Locomotion Efficiency of Underwater Snake Robots with Thrusters

E. Kelasidi, K. Y. Pettersen, P. Liljebäck and J. T. Gravdahl

Abstract—Lately there has been an increasing interest for subsea inspection and intervention tasks, and in particular on solutions which combine smaller size, increased flexibility and maneuverability, and decreased cost. Biologically inspired underwater snake robots (USRs) can provide both inspection and intervention capabilities, and are thus interesting candidates for the next generation inspection and intervention vehicles. In this paper, we focus on a new type of USR equipped with thrusters, which combine the flexibility and maneuverability of conventional USRs with the locomotion capabilities of traditional marine vessels with thrusters. This vehicle configuration represents a promising solution for operations inside narrow and restricted parts of subsea structures. The paper considers the locomotion efficiency of this new type of USR with thrusters by experimentally investigating fundamental properties of the velocity and the power consumption of a USR with and without thrusters, both for lateral undulation and eel-like motion.

I. INTRODUCTION

For several decades autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) have been widely used for different challenging subsea tasks [1]. Recently, the bio-robotics community has investigated a bio-inspired underwater snake-like robotic solution as an interesting alternative to conventional ROVs and AUVs. These biologically inspired systems have a long, slender and flexible body which gives them the ability to reach and operate in locations not accessible by larger and more conventional ROVs and AUVs. USRs thus bring a promising prospective to improve the efficiency and maneuverability of modern-day underwater vehicles [2], [3], [4], [5]. A large variety of snake-like robots have been developed over the years. A review of land-based snake-like robots can be found in [6]. The work of Hirose [7], one of the first approaches to develop a snake robot, is essential. While a variety of different snake-like robots have been constructed since then, only a few working examples of swimming snake robots currently exist. These include the eel robots REEL I [8] and II [9], the lamprey robot built at Northeastern University [10], Amphibot I [11], Amphibot II [12] and Amphibot III [13] from the EPFL lab, Perambulator III [14], the amphibious snake robot ACM 5 [15], [16], the HELIX-I [17], a biorobotic platform inspired by the lamprey [18], and the underwater snake robot Mamba, recently developed by the authors at NTNU in Norway [19]. The concept of an underwater swimming manipulator (USM), which is a hyper-redundant AUV with the potential to replace traditional ROVs and AUVs for routine inspection and lighter intervention tasks, is presented in [20]. In this paper, the authors study a particular case of USMs, namely the underwater snake robot Mamba with thrusters attached at the tail module of the robot. The tail thrusters induce linear forces along the body which increase the overall velocity of the robot. A control framework for USMs equipped with thrusters is presented in [21]. To the authors’ best knowledge, this is the first developed USR which combines the undulatory motion of a bio-inspired USR with thrusters.

In order to realize fully operational USRs for subsea applications, there is a need for addressing the locomotion efficiency of such vehicles. In particular, an autonomous USR (without an external power supply cable) can only carry a limited amount of onboard power (batteries). Its usefulness as an autonomous subsea vehicle thus relies on its ability to move energy efficiently under water. In [22], the relationships between the achieved forward velocity, the consumed energy, and the parameters of the gait patterns were investigated for USRs. In addition, empirical rules were proposed in order to choose the most efficient motion pattern. In [23], a simulation study was undertaken 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. The presented simulation results showed that a USR is more energy efficient than a ROV for all the compared motion modes. Note that in [23] the joints are assumed to be ideal since a detailed model of the servos are not considered. By using nonlinear averaging theory, in [24], fundamental properties are derived regarding the relationship between the gait parameters and the forward velocity. [25] investigates experimentally the validity of the empirical rules proposed in [22], [23] regarding the relationship between the gait parameters, the velocity and the power consumption using a physical USR [19]. Furthermore, [26] proposed a multi-objective optimization scheme to obtain optimal gait parameters for USRs. To our knowledge, however, no research has been published investigating experimentally the locomotion efficiency of the new type of USRs that are equipped with thrusters. To this end, this paper presents and experimentally investigates several fundamental properties of the velocity and the power consumption of an underwater snake robot with and without thrusters, both for lateral undulation and eel-like motion patterns for forward motion. In particular,
we present experimental results regarding the relationship between the parameters of the gait patterns, the forward velocity and the power consumption for different configurations of the swimming robot both with and without the use of thrusters.

The paper is organized as follows. Section II presents the USR Mamba equipped with thrusters, and the force mapping from the control inputs to the actual thruster forces. The experimental investigation of locomotion efficiency is presented in Section III. Finally, conclusions and suggestions for future research are given in Section IV.

II. UNDERWATER SNAKE ROBOT WITH THRUSTERS

In this section we present the underwater snake robot Mamba with thrusters and the experimental setup used for mapping the control inputs to the forces produced by the thruster modules attached at the tail of the robot. A more detailed description of the robot without the thruster module at the tail can be found in [19].

A. The underwater snake robot Mamba with thrusters

The USR Mamba with and without thrusters (Fig. 1) has recently been developed by the authors to investigate different types of underwater locomotion. The robot is watertight down to about 5 m and it has a modular design with a common mechanical and electrical interface between the modules. Each joint module is actuated by a Hitec servo motor (HSR 5990TG) and contains two temperature sensors, a 3-axis accelerometer, and a water leakage detector. Furthermore, each joint is controlled by a microcontroller card (TI-TechSH2 Tiny Controller from HiBot), and all microcontrollers in the robot communicate over a CAN bus. Power supply cables (35 V) run through all the modules along with the CAN bus. The robotic platform also includes a tail thruster module with two 400HFS-L thrusters from CrustCrawler, as shown in Fig. 2.

The configuration of the robot used for the experimental results presented in Section III consisted of 18 identical joint modules mounted horizontally and vertically in an alternating fashion [19]. During the experiments we covered the robot by a watertight skin in order to achieve an additional water barrier (Fig. 1). The skin was custom designed from Ground-sheet, Nylon, PU-coated, 120 g/m² material, and is sealed at the head and the tail parts using rubber bottle wrist seals, which are glued to the skin. Note that this type of cover makes the robot’s outer surface more smooth, thus reducing drag effects.

B. Mapping from control inputs to thruster forces

In order to study the energy efficiency of Mamba with thrusters, it is important to know the amplitude of the applied thruster forces as a function of the particular control inputs. The thruster module was controlled by a microcontroller programmed such that a control input in the range 0 - 100 controlled the speed of the thruster between zero and maximum. In this section we present the experimental setup used for determining the mapping from these control inputs, denoted by $u_c$, to the forces produced by the thrusters at the tail of the robot, and also the obtained mapping results. As seen in Fig. 3 the thruster module was attached to a straight smooth rod, and was able to move along the rod while being fully submerged in a basin. In the experiments, we used a digital scale in order to measure the force produced from the applied control inputs. The digital scale was attached to the back of the thruster module using a pulley. In particular, the control inputs, $u_c$, were sent from a computer running Labview to the thruster module, and afterwards the digital scale was observed to obtain the thruster forces $F_t$. We used a video camera recording to obtain the values measured by the digital scale.

Fig. 4 shows the experimental results of the force mapping. Note that initially we performed three trials for each control input, obtaining subsequently three measurements for each value of the control input $u_c$ as shown in Fig. 4a. Furthermore, we performed three different experiments by continuously increasing the values of the control input $u_c$ from 50 to 100 (Fig. 4b). In all the cases, we see that the mapping between the control inputs and the thruster forces is quite linear, and the repeatability of the results is clearly shown in Fig. 4.

III. EXPERIMENTAL INVESTIGATION OF LOCOMOTION EFFICIENCY

In this section we investigate the energy efficiency of the underwater snake robot Mamba with and without thrusters...
at the tail module. First, we describe the experimental setup employed for the investigation of the relationship between the gait patterns, the forward velocity and the power consumption for a new type of USR with thrusters. Then we present the experimental results.

A. Experimental setup

The experiments were performed in the MC-lab in Marintek, Trondheim, Norway [27], in a tank of dimensions L: 40 m, H: 1.5 m and W: 6.45 m. The camera system from Qualisys [28] installed at MC-lab consists of six identical underwater cameras providing a working area of dimensions $12\text{m} \times 1.35\text{m} \times 5.45\text{m}$ for real time measurements of the position and the orientation of the robot.

The underwater snake robot Mamba with and without thrusters, which is presented in Section II.A, was used for the experiments. Note that the results presented in this paper are obtained for horizontal motion of the robot, and thus the joint angles responsible for the vertical motion were set to zero degrees. Reflective markers were attached at the tail part of the robot, as shown in Fig. 8, for real time tracking of the position and the orientation of the tail link in the global frame. Afterwards, the position of the center of mass (CM), $p_{\text{CM}}$, and the absolute link angles, $\theta$, were calculated using the kinematic equations by combining the measured position and the orientation of the tail link and the individual joint angles. For more details regarding the experimental setup see [29].
TABLE I: Comparison results for the locomotion efficiency of a USR using thrusters and lateral undulation motion pattern.

<table>
<thead>
<tr>
<th>Case</th>
<th>max ( \bar{\upsilon} ) [m/s]</th>
<th>max ( P_{\text{avg}} ) [W]</th>
<th>min ( \bar{\upsilon} ) [m/s]</th>
<th>min ( P_{\text{avg}} ) [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.2713</td>
<td>49.6490</td>
<td>0.2581</td>
<td>48.6220</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.4436</td>
<td>158.9875</td>
<td>0.4229</td>
<td>156.1000</td>
</tr>
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</table>

TABLE II: Comparison results for the locomotion efficiency of a USR using thrusters and eel-like motion pattern.

<table>
<thead>
<tr>
<th>Case</th>
<th>max ( \bar{\upsilon} ) [m/s]</th>
<th>max ( P_{\text{avg}} ) [W]</th>
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B. Energy Efficiency

For USRs without thrusters, the propulsion is generated by the motion of the joints and the corresponding interaction between the robot body and the surrounding fluid, while for a USR with thrusters the propulsion is generated by the combined motion of the joints and the thruster modules.

For the experimental results presented in this paper, the average power consumption is calculated by using the following equation

\[
P_{\text{avg}} = V I_{\text{avg}},
\]

where \( V = 35 \) [V] and \( I_{\text{avg}} \) [A] is the average current that is measured using the high performance industrial logging multimeter FLUKE 289 [30]. The multimeter was connected to the power box on the tip of the power supply cable that is used for our experiments with Mamba. The current values were obtained for a wide range of the values for the gait parameters for two motion patterns: lateral undulation and eel-like motion. In particular, we measured the average, the maximum and the minimum values of the current for a certain time.

The CM position of the robot was calculated as described in Section III.B, while the average forward velocity for each experimental trial was calculated as

\[
\bar{\upsilon} = \frac{\sqrt{(p_{\text{stop},x} - p_{\text{start},x})^2 + (p_{\text{stop},y} - p_{\text{start},y})^2}}{t_{\text{stop}} - t_{\text{start}}},
\]

where \( p_{\text{start}} \) and \( p_{\text{stop}} \) represent the initial and the final points of the distance travelled in the time interval \( t_{\text{stop}} - t_{\text{start}} \).

The experimentally obtained properties for the gait parameters in this paper hold for USRs that follow a combined sinusoidal motion pattern and thrusters propulsive modules. As shown in [29], a general sinusoidal motion pattern can be achieved by making each joint \( i \in \{1, \cdots, n-1\} \) of the robot track the following reference signal

\[
\phi^*_i(t) = \alpha g(i, n) \sin(\omega t + (i - 1)\delta) + \phi_0,
\]

where \( \alpha, \omega \) and \( \delta \) represent the amplitude, the frequency and the phase shift between the joints, respectively. The parameter \( \phi_0 \) is a joint offset that induces turning motion and \( n \) stands for the number of links of the robot [29]. The scaling function \( g(i, n) \) is responsible for scaling the joint amplitude along the body of the robot, which allows (3) to describe a quite general class of sinusoidal functions. In particular, by choosing \( g(i, n) = 1 \) it is possible to obtain the motion pattern lateral undulation, and by choosing \( g(i, n) = (n - i)/(n + 1) \) the eel-like motion pattern is achieved.

The thrusters were controlled via Labview by sending
the control inputs directly to the low level controller implemented for the thrusters module. The mapping between the control inputs and the resulting thruster forces was known from the experiments described in Section II.B. An illustration of the experimental process that was followed in order to obtain the results presented in this paper, is shown in Fig. 9.

C. Experimental results

During the experiments we applied a sinusoidal motion patterns based on (3). We investigated the locomotion efficiency for different values of the gait parameters, both for lateral undulation and eel-like motion patterns. In particular, in each trial, the reference joint angles for \( n = 10 \), were computed by (3) and sent to the robot via the CAN. For each trial the average forward velocity was calculated by (2) for approximately 15 sec of motion. Note that the initial values of the link angels were set to zero before each trial.

In this section we present results regarding the achieved forward velocity and the average power consumption for the following different configurations of the robot:

- **Case 1**—for control input \( u_c = 60 \),
- **Case 2**—for control input \( u_c = 100 \),
- **Case 3**—for control input \( u_c = 60 \) combined with lateral undulation,
- **Case 4**—for control input \( u_c = 100 \) combined with lateral undulation,
- **Case 5**—for control input \( u_c = 0 \) combined with lateral undulation,
In particular, we have performed experiments for a quite wide range of values of the gait parameters $\alpha$, $\omega$ and $\delta$, both for lateral undulation and eel-like motion. For Cases 3-8, we have obtained three trials of measurements in order to investigate the repeatability of the performed experiments. In particular, Fig. 5 shows the results of the three trials for Case 3 for all the investigated values of the gait parameter $\alpha$, and we can clearly see that for all the trials both for the average forward velocity and the power consumption the obtained results are similar. In addition, Fig. 6 shows several trials for Case 1 where the locomotion efficiency is investigated using only thrusters, and as we can see the error between the different trials is negligible despite the inevitable noise on the measurements from the different sensors used for the experiments, thus demonstrating repeatability.

Experimental results for the USR Mamba using only thrusters for propulsion is presented in Fig. 7 for different values of $u_c$. From this figure, we can see that for both trials the average forward velocity and the power consumption are increased by increasing $u_c$. Furthermore, we have obtained comparison results for all the different cases, both for lateral undulation and eel-like motion patterns, by calculating the averaged value of the different trials obtained for each case as shown in Fig. 10 and Fig. 11, respectively. From these
figures, we can clearly see that the robot achieves faster motion using only the thrusters (Case 1 and Case 2). The obtained results show that the undulation does not contribute to the achieved speed while the power consumption increases significantly using the undulatory motion for a USR using servo motors for actuation of the joints. Note that the dip for Case 4 in Fig. 10f, results from that the multimeter lost the connection and we were not able to obtain results for the value $\omega = 70^\circ/s$. Table I and Table II present summarized results comparing the different investigated cases for the locomotion efficiency of Mamba with thrusters. As we can see from these obtained experimental results for Mamba, for all the cases for different values of the gait parameters $\alpha$, $\omega$ and $\delta$, except one case using thrusters with eel-like motion, the robot achieves faster motion using only thrusters and at the same time consumes less energy than using combined motion with thrusters and joints. The experiments thus suggest that for efficient transportation, the USR with thrusters should mainly use the thrusters for locomotion, while the articulation should be used for direction control instead of using a sinusoidal motion to support the locomotion. Equipping the USR with tail thrusters thus present an important benefit for forward velocity and power consumption. Furthermore, the slender and articulated body of the USR provides significant flexibility and increases the maneuverability of the robot for subsea applications.

IV. CONCLUSIONS AND FUTURE WORK

In this paper, we presented results regarding the locomotion efficiency of a new type of USR with thrusters, by
experimentally investigating fundamental properties of the velocity and the power consumption of the USR Mamba with and without tail thrusters, both for lateral undulation and eel-like motion patterns. Experimental results show that the USR with thrusters at the tail module achieves a significant increase of the forward velocity. In particular, the obtained experimental results showed that the robot is able to achieve faster motion by using only the thrusters attached at the tail part, and at the same time it consumes less power than using the combined motion with thrusters and body undulation. The experiments thus suggest that for efficient transportation, the USR with tail thrusters should mainly use the thrusters for locomotion, while the articulation should be used for direction control instead of using the conventional USR sinusoidal motion to support the locomotion. Equipping USRs with tail thrusters thus presents an important benefit for forward velocity and power consumption. In future work, the authors will investigate also other configurations, including fins and tail to the USR design. We will also investigate several other motion patterns in addition to the two most common motion patterns investigated in this paper, in order to study the locomotion efficiency of USRs with thrusters.

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REFERENCES