Ocean Engineering 149 (2018) 358–372

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Constrained multi-body dynamics for modular underwater robots — Theory and experiments

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ARTICLE INFO

Keywords:
Multi-body dynamics
Udwadia-Kalaba equation
Modular underwater robots
Constrained dynamics
Quasi-coordinates
Re-configurable robots

ABSTRACT

This paper investigates the problem of modelling a system of interconnected underwater robots with highly coupled dynamics. The objective is to develop a mathematical description of the system that captures its most significant dynamics. The proposed modelling method is based on active constraint enforcement by utilising the Udwadia-Kalaba Formulation for multi-body dynamics. The required description of a rigid constraint is defined, derived and implemented into a system of interconnected sub-models. An exhaustive experimental validation is conducted on a two-vehicle system, including towing tank tests on a BlueROV vehicle to determine the model parameters. The applicability of the modelling approach is assessed by comparing experimental data to simulations of an equivalent model synthesised using the proposed theory.

1. Introduction

Autonomy in the offshore sector is projected to increase rapidly as a result of attempts to reduce cost, increase safety and production in a progressively hostile environment. The future of sub-sea facilities are in deeper, colder and more remote locations. These sub-sea facilities are exposed to the harsh conditions in the open ocean that offers no shelter. Damages induced under such harsh conditions are inevitable and development of safe and reliable *Inspection, Maintenance and Repair* (IMR) equipment is an unparalleled necessity Schjølberg et al. (2016); Sanz et al. (2010).

IMR operations are currently conducted by *Remotely Operated Vehicles* (ROVs) operated by a team of pilots. The type of ROV used in IMR operations are most commonly the *working-class* ROV, which entails a multiple ton vehicle with an array of utility and a powerful propulsion system to overcome the effects of both the umbilical cable and the manipulation task. A common configuration for controlling working-class ROVs is one pilot to navigate the vehicle itself, while a co-pilot controls the manipulation and intervention itself. The size of the working-class ROV is a limiting factor, which restricts the operations to the exterior of the structures. Damages discovered by small *observation-class* ROVs may not be reachable by the appropriate sized intervention type ROV.

To overcome such a limitation it is envisioned that IMR operations could be conducted by groups of small sized cooperating ROVs or *Intervention Autonomous Underwater Vehicles* (I-AUVs) with intervention capabilities. Intervention capable AUVs is an active field of research and multiple authors have considered the modelling and control of I-AUVs Allotta et al. (2013), Palomeras et al. (2016), Moe et al. (2014), Casalino et al. (2014). Conti et al. (2015) presented a state-of-the-art method for using multiple I-AUVs in a cooperative manipulation task based on a potential-field approach. A cooperative system with persistent presence would allow for more reliable real-time feedback of the current conditions of the platform. Compared to the monolithic working-class vehicle each individual vehicle within the cooperative group could be outfitted with different payloads and thereby allow for more flexible and fault-tolerant operations at a lower cost.

A particularly relevant utilization of such as system would be the transportation of tools in confined sub-sea environments. In such a scenario multiple smaller vehicle could cooperatively work together in manoeuvring an intervention tool to areas otherwise inaccessible. Manoeuvring and control of cooperative systems will require insight into the interaction between the vehicles during motion and kinematic and dynamic modelling is necessary for any meaningful investigation on how to control such a system.

Modelling of marine systems has been researched extensively in the

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https://doi.org/10.1016/j.oceaneng.2017.12.007
Received 12 July 2017; Received in revised form 13 September 2017; Accepted 6 December 2017

0029-8018/

past. Parametric identification through towing tank tests are prohibitively expensive and preliminary analysis of any given design is often carried out using *Computational-Fluid-Dynamics* (CFD). CFD analysis can also be used post design using *Virtual Captive Test* (VCT) as was presented in Ramírez-Macías et al. (2016). System identification through usage of CFD, however, is not always reliable and experimental data is highly valued when available.

One approach to system identification is through the classical system identification methodology of input to output behaviour. These system identification techniques has been applied in various different scenarios such as Caccia et al. (2000); Pereira and Duncan (2000); Kim et al. (2002); Ridao et al. (2004); Marco et al. (1998); Valeriano-Medina et al. (2012) and Ferri et al. (2013). Common for all the methods is that the capture of motion data often requires a lot of both space and time.

Another approach is to apply specific known force externally to the system and measure the reaction. Ross et al. (2004) presented free decay tests as a method for identifying parameters for underwater vehicles using spring forces as excitation. A similar approach was presented in Eng et al. (2008) using pendulum motion to identify ROV parameters.

Motion based approaches to identify parameters most often lump parameters together to yield a cruder model. When available, towing tank tests using a Planar-Motion-Mechanism (PMM) is the preferred standard for modelling, as it allows modelling of the dynamics of all axes. Parameters of a ROV were identified using PMM tests in Avila and Adamowski (2011) and Avila et al. (2012). Recently, Eidsvik and Schjølberg (2016a) tested a new approximating modelling strategy against PMM tests with promising results.

Single vehicle models, such as the models in Fossen (2011), works particularly well for AUVs and surface vessels, however, the dynamics of a ROV is often dominated by the dynamics of the cable attaching it to the surface. Modelling of cables has been approached in different ways.

A series of papers Huston and Kamman (1982); Kamman and Huston (1985, 2001) modelled underwater cables using multi-body dynamics instead of using Finite-Element-Methods. Park and Kim (2015) modelled a system consisting of a semi-submersible vehicle towing a tow-fish by a cable using multi-body dynamics with a lumped-mass approximation. Gomes et al. (2016) modelled underwater cables using a finite chain of rigid-bodies connected using flexible joints and Eidsvik and Schjølberg (2016b) used beam equations to model the umbilical cable of a ROV.

New applications such as intervention missions have introduced new devices, including manipulator arms for interaction. Modelling and control of I-AUVs and *Underwater Vehicle-Manipulator System* (UVMS) have received attention in the field. Traditional approach to modelling of manipulator arms are by utilization of multi-body dynamics and for subsea application the multi-body perspective has also been applied successfully.

Tarn et al. (1996) applied Kane's method to model a Robotic Manipulator mounted on an Underwater Vehicle. Yang (2016) presented a modelling method based on graph-theoretical tools to generate a dynamic model for re-configurable underwater robots using Kane's method. Santhakumar (2013) modelled an UVMS using a closed-form multi-body dynamics approach. Huang et al. (2016) derived another UVMS model using a Newton-Eulerian formalism of dynamics instead of the classical Lagrangian Formulation often seen in manipulator derivation. A general overview of UVMS modelling and control was presented in Antonelli (2014).

With the advent of Biomimetics in underwater environments, recent articles have employed multi-body dynamics to model their systems. Krishnamurthy et al. (2009) introduced a general 6-DOF multi-body framework for modelling biomimetic underwater vehicles and demonstrated it using a ray-fish as application. Kelasidi et al. (2014b, 2014a, 2015) used multi-body dynamics to synthesize and validate an amphibious underwater snake model.

This article extends and validates the multi-body dynamic modelling approach in Nielsen et al. (2016a, 2016b), which using the Udwadia-Kalaba formulation Udwadia and Phohomsiri (2007). This article first presents the theoretical approach used to model a system of re-configurable underwater robots. As a first step, the paper develops the constraints necessary to rigidly connect the robots and then shows how the Udwadia-Kalaba formulation for multi-body dynamics is conveniently employed to obtain a dynamic model of an arbitrary configuration of modular robots. The article then presents experimental validations of the theoretical model. The validation use time-series comparisons between a range of motion patterns performed by a real system and an equivalent set of simulations. Finally, the hydrodynamic parameters of a BlueROV underwater vehicle is obtained as a by-product of the experimental validation.

The organization of the article is as follows. The theoretical background for the solution is presented in Section 2 along with derivation of relevant constraints. Section 3 then details on the experimental validation setup for both single vehicle and multi-vehicle experiments. Results of the experimental data are analysed and discussed in Section 4 and Section 6 holds the conclusions.

2. Theory

This section first introduces the notation used in the rest of the paper. Thereafter, the model for the single vehicle system is presented in Section 2.2. In Section 2.3 the theoretical multi-body model based on the Udwadia-Kalaba Formulation is given.

2.1. Kinematics

The notation adopted in this paper is the SNAME as presented in Fossen (2011) and used in Nielsen et al. (2016a).

Two reference frames are introduced, a global fixed frame to relate the pose of the individual models and a moving local frame attached to each rigid body of the system. The global frame is a flat-earth approximation frame assumed to be inertial and denoted by $\{n\}$ while the local body-fixed reference frame is denoted by $\{b\}$. A pose in the global frame is denoted $\boldsymbol{\eta}$ and consists of a position $\boldsymbol{p}_{b/n}^n \in \mathbb{R}^3$ and the orientation of the local frame relative to the global frame $\boldsymbol{q} \in \mathbb{R}^4$. The orientation is parametrised by a unit quaternion to avoid singularities in the description. The unit quaternion $\boldsymbol{q}$ is expressed using by one real part $\boldsymbol{\eta}$ and three imaginary parts $\varepsilon_i\, i \in \{1, 2, 3\}$ such that $\boldsymbol{q} = [\eta, \varepsilon_1, \varepsilon_2, \varepsilon_3]^T$. The body-fixed velocities are denoted $\boldsymbol{\nu}$ and defined as follows

$$\boldsymbol{\nu}_{b/n}^b = [u,\ v,\ w,\ p,\ q,\ r]^T \in \mathbb{R}^6 \tag{1}$$

As was the case of the pose vector, the body-fixed velocities can also be separated into linear and rotational sub-parts, where $\boldsymbol{v}_{b/n}^b = [u, v, w]^T$ represents the linear velocities and $\boldsymbol{\omega}_{b/n}^b = [p, q, r]^T$ represents the angular velocities. The transformation of linear velocity in body-fixed to the navigation frame is conducted through the rotation matrix below

$$\boldsymbol{R}_b^n = \begin{bmatrix} 1 - 2(\varepsilon_2^2 + \varepsilon_3^2) & 2(\varepsilon_1\varepsilon_2 - \varepsilon_3\eta) & 2(\varepsilon_1\varepsilon_3 + \varepsilon_2\eta) \\ 2(\varepsilon_1\varepsilon_2 + \varepsilon_3\eta) & 1 - 2(\varepsilon_1^2 + \varepsilon_3^2) & 2(\varepsilon_2\varepsilon_3 - \varepsilon_1\eta) \\ 2(\varepsilon_1\varepsilon_3 - \varepsilon_2\eta) & 2(\varepsilon_2\varepsilon_3 + \varepsilon_1\eta) & 1 - 2(\varepsilon_1^2 + \varepsilon_2^2) \end{bmatrix} \tag{2}$$

The attitude change $\boldsymbol{\omega}_{b/n}^b$ is related to the change of the relative orientation between local and global frame through the transformation matrix $\boldsymbol{T}_q$ defined below

$$\dot{\boldsymbol{q}} = \boldsymbol{T}_q \boldsymbol{\omega}_{b/n}^b \tag{3}$$

where the transformation matrix $\boldsymbol{T}_q$ is defined as

$$\boldsymbol{T}_q = \frac{1}{2}\boldsymbol{H}^T = \frac{1}{2}\begin{bmatrix} -\varepsilon_1 & -\varepsilon_2 & -\varepsilon_3 \\ \eta & -\varepsilon_3 & \varepsilon_2 \\ \varepsilon_3 & \eta & -\varepsilon_1 \\ -\varepsilon_2 & \varepsilon_1 & \eta \end{bmatrix} \tag{4}$$