GRIPPING FORCE ESTIMATION FOR AN ROV ROBOTIC ARM IN INTENSIVE AQUACULTURE
/
ESTIMAREA FORȚEI DE PRINDERE PENTRU UN BRAȚ ROBOTIC ROV ÎN ACVACULTURĂ INTENSIVĂ

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ABSTRACT

This paper presents a theoretical framework for estimating the gripping force of a three-degree-of-freedom robotic arm mounted on a remotely operated underwater vehicle, intended for sampling operations in intensive aquaculture systems. Using the static relationship based on the Jacobian transpose, the proposed method reconstructs the force and moment vectors acting at the end-effector from the estimated joint torques. The gripping force is determined by projecting the Cartesian force onto the normal directions of a two-finger gripper. Transmission efficiency and joint friction are incorporated into the model through the definition of an effective torque. The influence of hydrodynamic forces is treated as an external disturbance during quasi-static manipulation. The internal consistency of the model is evaluated through a numerical validation based on representative design parameters for compact underwater manipulators. The analysis indicates that a gripping force of approximately 150–200 N satisfies the friction-based stability condition for typical sampling loads of approximately 100 N. Furthermore, the resulting joint torques remain within the realistic operating limits of actuators commonly used in ROV-mounted manipulators. The findings confirm the dimensional consistency and physical plausibility of the proposed estimation framework, which may be applied to assisted underwater force estimation in aquaculture applications.

REZUMAT

Lucrarea dezvoltă un cadru teoretic pentru estimarea forței de prindere a unui braț robotic cu trei grade de libertate montat pe un vehicul subacvatic acționat de la distanță, care va fi utilizat în operațiunile de eșantionare într-un sistem intensiv de acvacultură. Folosind relația statică bazată pe transpunerea iacobiană, metoda reconstruiește vectorul forțelor și vectorul momentelor care apar la efectorul final de la cuplurile estimate în articulații. Forța de prindere este determinată prin proiectarea unei forțe carteziene pe direcțiile normale ale unui dispozitiv de prindere cu două degete. Eficiența transmisiei și frecarea articulară sunt încorporate în model printr-un cuplu efectiv. Efectul forțelor hidrodinamice este tratat ca forțe perturbatoare în timpul manipulării cvasi-statice. Consistența internă a modelului este evaluată prin intermediul unei validări numerice bazate pe parametri de proiectare reprezentativi pentru manipulatoare subacvatice compacte. Conform analizei, o forță de prindere de aproximativ 150–200 N îndeplinește condiția de stabilitate bazată pe frecare pentru sarcini tipice de eșantionare de aproximativ 100 N. Cuplurile articulare rezultate se încadrează în limitele realiste ale actuatoarelor utilizate în mod obișnuit în manipulatoarele montate pe ROV. Rezultatele analizei numerice confirmă coeziunea dimensională și plauzibilitatea fizică a cadrului de estimare sugerat, care poate fi utilizat în determinarea forței de manipulare subacvatică asistată în acvacultură.

INTRODUCTION

Recent developments in precision aquaculture have created a growing need to identify reliable solutions for underwater inspection and intervention, driven by the rapid expansion of intensive aquaculture (*Akram et al., 2022; Akram et al., 2025*).

Recent experimental studies have demonstrated the increasing use of remotely operated underwater vehicles for the inspection and monitoring of aquaculture nets, since these systems can operate efficiently in confined underwater environments and can integrate vision and control systems suitable for fish farm monitoring (*Cai et al., 2025*). In addition, the continuous evolution of autonomous and semi-autonomous strategies for the inspection of large fish cages has been observed. This trend has encouraged the integration of robust robotic manipulators on underwater platforms. The practical deployment of underwater robotic arms confirms the usefulness of these systems for maintenance, inspection, and intervention operations (*Vasileiou et al., 2025*).

For performing sampling operations, a robotic arm mounted on an ROV must be able to generate sufficient gripping force to prevent the manipulated object from slipping and, at the same time, limit contact loads to avoid damage to fragile or deformable samples. In current practice, direct force measurement at the end effector is frequently influenced by various factors such as operating costs, sealing requirements, space available for sensor integration, as well as long-term operational reliability. Thus, especially when the manipulation is performed slowly and the process is dominated by contact mechanics rather than fast dynamic effects, force estimation based on actuator signals and mathematical model relationships becomes a practical solution (*Bicchi, 1995; Yoshikawa, 1985*). The feasibility of coordinated vehicle–manipulator operation in complex environments has been validated through multibody models and control architectures in realistic underwater scenarios (*Di Vito et al., 2021*). Motion planning and coordinated control strategies have been proposed and implemented to deal with inertial effects and coupling between vehicle and manipulator (*Han et al., 2020*). Also, experiments have been performed to increase the robustness of the system to external disturbances through hybrid controllers and methods based on disturbance observers (*Li et al., 2019*). Studies on unmanned systems for aquaculture monitoring emphasized the growing integration of underwater robotic platforms, sensor technologies, and intelligent monitoring approaches for improving operational efficiency and environmental supervision in fish farming systems (*Ganie et al., 2025; Ubina and Cheng, 2022*). Recent experiments highlight adaptive approaches and model-free methods for interacting with unknown environments, highlighting the importance of robust force and motion control in underwater manipulation (*Yang et al., 2024*).

Since the robot must simultaneously manage model uncertainties, hydrodynamic perturbations, and contacts with deformable elements, its control plays a critical role in its underwater manipulation. Experimental research has been conducted to address this challenge, which has developed complex interaction control schemes for underwater vehicle–manipulator systems that ensure stable behavior during contact operations (*Heshmati-Alamdari et al., 2018*). Recent data-driven control studies for autonomous underwater vehicles have also demonstrated the potential of robust Koopman operator-based approaches for improving system stability and dynamic response under uncertain underwater operating conditions (*Liu et al., 2026; Rahmani and Redkar, 2024*). Studies have also been conducted that highlight the rapid development of underwater robots and the essential technologies required for their operational control, including dynamic modeling, sensor systems, and environmental interaction strategies, which have highlighted that interaction forces are essential for achieving safe and efficient underwater operations (*Sun et al., 2024*).

Classical robot modeling provides the mathematical foundation for relating joint variables to forces acting on the end effector, with standard kinematic and static relationships using the Jacobian matrix to transform joint torques into Cartesian vectors of forces and moments, which allows for force estimation when joint torques can be directly measured or inferred from motor currents (*Craig, 2005; Siciliano et al., 2009*). Experimental research has shown that underwater vehicle–manipulator systems introduce additional effects that influence the balance between torques and forces, including buoyancy, hydrodynamic drag, added mass, and coupling between vehicle motion and manipulator action (*Antonelli, 2014; Fossen, 2011*). Studies dedicated to underwater manipulators also show that real underwater systems are limited by joint friction, structural compliance, and sensor constraints, factors that directly affect interaction control and force reconstruction (*Sivčev et al., 2018*). Experiments on force and interaction control methods for underwater vehicle–manipulator systems have also been carried out, highlighting the need for high robustness against model uncertainties and deformable contacts, important aspects for gripping and sampling operations in aquaculture applications (*Heshmati-Alamdari et al., 2018*).

The novelty of this work consists in the development of an integrated theoretical framework that combines actuator signal interpretation, Jacobian-based static force reconstruction, transmission loss compensation, and gripper contact modeling for gripping force estimation in ROV-mounted underwater manipulators dedicated to aquaculture sampling operations. The proposed approach provides a physically consistent and modular methodology suitable for underwater environments where direct force sensing is difficult due to sealing, space, and reliability constraints.

MATERIALS AND METHODS

1. System Overview and Assumptions

In order to carry out the experimental research, a system was analyzed that includes: a remotely operated underwater vehicle (ROV that ensures positioning and coarse movements) equipped with a serial robotic manipulator and a parallel gripper with two fingers, intended for sampling operations in intensive aquaculture environments that performs fine positioning and gripping operations. The present paper focuses on the manipulator-gripper subsystem and treats the vehicle as a rigid base, whose movement is slow in relation to the handling load, and for the theoretical development the following hypotheses are adopted:

1. The handling load is quasi-static, and inertial effects are negligible in relation to the contact forces.
2. The gripper applies symmetric normal forces on the object.
3. The torques in the joints can be estimated based on the actuator signals.
4. Hydrodynamic effects are treated as external perturbations and are not included in the main static model.
5. The manipulated object is rigid or weakly deformable, and the contact occurs at well-defined points.

These assumptions are consistent with standard approaches used in robotic manipulation and in the analysis of underwater vehicle–manipulator systems (*Craig, 2005; Siciliano et al., 2009; Antonelli, 2014*).

2. Kinematic Model of the Manipulator

The manipulator is modeled as a serial kinematic chain with n revolute or prismatic joints. The joint coordinate vector is defined as:

$$q = [q_1, q_2, \dots, q_n]^T \tag{1}$$

where:

q – the joint coordinate vector of the manipulator, [rad] or [m];

$q_1, q_2, \dots q_n$ – the individual joint coordinates, and each term represents either a rotation angle for a revolute joint [rad] or a linear displacement for a prismatic joint, [m];

n – the total number of degrees of freedom of the manipulator, equal to the number of independently actuated joints, [-];

$[\,]^T$ – the transpose operator, which indicates that q is written as a column vector of size n x 1.

The kinematic structure of the ROV-mounted manipulator is illustrated in Fig. 1. The scheme defines the joint coordinates q_1, q_2, q_3, the end-effector frame, and the wrench F applied at the gripper, together with the joint torques τ_1, τ_2, τ_3. This representation provides the geometric basis for the derivation of the Jacobian matrix and for the static force mapping used.

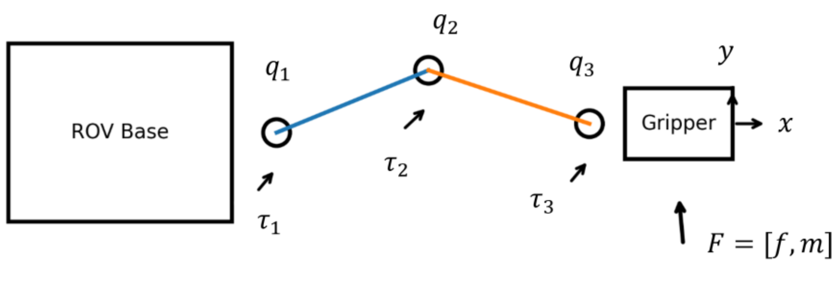

Fig. 1 – Kinematic scheme of the ROV-mounted manipulator and definition of joint variables and end-effector wrench

The pose of the end-effector is described by the vector:

$$x = [p^T, \varphi^T]^{\,T} \tag{2}$$

where:

p– the position, [m];

φ– the orientation, [rad].

The forward kinematics is expressed as:

$$x = f(q) \tag{3}$$

The differential kinematics is obtained by differentiation with respect to time:

$$\dot{x} = J(q)\dot{q} \tag{4}$$

where:

$J(q)$ – the manipulator Jacobian matrix.

The Jacobian relates joint velocities to end-effector linear and angular velocities and is computed using standard methods based on the chosen kinematic representation (*Craig, 2005; Siciliano et al., 2009*).

3. Static Force Relationship

Under quasi-static conditions, the relationship between joint torques τ and the wrench applied at the end-effector F is given by the principle of virtual work:

$$\tau = J^T(q)F \tag{5}$$

Here, F is defined as:

$$F = [f^T,\ \ m^T]^T \tag{6}$$

where:

f– force vector [N],

m – moment vector at the end-effector [N·m].

If the Jacobian transpose is full rank, or if a suitable pseudoinverse is used, the end-effector wrench can be estimated as:

$$F = (J^T\ (q))^{\dagger}\tau \tag{7}$$

where:

† represents the Moore–Penrose pseudoinverse operator.

From a dimensional point of view, the proposed formulation is coherent, with the electric current being expressed in amperes, the joint torques expressed in newton-meters, and the Cartesian forces expressed in newtons, and the Jacobian matrix and its transpose provide a physically meaningful correspondence between the joint space and the Cartesian space. This dimensional consistency allowed the estimated grip force to be directly correlated with the grip stability conditions, determined by friction and external loads. This relationship forms the basis for force estimation based on information on joint torques, a standard approach used in force control and interaction modeling in robotics (*Siciliano et al., 2009*).

4. Joint Torque Estimation from Actuator Signals

For electrically actuated joints, the motor torque τ_m is proportional to the motor current I

$$\tau_m = k_t I \tag{8}$$

where:

τ_m– the torque generated by the electric motor at its shaft, [N·m];

k_t– motor torque constant. It expresses the proportionality between the motor current and the produced torque, [N·m/A];

I– motor current supplied to the actuator, [A].

The joint torque τ is obtained by considering the transmission ratio r and the mechanical efficiency η:

$$\tau = \eta r \tau_m \tag{9}$$

where:

τ– the torque available at the robot joint after the transmission, [N·m];

η– mechanical efficiency of the transmission, it accounts for losses due to friction and other dissipative effects, [-];

r– transmission ratio (gear ratio), it relates the motor shaft torque to the joint torque, [-].

This relation shows how the motor torque is transformed into joint torque through the transmission mechanism, taking into account the gear ratio and the mechanical losses (*Craig, 2005; Siciliano et al., 2009*).

Friction and other parasitic effects can be represented by an additional torque term τ_f, leading to:

$$\tau_{eff} = \tau - \tau_f \tag{10}$$

where:

τ_{eff}– the torque actually available for producing motion or for balancing external forces at the joint, after subtracting losses, [N·m];

τ_f– the torque loss due to joint friction, seals, and other dissipative effects in the transmission, [N·m].

In this theoretical framework, τ_f is treated as an uncertainty term or as a parameter that can be compensated using standard friction models.

5. Gripper Contact Model and Gripping Force Definition

The gripper is modeled as a two-finger parallel mechanism applying normal forces F_n on opposite sides of the object. The total gripping force F_g is defined as:

$$F_g = 2F_n \tag{11}$$

where:

F_g– total gripping force applied by the gripper on the object, [N];

F_n– normal contact force applied by one gripper finger on the object surface, it is the force perpendicular to the contact surface at one finger, [N].

For static equilibrium, the gripping force must be sufficient to resist the external load W acting on the object. Assuming Coulomb friction with coefficient μ, the no-slip condition can be written as:

$$F_n \geq \frac{W}{2\mu} \tag{12}$$

where:

W– external load acting on the object (in practice, it represents the effective weight of the object, corrected by buoyancy in underwater conditions), [N];

μ– coefficient of friction between the gripper finger and the object surface, [-].

This relation is derived from basic grasp mechanics and is widely used for preliminary grasp force estimation (*Cutkosky, 1989; Salisbury and Mason, 1985*). In underwater conditions, the effective load W is corrected by buoyancy, but the same equilibrium principle applies (*Fossen, 2011*).

6. Extraction of Gripping Force from End-Effector Wrench

The estimated end-effector force vector f contains the interaction forces between the gripper and the object. The gripping force is obtained by projecting this force onto the normal directions of the gripper fingers. Let n_1 and n_2 be the unit normal vectors at the two contact points. The normal contact forces are:

$$F_{n1} = fn_1, \quad F_{n2} = fn_2 \tag{13}$$

where:

f– the resultant interaction force between the gripper and the object, expressed in Cartesian coordinates (the end-effector force vector acting at the gripper), [N].

Under symmetric grasp conditions:

$$F_{n1} \approx F_{n2} \approx F_n \tag{14}$$

and the gripping force is estimated as:

$$F_g = F_{n1} + F_{n2} \tag{15}$$

This procedure links the joint-level measurements to a physically meaningful gripping force value at the gripper-object interface.

7. Treatment of Underwater Effects

Hydrodynamic forces such as drag and added mass introduce additional torques at the joints and additional forces at the end-effector. For slow manipulation tasks, these effects are assumed to be small compared to contact forces and are treated as disturbances, following common practice in underwater manipulation modeling (*Antonelli, 2014; Fossen, 2011*).

The estimated force can therefore be expressed as:

$$F_{est} = F_{contact} + F_{dist} \tag{16}$$

where:

F_{est}– the force vector obtained from the model-based estimation process, which includes both the contact interaction force and additional disturbance effects, [N];

$F_{contact}$– the actual contact interaction force at the gripper–object interface, [N];

F_{dist}– disturbance force vector (it groups the contributions of unmodeled or parasitic effects, such as hydrodynamic drag, added mass effects, structural compliance, and measurement noise), [N].

This relation states that the force obtained from estimation is the sum of the actual contact force and additional disturbance-related force components.

RESULTS

This section presents the theoretical and numerical validation of the proposed gripping force estimation framework for a three-degree-of-freedom (3-DoF) serial manipulator mounted on an ROV, as illustrated in Fig. 1. The analysis focuses on the internal consistency of the mathematical formulation and on verifying whether the predicted force and torque levels are realistic for underwater sampling operations performed with compact robotic manipulators.

1. Logical workflow of the force estimation method

The estimation procedure follows the sequence illustrated in Fig. 2.

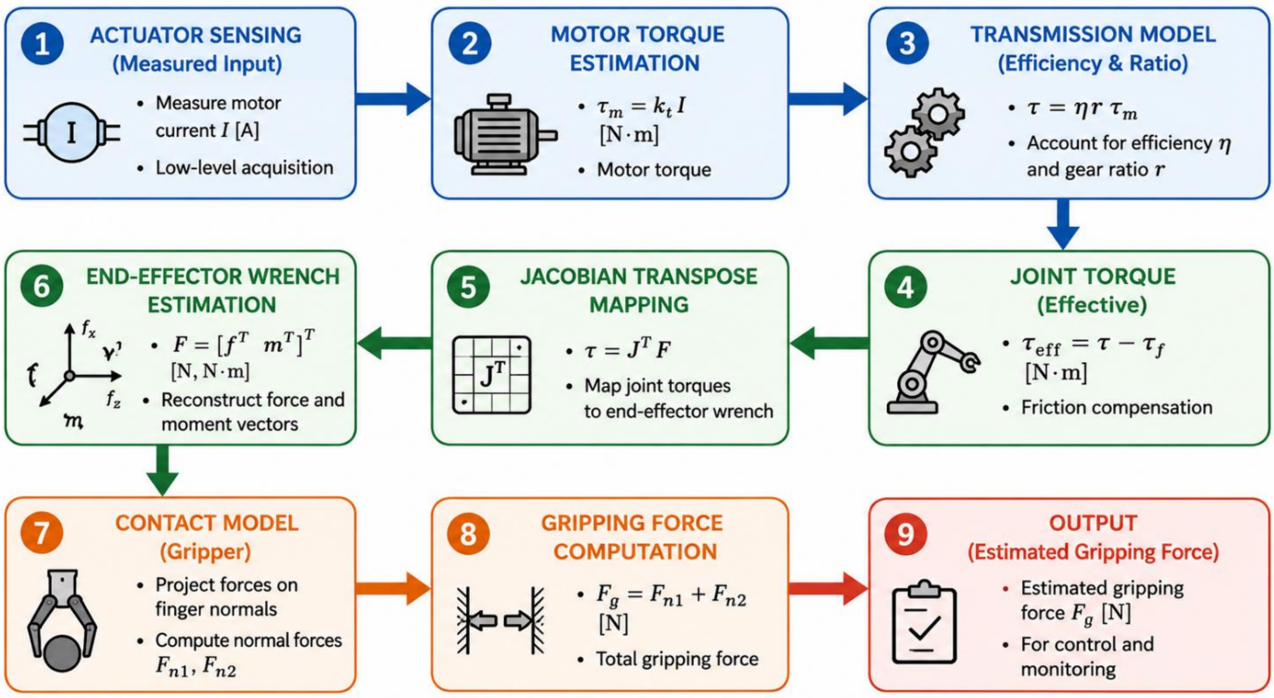

Fig. 2 – Logical block diagram for gripping force estimation

The process begins with actuator measurements, where the electric motor current is used to estimate motor torque. The transmission model converts the motor torque into joint torque, while mechanical losses are accounted for through an effective torque term.

2. Validation of gripping force requirements

To evaluate the physical plausibility of the model, representative design values typical for compact underwater manipulators were considered. Parallel grippers used for sampling tasks usually provide a nominal clamping capability in the range of 150–200 N. A representative external load associated with pulling or detaching a biological sample from a structure was assumed as:

$$W = 100 \text{ N} \tag{17}$$

From equations (12), (14), (15):

$$F_g \geq \frac{W}{\mu} \tag{18}$$

The minimum gripping force becomes:

$$F_{g,min} = \frac{100}{\mu} \tag{19}$$

The required gripping force therefore depends directly on the contact friction conditions:

- For $\mu = 0.5$

$$F_{g,min} = 200 \text{ N} \tag{20}$$

which corresponds to the upper bound of the considered gripper capability.

- For $\mu = 0.6$

$$F_{g,min} \approx 167 \text{ N} \tag{21}$$

which lies within the nominal operating range of compact parallel grippers.

- For a mid-range gripping force of approximately $F_{min} = 147$ N, the friction coefficient required to prevent slip becomes:

$$\mu_{min} = \frac{W}{F_g} = \frac{100}{147} \approx 0.68 \tag{22}$$

This result shows that grasp stability strongly depends on the contact interface. High-friction pads or textured surfaces significantly improve the safety margin of the grasp.

3. Joint torque validation for a 3-DoF manipulator

To validate the model, the external force was propagated through the kinematic chain of a 3-DoF planar manipulator corresponding to the structure shown in Fig. 1. The relationship between the Cartesian force and the joint torques is given by Eq. (5).

For a planar 3R manipulator, the end-effector position can be written as:

$$x = l_1 \cos q_1 + l_2 \cos(q_1 + q_2) + l_3 \cos(q_1 + q_2 + q_3) \tag{23}$$

$$y = l_1 \sin q_1 + l_2 \sin(q_1 + q_2) + l_3 \sin(q_1 + q_2 + q_3) \tag{24}$$

Hence, the Jacobian matrix associated with the planar force components is:

$$J(q) = \begin{bmatrix} -l_1 \sin q_1 - l_2 \sin(q_1+q_2) - l_3 \sin(q_1+q_2+q_3) & -l_2 \sin(q_1+q_2) - l_3 \sin(q_1+q_2+q_3) & -l_3 \sin(q_1+q_2+q_3) \\ l_1 \cos q_1 + l_2 \cos(q_1+q_2) + l_3 \cos(q_1+q_2+q_3) & l_2 \cos(q_1+q_2) + l_3 \cos(q_1+q_2+q_3) & l_3 \cos(q_1+q_2+q_3) \end{bmatrix} \tag{25}$$

For the considered case, the external force is purely vertical,

$$f = [0, -100]^T \quad \text{N} \tag{26}$$

Therefore:

$$\tau = J^T(q) f \tag{27}$$

reduces to: $\tau_i = J_{y,i} F_y$ (28)

where $J_{y,i}$ represents the element on row y, column i of the Jacobian matrix. Using l_1 = 0.20 m, l_2 = 0.18 m, l_3 = 0.156 m and $q_1 = 30°$, $q_2 = -45°$, $q_3 = 20°$, the following values are obtained:

$$J_{y,1} = 0.5025 \text{ m}; \; J_{y,2} = 0.3293 \text{ m}; \; J_{y,3} = 0.1554 \text{ m} \tag{29}$$

which yield the following joint torques

$$\tau_1 = -50.25 \text{ N} \cdot \text{m}; \; \tau_2 = -32.93 \text{ N} \cdot \text{m}; \;\; \tau_3 = -15.54 \text{ N} \cdot \text{m} \tag{30}$$

It is observed that the obtained torque values decrease from the base joint to the distal joint, which is consistent with the mechanical advantage of the serial manipulator. It is also found that the first joint supports the cumulative moment generated by all downstream segments, while the distal joint is mainly influenced by the local lever arm of the end effector, this evolution confirming the physical plausibility of the static relationship based on Jacobian used in the proposed model.

The value obtained for the third joint is practically identical to the direct moment balance around the wrist:

$$M = W \cdot l = 100 \cdot 0.156 = 15.6 \text{ N} \cdot \text{m} \tag{31}$$

This correspondence indicates that the Jacobian transpose mapping correctly captures the relationship between the external force applied at the gripper and the torques generated in the manipulator joints for the configuration illustrated in Fig. 1.

4. Interpretation of the validation results

The estimated gripping force lies inside the typical capability band of small parallel grippers, while the corresponding joint torques remain compatible with actuator sizes commonly employed in ROV-mounted robotic arms. In particular, the torque levels derived from the Jacobian-based mapping are consistent with those obtained from a direct mechanical moment balance, reinforcing the physical credibility of the model. The method can serve as a practical tool for monitoring and regulating gripping forces during underwater manipulation tasks, especially in situations where integrating dedicated force sensors at the end-effector is impractical due to sealing constraints, limited space, or cost considerations.

CONCLUSIONS

The paper presented a theoretical framework for estimating the gripping force of an ROV-mounted robotic arm intended for sampling operations in intensive aquaculture systems. The proposed approach combines actuator signal interpretation, transmission modeling, Jacobian-based force reconstruction, and gripper contact analysis to estimate the interaction force at the gripper-object interface.

The numerical validation demonstrated that the estimated gripping forces and joint torques remain within realistic operating ranges for compact underwater manipulators. The obtained torque distribution was consistent with the mechanical behavior of serial robotic structures, confirming the physical plausibility of the proposed model.

The modular structure of the method allows independent improvement of actuator, friction, hydrodynamic, and contact models, making the framework suitable for future extensions and experimental implementation in underwater manipulation applications.

Future research will focus on experimental validation under real operating conditions and on the integration of dynamic and hydrodynamic effects into the estimation process.

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