Dolphin-like propulsive mechanism based on an adjustable Scotch yoke
Junzhi Yu a,*, Yonghui Hu b, Jiyan Huob, Long Wang b

aLaboratory of Complex Systems and Intelligence Science, Institute of Automation, Chinese Academy of Sciences, P.O. Box 2728, Beijing 100190, China
bDepartment of Mechanics and Space Technologies, Peking University, Beijing 100871, China

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ABSTRACT
This paper addresses the design, construction, and motion control of an adjustable Scotch yoke mechanism generating desired kinematics for dolphin-like robots. Since dolphins propel themselves by dorsoventral oscillations following a sinusoidal path with alterable amplitudes, a two-motor-driven Scotch yoke mechanism is adopted as the primary propulsor to produce sinusoidal oscillations, where a certain combination of a leading screw mechanism and a rack and pinion mechanism driven by the slave motor are incorporated to independently change the length of the crank actuated by the master motor. Meanwhile, the output of the Scotch yoke, i.e., reciprocating motion, is converted into the up-and-down oscillations via a rack and gear transmission. A DSP-based built-in motion control scheme is then brought forth and applied to achieve dolphin-like propulsion. Preliminary tests, in a robotics context, confirm the feasibility of the devised mechanism severing as a dedicated propulsor for bio-inspired movements.

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1. Introduction
Bio-inspired swimming robots such as fish-like and dolphin-like robots are receiving widespread attention within the underwater robotics community, which provide innovative solutions to underwater propulsion and maneuvering [1–6]. Compared to propeller-type underwater vehicles, fishes and cetaceans can cruise greater distances at a significant speed, maneuver in tight spaces, accelerate and decelerate more swiftly, and even jump to remarkable height with the same integrated propulsion and steering system. As a discipline-integrated subject interweaving bio-mechanics and engineering technology, more researchers have focused on the development of novel fish-like or dolphin-like robots, ranging from hydrodynamics analysis, mechanisms and mechatronics, to control schemes. Building various artificial fish-like or dolphin-like robots, from the perspective of real-world applications, would be applied to underwater transportation, anti-terrorism, seabed exploration, search and rescue, military missions, and so forth. Additionally, since acquiring the necessary kinematic and hydrodynamic data from biological experiments remains a challenge, a synthetic, controlled study of artificial swimming machine is not only of engineering value, but also of biological relevance. For more detailed background discussion on the swimming robot, please refer to the latest literature [3–6].

Although the swimming mechanisms underlying both fishes and dolphins are very efficient, there exist some differences between them. The most significant difference is that dolphins have horizontal caudal fins (i.e., flukes) along the longitudinal main bodies in anatomy, but fishes have vertical ones. This corresponds to the propulsion behaviors that dolphins propel by vertical fluke oscillations, whereas the oscillations of fish tail are confined in the horizontal plane. Besides distinct anatomic difference, muscular tissue, and skin structure jointly contribute to more efficient and maneuverable motion in dolphins. As is observed, their propulsive efficiency is as high as 0.75–0.90, maximum swimming speed is over 11 m/s, and turning...
maneuverability are described as high as 450 deg/s with turning radii as low as 11–17% of the body length (BL) [1,7]. Not surprisingly, dolphins can jump out of the waters with ease and can carry out more complex motions. Driven by these potential advantages, dolphin-like robots (i.e., robotic dolphins) attempting at uncovering and simulating the propulsion and maneuvering mechanism used by dolphins have been paid increasing attention. More difficulties, of course, have to be overcome during both hardware and software development. Unlike fish swimming, on one hand, dolphins in nature are capable of generating stupendous thrust enabling them to jump out of water as high as 2.1 m. To achieve such a performance for the robot, we must provide it with powerful thrust and great prompt energy, which is chiefly associated with propulsive mechanism, power supply, as well as mechanical configuration. On the other hand, dolphins acquire high maneuverability via collaborating fast oscillating fluke with agile flippers which have multiple degrees of freedom. In practice, however, it is very tough to mimic such perfect coordination using conventional materials and motion control methods.

The objective of this paper is to develop an improved version of robotic dolphin by making use of an adjustable Scotch yoke as the primary propulsive mechanism. Compared with the previous multi-link robotic structures actuated by servomotors [8], a certain combination of a Scotch yoke mechanism and an amplitude modulation mechanism driven by DC motors is introduced to execute dorsoventral movements in dolphin swimming. The unique hallmark of this combined mechanism is that the outputted oscillatory amplitude can be continuously regulated online. With such a mechanism, the robot can flexibly be controlled through oscillatory frequency and/or amplitude in real time.

The rest of the paper is organized as follows. A brief review of previous related work on propulsive mechanism of dolphin-like robots is introduced in Section 2. Design scheme and procedure for the Scotch yoke centered propulsive mechanism is described in Section 3. Control system design and preliminary experimental results are provided in Section 4. Section 5 concludes the paper with an outline of future work.

2. Previous related work

Before describing the detailed design and implementation of the improved robotic dolphin, we first review some of the relevant results from the biological and robotic literature.

2.1. Review of dolphin swimming

Dolphin, in biology, is not categorized into fish but mammal. It is capable of efficient swimming mainly because of the streamlining shapes of the body and appendages that greatly minimize the drag. As illustrated in Fig. 1, this streamlined profile is featured by a fusiform shape with a rounded leading edge extending to a maximum thickness ($T$) and a slowly tapering tail. The fineness ratio (FR) associated with BL is defined an indicator of the degree of streamlining as $FR = BL/T$. In general, the FR value of 4.5 ensures the least drag and surface area for the maximum volume [1]. Besides FR, another parameter expressed as a percentage of BL is shoulder position (SP), which usually holds a range of 34–45%. Also, the cross-sectional design of flippers and the dorsal fin reveal the characteristics of fusiform design, which is of assistance in balancing and steering, particularly when they are fully extended. Additionally, the fluke span ($S$: tip-to-tip distance) and area ($A$) determine the mass of water that is affected for thrust generation. It is commonly believed that the more posterior SP is a feature of relatively faster swimming whales, and the combination of low sweep ($K$) with high aspect ratio ($AR = S^2/A$) hydrofoils are associated with highly efficient and rapid swimming [9].

![Fig. 1. Illustration of the natural dolphin. (a) Terminology to identify morphological features of dolphin. (b) Top view of the fluke.](image-url)
The oscillatory swimming motions exhibited by dolphins involve dorsoventral (up and down) movement of the posterior third of the body in conjunction with pitching of the fluke. Specifically, as shown in Fig. 2a, the motion of the fluke is regarded as a combination of pitching and heaving motions, tracing a sinusoidal pathway, which is symmetrical about the longitudinal axis of the body and in time. Rotating the fluke around the pitching axis, in particular, allows for control of angle of attack. As suggested by Romanenko, the periodic excursions of the body centerline in a dolphin swimming are approximated as

\[
h(x_n, t) = h_T f(x_n) \sin(2\pi ft)
\]

where \( h_T \) is the maximal vertical excursion of the fluke, \( x_n = x/BL \) is the longitudinal coordinate measured from the beak, divided by the animal's body length (BL), \( f(x_n) \) is the polynomial expression of \( x_n \), taking a form of \( 0.21 - 0.66x_n + 1.1x_n^2 + 0.35x_n^3 \), \( f \) is the tail beat frequency, and \( t \) is the time.

The symmetrical, sinusoidal fluke oscillations in the vertical plane produce approximately 90% of the total thrust. Particularly, the fluke heaving and pitching motions change pitch angle between the fluke and the horizontal plane. The pitch angle is zero when the vertical excursion of the fluke is at its maximum, and the pitch of the fluke is at its maximum when the tail is horizontal. The oscillatory frequency of the fluke tip, when swimming, is proportional to its swimming speed. But the peak-to-peak amplitude (\( 2h_T \)) is independent of its swimming speed. Furthermore, the peak-to-peak amplitude remains a constant proportion of its body length, ranging from 2–6% BL at the rostrum and 17–30% BL at the fluke tip.

2.2. Review of propulsive mechanism in dolphin-like robots

With a special emphasis on emulating dolphin-like oscillations, the crucial elements of the mechanical design are naturally how to develop an efficient and compact mechanism to realize sinusoidal motions. Existing robotic dolphin prototypes involve Nakashima's two-joint dolphin, Dogangil's four-link robotic dolphin, and Yu's five-link robotic dolphin with a pair of flipper apparatus, etc. Most of these prototypes adopt multiple concatenated links based mechanisms responsible for dominant thrust generation. Taking our five-link robotic dolphin as an example, the dolphin's up-and-down motion shown in Fig. 2b is achieved by fitting the body centerline taking the form of Eq. (1). That is, the up-and-down movement is discretized both in time and at distance. In detail, the discretization in time is to transform continuous movement into a series of position information at different time, whereas the discretization at distance is to approximately utilize folding line

![Fig. 2. Schematic diagram of dolphin-like swimming and its multi-link configuration. (a) Sinusoidal path of oscillating dolphin fluke in a stroke cycle. (b) Multi-link mechanism fitting the propulsive curve of the tail. Adapted from [8].](image-url)
instead of continuous wave. Thus the flexible movement of dolphins is implemented by the rigid linkages driven via DC servomotors. While mechanically simple and modular in structure, the multi-link based propulsion mechanism can rarely yield efficient swimming equivalent to a biological counterpart, e.g., our previously developed robotic dolphin only attained a maximum swimming speed of 0.44 m/s (i.e., 0.63 BL/s) [8]. In particular, each link actuated by a traditional DC servomotor adopts a position-based control, but an aquatic animal in nature adopts a force-based control, which is able to shape a dynamic wave in the body and reacts to external forces quickly and with low energy expenditure. Also, as a result of joint range limits in the conventional servomotors, asymmetric load to actuators caused by gravity, and iterative operations involving starting, acceleration, braking, and reversing in actuators, the effective thrust is far below the expected yields, accompanying with a relatively low propulsive efficiency. So some alternative propulsive mechanisms should be sought. For example, inspired by force-based control, Stefanini et al. [13] developed a combined actuator for a lamprey-like robot, in order to replicate the force/elongation of natural muscles.

In contrast to the above mentioned efforts, an updated, two-motor-driven Scotch yoke mechanism will expressly be designed as a well-integrated whole body to mimic sinusoidal motions in dolphins, which mainly consisting of a conventional Scotch yoke actuated by the master motor and an amplitude modulation mechanism actuated by the slave motor.

3. Scotch yoke based propulsive mechanism

With the purpose of fully mimicking the great locomotion capability of natural dolphin, we attempt to build a swimming robot having both structural and functional characteristics similar to its biological counterpart. More importantly, this device should possess compact construction suitable for developing large-scale integrations via available engineering means.

3.1. Integrated design of dolphin-like propulsion system

Considering that dolphins rely heavily on multiple control surfaces including caudal fin, flippers, and dorsal for efficient and agile propulsion, we try to incorporate these artificial mechanisms into a compact, mobile body. More concretely, the tail and the caudal fin provide the main propulsive and deflecting forces. The flippers are too small to affect forward motion, whose function is to help keeping balance and steering, particularly when they are fully extended. The multiple control surfaces are expected to allow precise control of position and orientation.

Fig. 3 illustrates the schematic layout of an improved robotic dolphin with mechanical flippers. Generally, the robot can be divided into several modular, standardized units: (a) a moveable head driven by a cross linkage mechanism, performing right-and-left swing as well as up-and-down pitching; (b) a hollow body, affording enough interior capacity to house additional accessory placements and to enable further modifications; (c) a pair of mechanical flippers capable of feathering and lead-lag motion, aiming at enhancing stability and generating lift during rectilinear swimming; (d) a set of tail and horizontal caudal fin capable of sinusoidal motions, consisting of an adjustable Scotch yoke centered propulsive mechanism and a fluke oscillating mechanism to provide great thrust and maneuver forces; and (e) a skeletal framework composed of lightweight ribs and interconnected springs, not only converts a discrete movement of the underlying linkages to a smooth movement of the dolphin tail, but also increases the flexibility and elasticity of the movements. Since our attention is only attached to the improved mechanical design enabling efficient sinusoidal motions, the combined, adjustable Scotch yoke mechanism
responsible for dominant thrust will be detailed, and other mechanisms will hence be neglected. More importantly, being able to vary oscillatory amplitude will enhance both the controllability and maneuverability of the robot.

As opposed to previous efforts on the multi-link based mechanical configuration, the adjustable Scotch yoke centered propulsive mechanism described here intends to meet the following requirements:

1. **Compact mechanism**: The developed mechanism must embed into an approximate cylinder with 140 mm long and 175 mm in radius. This requires the final version has to be built as compact as possible.

2. **Adjustable motion**: The mechanism should implement not only predefined kinematics, but also adjustable kinematics with desired amplitudes.

3. **Biomimetic extraction**: The designed mechanism should realize dolphin-like, dorsoventral oscillations, implemented by engineering means.

4. **Built-in actuation**: The need for a robust, self sufficient mechanism for prolonged testing takes precedence over tethered or towed experiment. For ease of use and power efficiency, rotary DC motor is a preferred actuator. Especially, the microcontroller based built-in control system governs the overall operations from head motions, flippers motions, to tail motions.

### 3.2. Design scheme selection

A conventional Scotch yoke, as outlined in Fig. 4, is commonly adopted as the converting mechanism from rotational motion to reciprocating motion of a slider or vice versa. It performs much the same function as a simple crank, but the linear output motion is a pure sinusoid [14]. That is, for pin \( P \) contacting the slotted T-shaped body \( L_2 \), it is also at the free end of the crank \( L_1 \), having

\[
\begin{align*}
\dot{x}_P &= L_1 \cos \theta \\
\dot{y}_P &= L_1 \sin \theta
\end{align*}
\]

(2)

where \( x_P \) and \( y_P \) are the \( X \) and \( Y \) coordinates of the point \( P \), respectively. The velocity vector \( V_P \) perpendicular to \( L_1 \) can be obtained by differentiating Eq. (2) with respect to time. Such differentiation yields

\[
\begin{align*}
V_{Px} &= -\omega_1 L_1 \sin \theta \\
V_{Py} &= \omega_1 L_1 \cos \theta
\end{align*}
\]

(3)

where \( V_P \) is resolved into components \( V_{Px} \) in the \( X \) direction and \( V_{Py} \) in the \( Y \) direction, and \( \omega_1 \) is the angular velocity of link \( L_1 \). Further more, it may be seen that \( Y \) coordinate of the point \( Q \) on the output-slide link is determined by

\[
x_Q = L_1 \cos \theta + L_2
\]

(4)

from which it can easily be derived that as \( \theta \) varies continuously from 0\(^\circ\) to 180\(^\circ\), the position of point \( Q \) varies between \( x_{Q_{\text{max}}} = L_2 + L_1 \) and \( x_{Q_{\text{min}}} = L_2 - L_1 \) for a total travel \( 2L_1 \). Note that it is necessary to choose a crank that has a length equal to one half of the total travel when designing a Scotch yoke with a desired travel.

Taking into account that the shape of the motion is a pure sine wave over time at a given constant rotational speed, we decide to use the Scotch yoke along with a rack and pinion gearing for generating desired sinusoidal motions. However, the conventional Scotch yoke in effect implements a fixed-motion envelope, i.e., the reciprocating envelop cannot be regulated once the device is assembled. In this case, it will be a feasible way to perform sinusoidal motions capable of amplitude adjustment if the length of the crank \( L_1 \) can be dynamically altered. According to this idea, there are four potential candidate mechanisms competent for adjustable sinusoidal motions. The advantage and disadvantage of these candidates are demonstrated as follows:

![Schematic drawing of a conventional Scotch yoke.](image-url)
(1) **Linkage + servomotors:** The displacement of the R/C servomotor is directly converted into tail motion by a simple transmission. Especially, the servomotor has an internal position feedback and the degree of the turn of the axis depends upon the input pulse width modulation signal, which is basically position-controlled and hardly back-drivable [13]. This scheme has the virtue of straightforward mechanical structure, amplitude-modulation, as well as motion control implementation. Its drawbacks involve the need for fast, high torque servomotors which are hard to commercially purchase, the low oscillatory frequency not more than 3 Hz (supposing that the highest oscillatory speed is 0.06 s per 60° for the selected servo), and the inadequate oscillatory amplitude when in a heavy loads case.

(2) **Linkage + DC motor:** Compared to the position-controlled servomotors, the direct drive DC motor can produce higher torque and is also commercially available in great variety. An accompanying flaw is that frequent starting-accelerating-braking-reversing in actuators will lead to a low mechanical efficiency. Meanwhile, a precise speed or position control for DC motor is relatively complex. This mechanical configuration, moreover, is unable to implement fast, force driven actuation.

(3) **Crank rocker + DC motor:** The crank rocker, having a merit of using a rotary DC motor as the actuator, can efficiently travel in accordance with the desired position and orientation. But the drawbacks here include the inherent quick-return characteristics and non-sine motion envelop.

(4) **Scotch yoke + amplitude modulation mechanism + DC motor:** Here, the rotary motion of a DC motor is converted into an adjustable sinusoidal motion by a combination mechanism comprising a conventional Scotch yoke and an amplitude modulation part. The motor speed is proportional to the oscillatory frequency of the tail. The oscillatory amplitude, at the same time, can be regulated inline. However, the presence of two actuators and a complex transmission gearing, to some extent, will make the design somewhat complicated and the control difficult.

Since servomotor is considered unsuitable for actuator mode, while crank rocker is a quick-return mechanism, designs 1, 2, and 3 are not favored. We remark that there exists multiple actuator choices for bio-inspired robots, which mainly include servomotors and direct drive actuators (e.g., electromagnetic/solenoid based solutions, pneumatic or hydraulic effectors or shape memory alloys elements). But for the circumstance needing compact, on-board actuators, DC motor may be a preferable choice. For more details about actuators for bio-inspired robots, please refer to Ref. [13]. Thus, the ultimate choice for the implementation of sinusoidal motions is through an adjustable Scotch yoke driven by two DC motors.

### 3.3. Design of the adjustable Scotch yoke centered propulsive mechanism

**Fig. 5** schematically depicts a general view of the adjustable Scotch yoke. Because an oscillating fluke is attached to the output pinion through a mechanical connection, the Scotch yoke should provide and transmit a high torque to push water powerfully when in motion. For ease of analysis, the devised mechanism is decomposed into three sub-mechanisms: Scotch yoke part, amplitude modulation part, and rack and pinion part, which would permit a convenient mechanical description and a simple engineering realization.

For the Scotch yoke part, as illustrated in **Fig. 6**, the yoke with an elliptical slot is equipped with two linear bearings, capable of fast sliding along the guide rod. The main shaft driven by a high torque DC motor (referred to as the master motor) drives the eccentric shaft to move within the yoke. As is mentioned previously, the stroke of reciprocating motion is determined by the length of the crank, i.e., the crank radius $R$. Based upon this simple principle, the amplitude modulation concept is formed by adjusting $R$ dynamically when in motion. Notice that to void undue wear of the slot in the yoke caused by sliding friction, a cylindrical roller bearing is employed so that the undergone friction is converted into rolling friction, which alleviates the added friction as well as wear problems to a great extent.

![Fig. 5. General view of the conceived adjustable Scotch yoke mechanism.](https://example.com/fig5.png)
As far as the amplitude modulation part, Fig. 7 illustrates the mechanical configuration. The leading screw driven by the slave motor engages with the screwed shifting fork, which linearly brings the grooved drive rack up and down along the main shaft. Thereby transition pinion engaging with the moving grooved rack further passively propel the driven rack with a pin. In such a case, to guarantee a favorable gear engagement, both the drive and driven racks are orthogonally mounted with respect to the support bracket. Thus, the length of the crank will be varied as the leading screw implements forward/reversal rotation. In particular, the adjustable travel is restricted by the length of screw thread. So a position sensor (e.g., photoelectric switch) is fixed to detect the initial location of the shifting fork. Since the rack and pinion gearing is capable of strong-force transmission, plus the rotation of the slave motor is independent of the master motor, this amplitude modulation mechanism is competent enough to accomplish the desired limit motion.

To convert the reciprocating motion produced by the Scotch yoke to up-and-down oscillation, as illustrated in Fig. 5, a semicircle-shaped, incomplete pinion is imported, which engages with the output rod connected to the sliding yoke and turns it. Note that a position sensor should be fixed to detect the initial state of the semicircle pinion, which provides a feedback signal for judging the alignment for the robot to correct itself. Also, a potentiometer attached to the output rod of the semicircle pinion detects the relative angle between the body and the rod connected to the fluke.

Furthermore, to accomplish dolphin-like propulsion, as depicted in Fig. 8, a fluke oscillating mechanism is attached to the oscillatory output rod (i.e., the free end of the semicircle pinion), which provides an appropriate angle of attack to propel. Currently, the pitching motion of the fluke is directly driven by a servomotor (i.e., Hitec HS-5995). The exoskeleton of the tail consists of tens of aluminum ribs coaxially concatenated by elastic steel sheets, which is interlinked anteriorly to the body and posteriorly to the servomotor. Moreover, the oscillatory output rod runs through the interior exoskeleton, acting as the backbone of the tail structure. As suggested by the hydrodynamic researcher, for a two-dimensional oscillating foil, the angle of attack that provides optimal thrust production is ranged from 15° to 25° [15]. By designing a certain control algorithm, the heaving and pitching motions will oscillate at the same frequency with a prescribed phase shift between them.
(i.e., maintaining some favorable angle of attack). In our case, with an expectation of efficient propulsion, the angle of attack for the fluke is set to 25°. So far, a complete dolphin-like propulsive mechanism has been developed.

4. Mechanical implementation and motion control

4.1. Mechanical functioning and testing

Fig. 9 shows the adjustable Scotch yoke mechanism assembled and ready for testing, with a dimension of 125 mm in length, 143 mm in width, and 147 mm in height. The selected DC motors that satisfy the actuator requirements are the RE40 from Maxon Motors as the master motor and the RE13 as the slave motor, whose maximum powers are 150 W and 20 W, respectively. The nominal voltage is chosen as 24 V to output high power for fast oscillation. The determination of the required motor driver capabilities (voltage and current supply range) is accomplished through a closed loop simulation offered by Maxon Motors [16]. As the output terminal, the semicircle pinion whose modulus is 1 and pitch diameter is 100 mm, vertically oscillates in sine waves fashion. Its limit amplitude can vary from $\pi/6$ with the screwed shifting fork driven by the slave motor reaching the zero-position, to $\pi/3$ with the screwed shifting fork arriving at the maximum modulation position, which corresponds to an adjustable crank length of 25 mm. In this case, an assumption is made that the semicircle pinion (i.e., the tail) starts from the minimum and then gradually increases its oscillatory amplitude. Notice that...
the increasing oscillatory amplitude assumption is valid not only for control simplification but also for biological relevance, since dolphins experience a steady increase in oscillatory amplitude when starting up from rest.

In order to accomplish the desired, adjustable sinusoidal motions, a simple closed loop control system is developed, whose hardware architecture is illustrated in Fig. 10. Based on a special DSP integrated circuit for motor control, TMS320LF2407A, a two-axis motion controller is developed, which is responsible for motor driver and servo control. Specifically, the two-axis motion controller not only provides two-channel signal interfaces for digital MR encoders as well as multi-channel I/O interfaces, but also receives sensor signals from both the encoders and the photoelectric switches, enabling speed-based or position-based closed control for the master and slave motors.

Preliminary tests on the developed adjustable Scotch yoke mechanism with an oscillating fluke have been conducted in an indoor swim tank. A crescent tail-fin (see Fig. 11) acting as the temporary fluke is attached to the output end of the Scotch yoke via a rigid rod connector. When the master motor with a reduction ratio of 26:1 rotates in a range of 1000–5000 rpm (roughly corresponding to an oscillatory frequency range of 0.64–3.21 Hz), the mechanism can make the full submerged fluke stroke powerfully. More excitedly, the maximum oscillatory amplitude, as we expected, can steadily be adjusted at a wide range. Fig. 12 plots the sampled rotational angle detected from the potentiometer at the axis of oscillation output.
rod over 6 s, in which the output rod oscillates at 0.96 Hz. As can be seen, the amplitude modulation starts at about 2.0 s to continuously raise the amplitude of the oscillation and stops at 4.0 s. Note that the enhanced rotational angle amounts to about 16° during this amplitude modulation, which potentially demonstrates a smooth switching capacity in different oscillations.

Furthermore, as shown in Fig. 13, a robotic dolphin prototype that uses the adjustable Scotch yoke as the onboard propulsive generator has been developed, whose specifications are listed in Table 1. To enable self-propelled swimming verification, the constructed robot should be well packaged and balanced. We remark that the robot swam near the surface in the following tests, causing surface waves occur. Also the mechanical flippers did not participate in forward propulsion but only assist in whole balance, for the purpose of displaying the propulsive function of the adjustable Scotch yoke based oscillating tail. Fig. 14 shows the relationship between the oscillatory frequency ($f_i$) and the forward speed ($U$) when the oscillatory amplitude of the output rod ($x_{\text{max}}$) holds about 35°. Notice that the forward speeds of the robot are estimated by using image/video analysis of underwater testing, while the oscillatory frequencies are stored and manipulated in the DSP. As can be observed, larger $f$ leads to higher $U$ and that the tendency to augment in $U$ becomes relatively slow as $f$ is larger than 1.92 Hz. In addition, the relationship between $x_{\text{max}}$ and $U$ is described in Fig. 15, in which the Scotch yoke oscillates at $f = 1.92$ Hz while $x_{\text{max}}$ is shifted to different values via modulating the slave motor. As can be observed, larger $x_{\text{max}}$, higher $U$. Apparently, $U$ is brought about predominantly by an increase in $f$ or $x_{\text{max}}$. Note that the data points shown in Figs. 14 and 15 are connected with dotted B-Spine curves just to display an underlying tendency among sampled data. Notice also that the impact and vibration resulting from the Scotch yoke increases with increasing of the frequency and/or amplitude, which partially implies that high oscillatory frequencies and/or amplitudes will lead to high thrust. Of primary importance is the speed control means via amplitude or frequency cues alone, or a combination of both, since fishes or dolphins in nature are observed to use a combination of amplitude and frequency for speed control.

![Fig. 12. Rotational angle sampled from the potentiometer during an amplitude modulation.](image)

![Fig. 13. Photograph of the assembled dolphin-like prototype.](image)
Table 1
Technical specification of the dolphin-like robot actuated by an adjustable Scotch yoke

<table>
<thead>
<tr>
<th>Items</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension ($L \times W \times H$)</td>
<td>~1200 mm × 420 mm × 380 mm</td>
</tr>
<tr>
<td>Total mass</td>
<td>~22 kg</td>
</tr>
<tr>
<td>Sensors</td>
<td>Infrared sensors + ultrasonic detector</td>
</tr>
<tr>
<td>Propulsive mechanism</td>
<td>Scotch yoke + amplitude modulation + oscillating fluke</td>
</tr>
<tr>
<td>Maximum forward speed</td>
<td>~0.8 m/s</td>
</tr>
<tr>
<td>Actuator mode</td>
<td>DC brush motors + servomotor</td>
</tr>
<tr>
<td>Working voltage</td>
<td>24 V</td>
</tr>
<tr>
<td>Operation time</td>
<td>~1 h</td>
</tr>
<tr>
<td>Control mode</td>
<td>RF (433 MHz)</td>
</tr>
</tbody>
</table>

Fig. 14. Relationship between oscillatory frequency and forward speed.

Fig. 15. Relationship between oscillatory amplitude of the output rod and forward speed.

4.2. Discussion

Based on the obtained results, it is confirmed that the improved Scotch yoke centered propulsive mechanism is workable. Although this combined mechanism is not very complicated, it requires significant manufacturing experience. The Scotch
yoke, as is observed, is sensitive to manufacturing quality and may be deadlocked if two slide bearings are not enough parallel, or due to asymmetric loads. Also, experiments conducted so far have demonstrated that some metallic parts undergo different wear. To remedy this, the yoke, particularly around the pins, should be lubricated to eliminate any damping during fast operation. Moreover, a balance between the weight and the fatigue strength of used materials should be struck since the devised mechanisms are required to climb or diving freely under water [17]. Then, an integrated design methodology for lightweight materials and structures should be further investigated. Though we only acquired a limited propulsive performance presently, the robot will render higher dolphin-like swimming capability after adjustment of the characteristic parameters of the Scotch yoke as well as the control variables. Also, two-DC-motor-driven other than servomotors-driven propulsive mechanism will be extended to fabricate large-scale propulsors aimed at real-world applications.

Another issue to be stated is the Scotch yoke based oscillating mechanism. Recently, there is an increasing tendency of applying a special four-bar linkage mechanism, the Scotch yoke, to achieve rhythmic movement. For instance, based on a double spherical Scotch yoke, Galinski and Zbikowski [18] realized a fixed-motion mechanism for insect-like flapping wing inspired by Diptera; while Hirata and Kawai [19] used a conventional Scotch-yoke mechanism to generate fish-like motion. In our work, a certain combination of the Scotch yoke and amplitude modulation mechanism is employed to achieve adjustable, dolphin-like movements. However, the displayed animal behaviors are the business of survival and procreation under a certain environment. Hence, purely depending on mechanical means to implement animal-like is not enough. In particular, dorsoventral motion of dolphins emerges as the result of the mutual interaction among the neural oscillator dynamics, body dynamics, and environmental dynamics (hydrodynamics) [6,20]. In this sense, the neural oscillator controller for the dolphin-like motion produced by the adjustable Scotch yoke may be a plus for further investigation.

5. Conclusions and future work

This paper first presents the overview of dolphin-like swimming and then concentrates on the improved Scotch yoke centered propulsive mechanism mimicking the dorsoventral movement for the robotic dolphin. Both the mechanical principle and configuration of the parts have been described. Motion control of the developed mechanism has been implemented by a custom-built, DSP-based, two-axis controller. Preliminary tests have been conducted to show the feasibility of thrust generation and amplitude modulation.

Future work will focus on two aspects: first, more underwater experiments will be conducted to investigate the kinematic and hydrodynamic characteristics of the developed mechanisms; second, based on this work, great technical efforts should be devoted to the development of a self-contained, dolphin-like robot, which provides a test bed for further bio-inspired mechanical and hydrodynamic studies.

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