_u are diagonal weight matrices for virtual control inputs and thrusters, respectively, and ϵ is the integral weight coefficient.

Thrust allocation of overactuated AUV with vertical tunnel thruster is the velocity-dependent problem. For example, the pitch motion of the vehicle at zero velocity is better to create by tunnel thrusters due to the large thrust arm. But the effectiveness of tunnel thruster tends to zero on high speed.

3. Through-body thruster model

The model of a through-body (or tunnel) thruster is much more complicated than the main thruster. It is caused by peculiarities of the interaction of the propulsive jet created by the through-body thruster with the incoming flow and a hull of the underwater vehicle. Researches devoted to the hydrodynamic interactions of tunnel thruster's propulsive jet and incoming flow were primarily carried out during the study of the efficiency of a propulsion system of ships [9–11]. A large study of this problem was carried out in the PhD dissertation [12]. The general conclusion of the presented works and the results of field experiments is that thrusters of a tunnel type become ineffective at a vehicle speed above 1–1.5 m/s [13]. A large study of the efficiency of the AUV thrusters was carried out in the paper [13]. Further development was presented in the doctoral work [14]. Experimental studies of the efficiency of the through-body thruster for the AUV were also carried out in [15].

The model of a through-body thruster in the absence of an incoming flow is fully equivalent to the model of the main AUV thruster.

In the case of vehicle motion with a longitudinal speed u, the propulsive jet of a through-body thruster forms a hydrodynamic shadow (it's shaded in gray in the Figure 1) on the vehicle's hull in the area behind the thruster. Due to the pressure difference between the highest and lowest point of the hull, an additional hydrodynamic force T_s appears. The direction of this force is opposite to through-body thrust T_t.

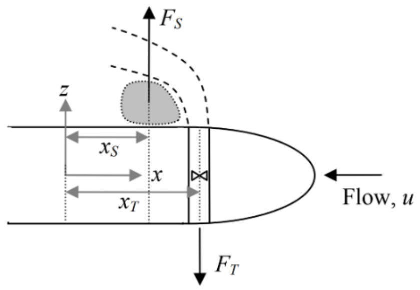


Figure 1. Propulsion jet of through-body thruster.

In [14] the following expression the hydrodynamic force T_s was proposed:

$$T_s = T_t\left(1 - \exp\left[-c\left(\frac{u}{u_j}\right)^2\right]\right) \tag{3}$$

where u is incoming flow, u_j is the jet velocity of the through-body thruster, and c is the efficiency drop parameter depending on form and shape of the through-body thruster and the vehicle hull. The propulsive jet velocity of the through-body thruster can be determined by the following equation:

$$u_j = \sqrt{\frac{T_t(u=0)}{\rho A}} \tag{4}$$

where $T_t(u=0)$ is thrust of the tunnel thruster without the incoming flow, ρ is density of the water and $A = \pi R^2$ and R is a radius of through-body thruster's tunnel.

Due to Equation 3 the efficiency drop of the through-body thruster in the matrix $K(v)$ can be expressed as follows:

$$K_t(v) = \begin{pmatrix} \exp\left[-c_1\left(\frac{u}{u_j^1}\right)^2\right] & 0 & \ldots \\ 0 & \ldots & 0 \\ \ldots & 0 & \exp\left[-c_q\left(\frac{u}{u_j^q}\right)^2\right] \end{pmatrix} \tag{5}$$

where c_q is the efficiency drop parameter and u_j^q is propulsion jet velocity of the q-th thruster.

4. Iterative optimal allocation method

To be used in real-time operating systems, the method for solving the optimization problem for a given functional (expression 2) must be efficient, simple, and executed in a certain fixed time or support a "hot" start. "Hot" start means that at the next iteration of the vehicle control system, it should be able to continue computing the optimal control from the point at which it stopped during the previous cycle. suppose a considered problem does not provide any constraints (i.e., $\boldsymbol{U} = \boldsymbol{R}$) or the solution of the optimal control problem fits into the given constraints, i.e. $\boldsymbol{u}^* \in \boldsymbol{U}$, then the solution can be obtained analytically through the partial derivative of the functional $\partial J/\partial \boldsymbol{u}$. Then the optimal control vector will be as follows:

$$\boldsymbol{u}^* = (1-\epsilon)\left[(1-\epsilon)\big(BK(v)\big)^{-1}Q_v BK(v) + \epsilon Q_u\right]\big(BK(v)\big)^T Q_v \boldsymbol{v_c} \tag{6}$$

If the target $\boldsymbol{v_c}$ is not realizable within the specified constraints $\boldsymbol{U}$, then the problem is solved using standard methods for solving quadratic optimization problems with constraints [16]. But general methods are often rarely implemented in real-time operating systems due to strict criteria for completing the iterative search for the optimum.

In articles [8, 17], it is shown that in the case of constraints describing by Equation 7, a globally descending solution can be found quite simply.

$$\underline{u_i} < u_i < \overline{u_i} \;\; \forall\, u_i \in \boldsymbol{u} \tag{7}$$

where $\underline{u_i}, \overline{u_i}$ are the maximum and minimum value of the control of the i-th thruster, respectively.

Let the saturation function $sat(x): R^n \to R^n$ be given and the result of its action $y = sat(x)$ is defined as follows:

$$y_i = \begin{cases} \overline{u_i}, x_i \geq \overline{u_i} \\ x_i, \underline{u_i} < x_i < \overline{u_i} \\ \underline{u_i}, x_i < \underline{u_i} \end{cases} \tag{8}$$

Then an iterative solution to the optimization problem 2 can be found through the fixed point theorem as follows:

$$\boldsymbol{u}_{n+1} = sat\left[(1-\epsilon)w\big(BK(v)\big)^T Q_v \boldsymbol{v} - (wH - I)\boldsymbol{u}_n\right] \tag{9}$$

where $H = (1-\epsilon)\big(BK(v)\big)^T Q_v B + \epsilon Q_u$, $w = 1/\|H\|_2$ ($\|\cdot\|$ is a vector norm in L_2), I is an identity matrix, $\boldsymbol{u}_{n+1}$ is an iterative solution in the $n+1$ step of calculation, and $\boldsymbol{u}_n$ is the solution on the previous calculation step.

The iterative calculation of the vector $\boldsymbol{u}$ ends when the following expression has been met:

$$|J(\boldsymbol{u}_{k+1}) - J(\boldsymbol{u}_k)| < J_{end} \tag{10}$$

where J_{end} is an adjustable parameter depending on actuators' discreteness.

5. Simulation results

The model of the AUV MMT-300 propulsion system (Figure 2) was used for comparative study of two control allocation methods. The propulsion system consists of six thrusters: four thrusters located at the stern of the vehicle with δ angle to the longitudinal axis, and the vertical and horizontal tunnel thrusters located at the forward part of the vehicle. Geometry parameters of the propulsion system are listed in Table 1.

Table 1. Geometry parameters of the AUV "MMT-300" propulsion system.

Parameter	Value
δ	22.5^o
L_s^x	1.6 m
L_s^y	0.14 m
L_{tv}	0.3 m
L_{th}	1.0 m

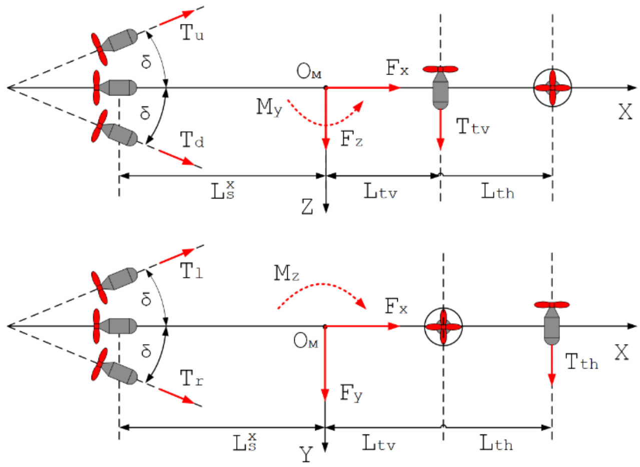


Figure 2. The principal structure of the AUV "MMT-300" propulsion system.

The prioritized direct allocation method was used for comparative study [18]. This method implies the search for such a set of linear compression coefficients $\alpha = [\alpha_1, \dots, \alpha_m]$ for the control vector $\boldsymbol{v_c}$ that ensures localization of the control vector $\boldsymbol{v_c}$ within feasible control region, i.e. $\boldsymbol{u} = \alpha B^+ \boldsymbol{v_c} \in \boldsymbol{U}$ where B^+ is the pseudo-inverse matrix to B obtained by the Moore–Penrose inverse method.

Adaptation to variations of vehicle speed of vehicle motion provided by modifying the geometry matrix $B(v)$ as follows:

$$B(v) = \begin{cases} B, & if\ v < v_{cruze} \\ B_m, & if\ v \geq v_{cruze} \end{cases} \tag{11}$$

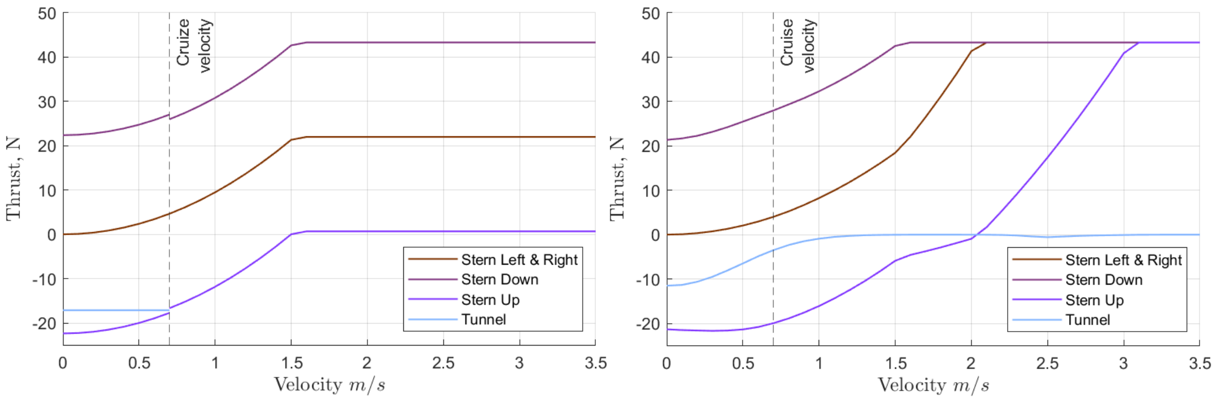
where v is forward velocity of the vehicle, and v_{cruize} is threshold between low and high velocity. Equation 11 means that with high velocity ($v \geq v_{cruze}$) all through-body thrusters switch off.

Depth maneuver was simulated to test the proposed control allocation method. Depth maneuver consists of longitudinal vehicle movement with simultaneous pitch motion. Let $\boldsymbol{v_c} = [f_x, f_y, f_z, m_x, m_y, m_z]^T$ where f_i is force projection of i-axis and m_i is moment projection of i-axis in the body-fixed coordinate frame. In the simulated case, the target force is determined by the following expression:

$$\boldsymbol{v}_c = \begin{bmatrix} c_x v^2 & 0 & 0 & 0 & m_y^0 & 0 \end{bmatrix}$$

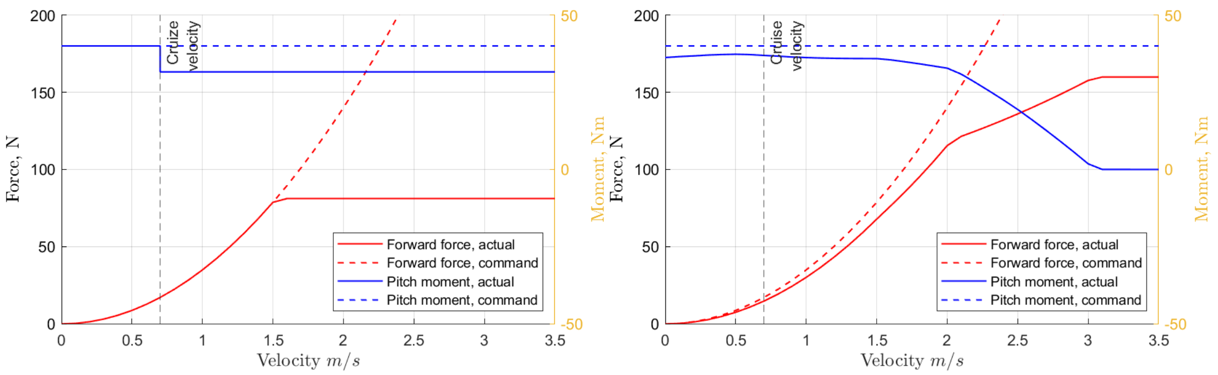
where c_x is the drag coefficient of the vehicle through the x axis, m_y^0 is fixed pitch moment vehicle control system. The following coefficients were taken: $c_x = 35.0$ Nm/s and $m_y^0 = 40.0$ Nm. The through-body efficiency drop was simulated with following parameters: $c = 2.0$, thruster propeller diameter $D = 0.14$ m, and water density $\rho = 1000$ kg/m3. Main and through-body limits were simulated with equal parameters: the lowest thrust $\underline{u_i} = -44$ N and the highest thrust $\overline{u_i} = 44$ N.

Comparative study results of the presented optimal control allocation and the prioritized direct allocation method are presented in Figure 3 and Figure 4. It's shown that though-body thrusters smoothly and exponentially switch off after the cruising velocity threshold. Besides adaptive optimal control allocation method provides greater maximum achievable velocity in comparison with the prioritized direct allocation method (2.0 m/s vs 1.5 m/s).



a) b)

Figure 3. Control allocation with the prioritized direct allocation method. There are thrust (a) and forces (b) allocation in the left and right image, respectively.



a) b)

Figure 4. Control allocation with the adaptive optimal allocation method based on the fixed point theorem. There are thrust (a) and forces (b) allocation in the left and right image, respectively.

6. Conclusion

Development multi-purpose AUV with through-body thrusters capable of undertaking both survey-style missions and low speed interaction requires the sophisticated thruster allocation algorithms. This paper presents adaptive optimal control allocation for vehicles with through-body thrusters. The fixed point iteration algorithm was used to solve the quadratic optimal problem. The presented method is compared with the prioritized direct allocation method. A comparative study of two control allocation methods with the propulsion model of the AUV "MMT-300" was presented.

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