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Energy efficiency of underwater robots

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Abstract: Increasing efficiency by improving locomotion methods is a key issue for underwater robots. In this paper, we investigate the power consumption of different underwater robotic systems and compare the energy efficiency of the different robots depending on the desired motion. In particular, we compare the energy efficiency of underwater snake robots, which can provide both inspection and intervention capabilities and thus are interesting candidates for the next generation inspection and intervention AUVs, with those of the widely used robots for subsea operations which are the remotely operated vehicles (ROVs). In order to compare the energy efficiency of underwater snake robots with the energy efficiency of the ROVs, a simulation study is performed comparing the total energy consumption and the cost of transportation of underwater snake robots and ROVs. The simulation results show that with respect to the cost of transportation metric and the total energy consumption the underwater snake robots are more energy efficient for all the compared motion modes compared to the ROVs.

Keywords: Underwater snake robots, energy consumption, energy efficiency of swimming robots.

1. INTRODUCTION

The use of underwater vehicles has rapidly increased the last decades since these systems are able to operate in deep and high risk areas which humans can not reach. Nowadays, autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) are widely used in the subsea environment for different challenging tasks (Fossen, 2011). These vehicles are suitable for various work assignments such as inspection, surveillance, maintenance, repairing equipment, building structures, and data collection, and they are extensively used in the subsea oil and gas industry and by the science community. For the long term autonomy of these systems, energy efficiency is one of the main challenges.

As has been noted in the bio-robotics community, underwater swimming robots bring a promising prospective to improve the efficiency and maneuverability of next generation underwater vehicles (Kelasidi et al., 2014b). They have several promising applications for underwater exploration, monitoring, surveillance and inspection, and they carry a lot of potential for inspection of subsea oil and gas installations. Also, for the biology and marine archeology communities, snake robots that are able to swim smoothly without much noise, and that can navigate in difficult environments such as ship wrecks, are very interesting (Kelasidi et al., 2014b). To realize operational snake robots for such underwater applications, a number of different control design challenges must first be solved. An important control problem concerns the ability to achieve efficient motion with preferably a minimum amount of consumed energy in order to be able to undertake longer missions, and this is the topic of this paper.

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Studies of hyper-redundant mechanisms (HRMs) have largely restricted themselves to land-based studies, where several models for snake robots have been proposed (Liljebäck et al., 2013). Empirical and analytic studies of snake locomotion were reported by Gray (1933), while the work of Hirose (1993) is among the first attempts to develop a snake robot prototype. Comparing amphibious snake robots to the traditional land-based ones, the former have the advantage of adaptability to aquatic environments. In Kelasidi et al. (2014b), the authors propose a model of underwater snake robots, where the dynamic equations are written in closed form. This modeling approach takes into account both the linear and the nonlinear drag forces (resistive fluid forces), the added mass effect (reactive fluid forces), the fluid moments and the current effects. Compared to other models (Boyer et al., 2006; Chen et al., 2011; Wiens and Nahon, 2012; Khalil et al., 2007), it is an advantage from an analysis point of view that the model is in closed form, as opposed to including numerical evaluations of the drag effects. In addition, it is beneficial that it includes both resistive and reactive fluid forces, since swimming snake robots operate at Reynolds numbers that require both these effects to be taken into account. Therefore, the analysis in this paper will be based on the dynamic model presented in Kelasidi et al. (2014b).

In Kelasidi et al. (2015), the relationships between the parameters of the gait patterns, the consumed energy and the forward velocity for different motion patterns for underwater snake robots were investigated. In addition, empirical rules were proposed in order to choose the most efficient motion pattern. In this paper, we present simulation results in order to compare the power consumption of swimming snake robots with that of today's benchmark solution for subsea inspection, maintenance and repair, which are ROVs, and comparison results are thus obtained for the power consumption of underwater snake

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robots and ROVs. This paper presents results by investigating the power consumption of different underwater robotic systems and pointing out the most efficient vehicle depending on the desired motion. The purpose of this study is to investigate the issues that could influence both the motion performance and the transportation performance of underwater snake robots and ROVs. In particular, the energy index (Shi et al., 2008), is used in order to compare the energy efficiency of underwater snake robots compared with the widely used remotely operated vehicles. A similar approach is used in order study the energy index of different transformation modes for ships in Shi et al. (2008). Comparison results are obtained for the total energy consumption and the cost of transportation of underwater snake robots and ROVs. The simulation results show that, with respect to the cost of transportation metric and the total consumed energy the underwater snake robots are more energy efficient for all the compared motion modes. To the authors' best knowledge, a comparison of the consumed energy between underwater swimming snake robots and remotely operated vehicles have not been investigated in previous literature.

The paper is organized as follows. Section II presents the dynamic model and the motion pattern of an underwater snake robot, while the kinematics and the dynamics of remotely operated vehicles are outlined in Section III. The energetics of underwater snake robots and ROVs are presented in Section IV, followed by simulation results for both underwater snake robots and ROVs in Section V. Finally, conclusions and suggestions for further research are given in Section VI.

2. UNDERWATER SNAKE ROBOTS

This section briefly presents a model of the kinematics and dynamics of an underwater snake robot moving in a virtual horizontal plane. A more detailed presentation of the model can be found in Kelasidi et al. (2014b). In addition, a general sinusoidal motion pattern proposed in Kelasidi et al. (2014a) will be presented, and also a low-level joint controller is presented.

2.1 Notations and defined symbols

The underwater snake robot consists of n rigid links of equal length $2l$ interconnected by $n-1$ joints. The links are assumed to have the same mass m and moment of inertia $J = \frac{1}{3}ml^2$. The mass of each link is uniformly distributed so that the link CM (center of mass) is located at its center point (at length l from the joint at each side). The total mass of the snake robot is therefore nm. In the following sections, the kinematics and dynamics of the robot will be described in terms of the mathematical symbols described in Table 1 and illustrated in Fig. 1. The following vectors and matrices are used in the subsequent sections:

$$\mathbf{A} = \begin{bmatrix} 1 & 1 & & \\ & \ddots & \ddots & \\ & & 1 & 1 \end{bmatrix}, \mathbf{D} = \begin{bmatrix} 1 & -1 & & \\ & \ddots & \ddots & \\ & & 1 & -1 \end{bmatrix},$$

where $\mathbf{A}, \mathbf{D} \in \mathbb{R}^{(n-1)\times n}$. Furthermore,

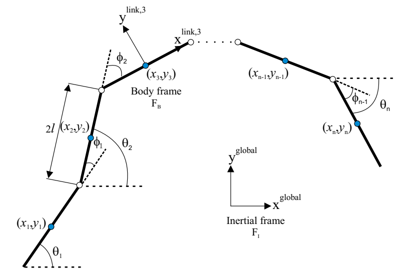
$$\mathbf{e} = \begin{bmatrix} 1 & \dots & 1 \end{bmatrix}^T \in \mathbb{R}^n, \ \mathbf{E} = \begin{bmatrix} \mathbf{e} & \mathbf{0}_{n\times 1} \\ \mathbf{0}_{n\times 1} & \mathbf{e} \end{bmatrix} \in \mathbb{R}^{2n\times 2},$$

$$\mathbf{S}_\theta = \mathrm{diag}(\sin\boldsymbol{\theta}) \in \mathbb{R}^{n\times n}, \qquad \mathbf{C}_\theta = \mathrm{diag}(\cos\boldsymbol{\theta}) \in \mathbb{R}^{n\times n}$$

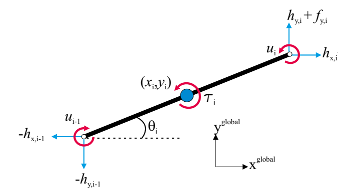
$$\dot{\boldsymbol{\theta}}^2 = \begin{bmatrix} \dot{\theta_1}^2 & \dots & \dot{\theta_n}^2 \end{bmatrix}^T \in \mathbb{R}^n, \ \mathbf{J} = J\mathbf{I}_n, \mathbf{K} = \mathbf{A}^T \left(\mathbf{D}\mathbf{D}^T\right)^{-1} \mathbf{D}$$

2.2 Kinematics of the underwater snake robot

The snake robot is assumed to move in a virtual horizontal plane, fully immersed in water, and has n+2 degrees of freedom



(a) Kinematic parameters



(b) Forces and torques acting on each link

Fig. 1. Underwater snake robot

Table 1. Definition of mathematical terms

Symbol	Description	Vector
n	The number of links	
l	The half length of a link	
m	Mass of each link	
J	Moment of inertia of each link	
θ_i	Angle between link i and the global x axis	$\boldsymbol{\theta} \in \mathbb{R}^n$
ϕ_i	Angle of joint i	$\boldsymbol{\phi} \in \mathbb{R}^{n-1}$
(x_i, y_i)	Global coordinates of the CM of link i	$\mathbf{X},\mathbf{Y} \in \mathbb{R}^n$
(p_x, p_y)	Global coordinates of the CM of the robot	$\mathbf{p}_{CM} \in \mathbb{R}^2$
u_i	Actuator torque of joint between link i and link $i+1$	$\mathbf{u} \in \mathbb{R}^{n-1}$
u_{i-1}	Actuator torque of joint between link i and link $i-1$	$\mathbf{u} \in \mathbb{R}^{n-1}$
$(f_{x,i}, f_{y,i})$	Fluid force on link i	$\mathbf{f}_x,\mathbf{f}_y \in \mathbb{R}^n$
τ_i	Fluid torque on link i	$\boldsymbol{\tau} \in \mathbb{R}^n$
$(h_{x,i}, h_{y,i})$	Joint constraint force on link i from link $i+1$	$\mathbf{h}_x,\mathbf{h}_y \in \mathbb{R}^{n-1}$
$-(h_{x,i-1}, h_{y,i-1})$	Joint constraint force on link i from link $i-1$	$\mathbf{h}_x,\mathbf{h}_y \in \mathbb{R}^{n-1}$

(n links angles and the x-y position of the robot). The *link angle* of each link $i \in 1, \dots, n$ of the snake robot is denoted by $\theta_i \in \mathbb{R}$, while the *joint angle* of joint $i \in 1, \dots, n-1$ is given by $\phi_i = \theta_i - \theta_{i-1}$. The *heading* (or *orientation*) $\bar{\theta} \in \mathbb{R}$ of the snake is defined as the average of the link angles, i.e. as (Liljebäck et al., 2013)

$$\bar{\theta} = \frac{1}{n}\sum_{i=1}^{n} \theta_i. \tag{1}$$

The global frame position $\mathbf{p}_{\text{CM}} \in \mathbb{R}^2$ of the CM (center of mass) of the robot is given by

$$\mathbf{p}_{\text{CM}} = \begin{bmatrix} p_x \\ p_y \end{bmatrix} = \begin{bmatrix} \frac{1}{nm}\sum_{i=1}^{n} m x_i \\ \frac{1}{nm}\sum_{i=1}^{n} m y_i \end{bmatrix} = \frac{1}{n}\begin{bmatrix} \mathbf{e}^T\mathbf{X} \\ \mathbf{e}^T\mathbf{Y} \end{bmatrix}, \tag{2}$$

where (x_i, y_i) are the global frame coordinates of the CM of link i, $\mathbf{X} = [x_1, \dots, x_n]^T \in \mathbb{R}^n$ and $\mathbf{Y} = [y_1, \dots, y_n]^T \in \mathbb{R}^n$. The forward velocity of the robot is denoted by $\bar{v}_t \in \mathbb{R}$ and is defined as the component of the CM velocity along the current heading of the snake, i.e.

$$\bar{v}_t = \dot{p}_x \cos\bar{\theta} + \dot{p}_y \sin\bar{\theta}. \tag{3}$$

2.3 Hydrodynamic modeling

As has been noted in the bio-robotics community, underwater snake (eel-like) robots bring a promising prospective to improve the efficiency and maneuverability of next generation underwater vehicles. The dynamic modeling of the contact forces is, however, quite complicated compared to the modeling of the overall rigid motion. In Kelasidi et al. (2014b) it is shown that the fluid forces on all links can be expressed in vector form as