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HISTORY OF DEVELOPMENT OF SQUID-LIKE BIOMIMETIC UNDERWATER ROBOTS WITH UNDULATING SIDE FINS

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Graphical abstract

Abstract

The underwater robot is a basic tool to explore the unknown territories in the underwater region of the coastal areas and oceans, both from the scientific and industrial perspectives. With the aim of developing an efficient and environmentally friendly underwater robot, a Squid-like robot with two undulating side fins has been developing for many years by the authors' group in Osaka University, Japan. The high ambitious project started in 2002; from then different models have been developed to reach the goal of achieving a high-performance underwater vehicle. The body and propulsion system of the robot have been developed by following the swimming mechanism of flat-fishes that use undulating side fins, e.g. Squid, Stingray Cuttlefish and Manta. The Squid-robot is now in its fifth generation of development. In the present paper, the review of the development of models of the Squid-robot is presented. The development of the mechanical system and the control system of each model is described in brief. Some CFD computations and motion simulations of Model-4 are also discussed. The background of developing a new model and the updated features are stated for each model respectively. The future target of development of the robot is also pointed out. The objective of this paper is to provide relevant and useful information to the engineers involved in underwater vehicle design, and for those with an interest in the fast-growing area of biomimetic swimming robots.

Keywords: Underwater robotics, biomimetics; squid-robot, undulating fin propulsion system

Abstrak

Robot bawah air adalah alat asas untuk meneroka wilayah yang tidak diketahui di dalam rantau bawah air di kawasan pantai dan laut, daripada perspektif saintifik dan industri. Dengan bermatlamat membangunkan robot bawah air yang efisien dan mesra alam, robot seperti sotong dengan dua sirip sampingan beralun telah dibangunkan selama beberapa tahun oleh kumpulan pengarang di Osaka University, Jepun. Projek impian tinggi ini bermula pada 2002, daripada waktu tersebut model-model berbeza telah dibangunkan untuk mendapat matlamat menjadi sebuah kenderaan bawah air yang berprestasi tinggi. Badan dan sistem tujahan robot telah dibangunkan dengan mengikut mekanisme berenang untuk ikan-ikan rata yang menggunakan dua sirip sampingan seperti sotong dan ikan pari Manta. Robot sotong sekarang berada pada generasi kelima pembangunan. Dalam kertas ini, ulasan pembangunan model-model robot sotong ini dipersembahkan. Pembangunan sistem mekanikal dan kawalan setiap model diterangkan secara ringkas. Pengiraan CFD dan simulasi gerakan untuk Model-4 juga dibincangkan. Latarbelakang pembangunan model baru dan tambahan ciri telah dinyatakan untuk setiap model. Sasaran masa depan pembangunan robot juga diterangkan. Objektif kertas ini ialah untuk memberikan maklumat berguna kepada jurutera yang terlibat dalam rekabentuk kenderaan bawah air dan untuk mereka yang mempunyai minat dalam robot berenang biomimetik.

Kata kunci: Robotik bawah air, biomimetik, robot sotong, sistem tujahan dua sirip sampingan beralun

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1.0 INTRODUCTION

Oceans, seas and adjoining coastal regions are essential constituents of the Earth's ecosystem playing critical roles in global food security, transportation and more generally the human existence. Mankind has conquered the surface of the water world, and their footprints are visible everywhere on the surface of the hydrosphere. However, the world of underwater - the main source of resources has remained almost unexplored largely due to the inaptness of traditional exploration technology. The underwater robot is a basic tool to explore the unknown resources or sunken objects (e.g. ship, airplane etc.) in the complicated sea bed region of the oceans, both from the scientific and industrial perspectives. In order to design a competent and environmentally-friendly underwater vehicle, usually robotic engineers borrow the sense and structure features from the animals of the ocean to improve their designs. Aquatic animals are smart swimmers; therefore naval architects investigate their swimming mechanisms to improve the design of underwater vehicles. Different types of underwater vehicles and robots have been developed for solving different purposes; a lot of studies were conducted [for example, 1-2] to fulfil the requirement of underwater exploration. However, there is still enormous scope to contribute this vast and challenging field.

Based on the propulsive structure, Breder [3] identified two modes in fish swimming - Body and/or Caudal Fin (BCF) and Median and/or Paired Fin (MPF). The BCF movement yields greater thrust and accelerations while the MPF is employed at slower speeds to attain greater maneuverability and better propulsive efficiency. The present study mainly focused on the undulating side-fin propulsion robot belonging to the MPF group. In the field of underwater robotic research, undulating-fin robot offers exceptional advantage over propeller in preserving an undisturbed condition of its surroundings for data acquisition. Though the movement of this biomimetic type of robot is slow, it has compelling areas of applications such as the underwater localization, acoustic communications, optical and acoustic imagery, guidance navigation and control, mission planning and mapping, etc. Military and defense are the most important areas where biomimetics finds its significant role in ensuring safety and covertness. The undulating finned robot might be undetected when swims with a school of fish and therefore may find its application as an espionage tool. The increasing demand for high-performance underwater vehicle has attracted many researchers in studying this challenging but intellectually satisfying field. Many new concepts of biologically inspired underwater propulsion systems have been developed including several undulating-finned underwater robots [4, 5]. Unfortunately, till date, the development of capable and eco-friendly underwater vehicle with undulating side fin propulsion system is not up to the mark, and it offers adequate opportunity to contribute to this field.

A squid-like underwater robot with two undulating side fins has been studying in the Laboratory of Hull Form Design of Osaka University, Japan for more than twelve years. The investigation aimed at the development of a competent and eco-friendly underwater vehicle. The idea was borrowed from some fishes that use undulating side fins for swimming in the underwater; e.g. Squid, Stingray, Cuttlefish, Manta, etc. The high-ambitious project started in 2002, and the Squid-robot is now in its fifth generation of development. This paper presents an overview of the development process of the models of the Squid-robot

2.0 DEVELOPMENT OF THE MODELS OF THE SQUID-ROBOT

2.1 Model-1

The project started with a fundamental study on the computation of the flow field around a simple flat-fish like robot with two undulating fins [6]. The feature of flow field and hydrodynamic forces acting on the body and fins was elucidated based on the computed results to augment the understanding of the complex fluid mechanics that fishes use to propel themselves. These results were good information for understanding the complex fluid mechanics that a kind of fishes uses to propel itself. Based on the study, the primary model, Model-1 (Figure 1) was constructed. The first model had a resistance body, and the two side fins were attached to the side of the resistance body. The drive unit part was composed of one motor and 15 Scotch-yokes that drive the 15 bones of the side fin through the vertical push rods in the strut.

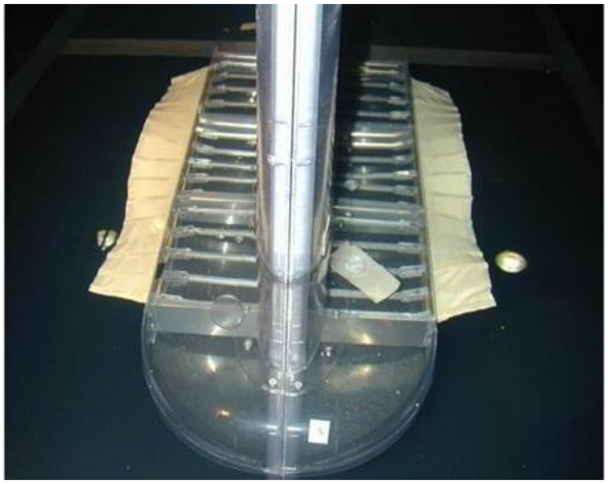


Figure 1 Model-1 of Squid-robot

Each fin ray was controlled by Scotch-yoke mechanism to make the progressive wave fin's motion. In this drive unit, the rotational motion of the motor was changed into vertical motion of the vertical push rod that was connected to the bone of the fin. The bones could be moved in a rotating direction within a range of ±30 degrees. The amplitude and the phase of each bone movement could be adjusted with an adjustment of the gear angle and position. By using the Model-1, the free-run tests with floating bodies and hydrodynamic force measurements were carried out. From the experiments with Model-1, it was found that the undulating side fins could produce the thrust and could be used as the propulsion of underwater robot. However, the control of the fin's shape and amplitude distribution was difficult for this model, and the resistance for the body with flat fins was difficult to measure.

2.2 Model-2

Therefore, a new model, Model-2 was introduced in 2004. This model had servomotors for both side fins to make the undulating fin's motion (Figure 2). As shown in the photo, the model had 32 servomotor units. From those units, cables were connected to the control unit. Each servomotor was controlled separately by a remote computer to make any mode of fin motion. Free-run tests were also carried out for Model-2 [7]. It was found that the forward-backward motion and turning motion were faster than for the case of Model-1 at the same frequency due to its small resistance and small mass. From Figure 2, it is seen that this model was free from strut but still consisted of large cables that also hindered the free movement of the robot.

Figure 2 Model-2 of Squid-robot

2.3 Model-3

The strut of Model-1 and the bulky cables of Model-2 delayed their free movement for which Model-3 was constructed without strut and hefty cable in 2006 [8]. The head of the Model-3 was round shaped, and it had 17 servo motors for both sides to produce any fin's motion with the servo controller and the microcomputer being housed inside the model (Figure 3). The model had one thin cable that was connected to the floating wireless communication units to a computer on the ground for control. It could run freely to any direction and change the angle around any axis. It had the dorsal fin to keep the direction and the caudal fin to change the depth. These fins could be controlled timely by the ground computer. The adjustment of vertical gravity center was also attached and controlled by the ground computer. Various motions were demonstrated through free-run tank experiment and numerical simulation using the hydrodynamic coefficients obtained by captive model tests. The model could turn over on its back. By using Model-3, the motion in the 6 degree of freedom direction was demonstrated and controlled easily. But the gravity center adjustment device was attached on the resistance body. So, it had the resistance and made some asymmetric hydrodynamic forces. RS232C protocol was used for wireless communication. So, it had trouble in communication at large distance.

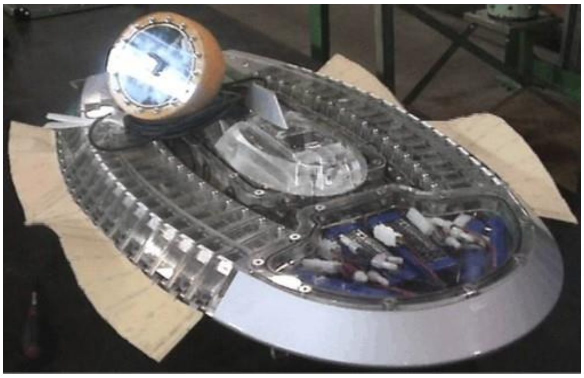


Figure 3 Model-3 of Squid-robot

2.4 Model-4

The Model-4, a better creation than the previous models, was constructed in 2009. Alike the second and third models, this model had the 17 servo motor units at each side to produce any fin's motion; the servo controllers and the microcomputer unit were installed inside the model. The model had a thin cable (6 m long) to connect with the floating wireless communication unit. The robot could be controlled from the computer on the ground. The robot could move freely to any direction and change the angle around any axis. It was possible to move the model for about 4 hours using ten batteries installed inside the model. It also had two caudal fins longer than Model-3 that was used to change the trim angle to change the depth during swimming. These fins could also be controlled by the ground computer. The pictures of Model-4 and the principal dimensions were shown in Figure 4 and Table 1, respectively.

Figure 4 Model-4 of Squid-robot

The wireless communication system was changed to the general wireless LAN from RS232C system for better communication for both distance and speed. The usual devices of home use were used for wireless LAN. The center of gravity position could be adjusted by the system inside the model both vertically and horizontally (longitudinally and laterally). The weights could be moved by servo motors. The buoyancy could be controlled by the change of the air volume of the two pistons (100 cm^3 each) at both sides, and the pistons were controlled by servo motors. On the control board, the CPU (Renesas SH1 HD6417032F-20), position signal generator, LAN port (LANTRONIX XP100200S- 03R) and servo motor controllers were installed inside the model. The control system and the process of data collection were discussed in detail at the 4th ISABMEC conference [9].

Table 1 The principal particulars of Model-4

	Fuselage (m)	Side fin (m)	Tail fin (m)
Length	1.3	0.874 (outside)	0.22
Width	0.714	0.075	0.17
Thickness	0.1	0.0005	0.0005
BG*	0.0002 ~ 0.003		
Total weight	62.8 (kg)		

**BG: Distance between gravity and buoyancy center*

The swimming performance of Model-4 was demonstrated at Suma Aqua life Park with the real fishes (Figure 5) and in some Underwater Robot Festivals in Kobe, Japan. The robot swam freely in the environment similar to real coastal water with tidal current. It was quite interesting to note that the robot did not annoy the fishes – fishes were not scared swimming together with it and they did not attack it.

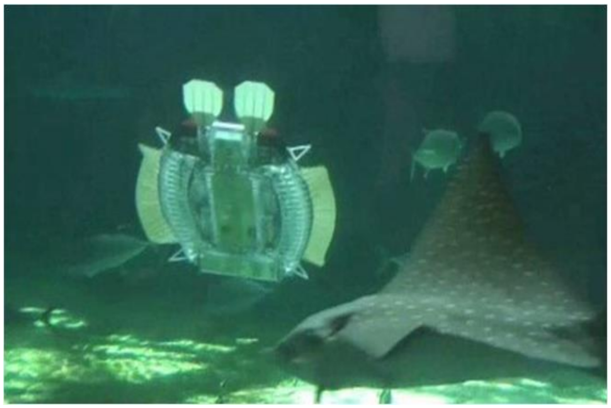


Figure 5 Model-4 of Squid-robot is swimming with the real fishes at Suma Aqua-life Park in Japan

It proved the environment friendliness of the robot. The robot also showed excellent manoeuvrability in swimming and it could move in any direction in the 3D space.

2.5 Model-5

In the continuous development of a competent and eco-friendly underwater robot, recently Model-5 has been constructed (Figure 6). The new model was designed by using underwater scotch yoke systems for both side fins. Although the scotch yoke systems were used for Model- 1 to make smooth the fin's undulating motion, the gear systems and motors were in the air, and the systems to make the fin's undulating motion were in the underwater body that was not water tight. However, for Model 5, the underwater scotch yoke systems including gear systems were attached to the both side of resistance body. In the present section, only the mechanical part is explained a little bit because the two DC motors for side fins, two servo motors for caudal fins and controller for them were taken from the market for preliminary free running experiment. As shown in figure (Figure 6), the water tight body was made by acrylic plates. Bottom and top plates were same shape and in the top plate, the water tight covers were made to put the receiver, controller, batteries and weights. In the head part, two DC motors with reduction gear were installed to make the rotation of each side shaft. Two same servo motor units that were used for model-4 for caudal fins were attached to the rear end of water tight body. From the water tight body, two rotating shafts driven by DC motors with reduction gear went out through the water tight bearings.

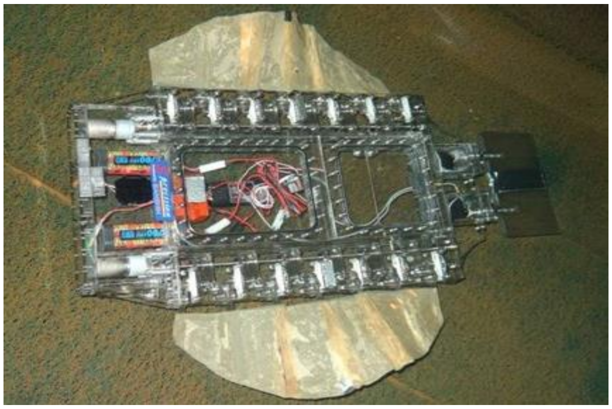


Figure 6 Model-5 of Squid-robot

The drawing of Model-5 and the principal particulars of Model-5 are shown in Figure 7 and Table 2 respectively. As shown in Figure 7, the seven scotch yoke units to make the angular periodic motion of fin's seven frame were placed in longitudinal direction at equal spacing. One scotch yoke unit is shown in Figure 8; the small gear shaft was continuous shaft driven by DC motor and turns one direction (clockwise or counter clockwise by controlling DC motor and number of revolution was same for all seven mechanisms and could be changed by controller). By this small gear, the large gear was turned in one direction as the wheel of scotch yoke. Note that the ratio of radius was 1:2 and the number of teeth of small gear and large gear were 36 and 72 respectively. As shown in Figure 8, the pin on the wheel gear sits in the slot in the yoke. As the gear turns, the yoke is forced up and down. This vertical motion is sinusoidal motion. The pin on the other end of the frame from the pivot sits in the slot of the other side of the yoke. The other end of the frame height was forced sinusoidal motion; so, the tip of frame moved vertically in sinusoidal motion.

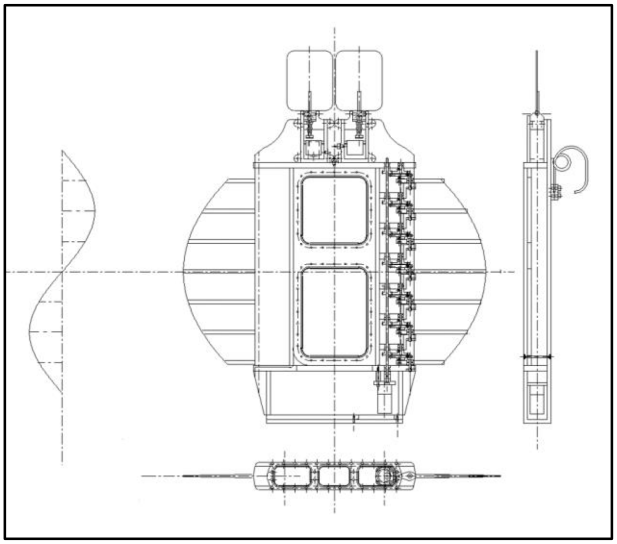


Figure 7 Drawing of the Model-5

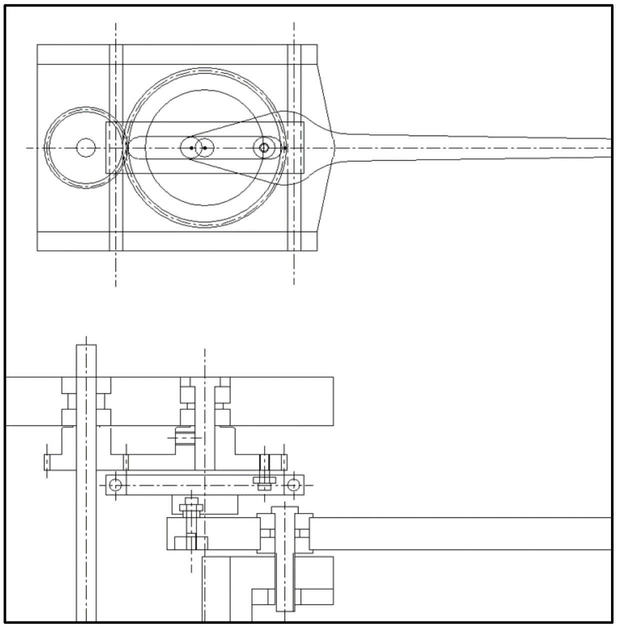


Figure 8 A single unit of scotch yoke system

If the number of revolution of the geared DC motor output shaft is n and the number of revolution of large gear is n/2 = f and f is frequency of sinusoidal motion. If the pins are placed for seven large wheels at 45 degree interval. The rotating angle of kth frame is expressed as follows:

$$\theta = \sin^{-1}\left(\frac{18}{28.3}\sin\left\{\pm(2\pi f)t + (k-1)\frac{\pi}{4} + C_0\right\}\right)$$

where 18 is the distance between large gear center and pin (mm), 28.3 is the distance between pivot and the pin center of the other tip on frame (mm), k is kth frame from the leading edge of side fin (for k = 1 to 7) and C_0 is the phase of 1st frame. The ± sign represents the rotational directions whereby + sign is clockwise turning and – is counter clockwise turning.

Table 2 The principal particulars of Model-5

Resistance Body		**Side fin frame length**	
Length	800 mm	**1 st & 7th**	87.5 mm
Width	400 mm	**2 nd & 6th**	150 mm
Thickness	72 mm	**3 rd & 5th**	187.5
Weight	25 kg	**4 th (middle)**	200 mm

Each side fin		**Caudal fin**	
Length	490 mm	**Length**	158 mm
Thickness	1 to 2.5 mm	**Width**	123 mm
Maximum angle of oscillation	39.50	**Thickness**	1 mm
Wave length / Fin length	4 / 3		

The fin's surface was approximately expressed by seven frames as travelling wave. So, the both side fin show travelling wave which phase velocity was in backward direction if both motors turn in clockwise direction and the model moved forward. The detail mechanical design with some preliminary experimental test results were presented recently at the 6th ISABMEC conference in Hawaii, USA [10].

3.0 CFD COMPUTATION AND MOTION SIMULATION OF THE SQUID-ROBOT

With the development of the mechanical bodies and control system, the computational model of the Squid-robot has also been developed for better analysis. Though a lot of experimental studies have been done for different models to examine its proficiency and to find the optimum structure of the robot, any change of the mechanical part requires huge money, and it is also wastage of time. On the other hand, these types of changes can be done easily in the computational model. The experimental and numerical studies are complementary to each other. As an example, experiments can give the total force characteristics while the detailed analysis of force can only be obtained through the numerical study. So, the Computational Fluid Dynamics (CFD) analysis and the 3D motion simulation were conducted to recognize the flow physics around the undulating fin and to investigate the mechanism of thrust generation. The CFD computation and motion simulation were conducted for different models; however, in this paper, the discussion is only based on Model-4 for convenience.

3.1 CFD Computation

In CFD Computation, at first, the numerical grid was constructed around a rectangular flat plate of the same area of the robot (including fin) for simplicity in grid generation. Then two fins were produced at the lateral sides of the flat plate by gradually increasing the vertical amplitude. A numerical moving grid was constructed around the body at each time step using Poisson equation to handle the unsteady motion. In the computation, the Finite Analytic Method (FAM) for space discretization and Euler Implicit Scheme for time discretization along with the PISO algorithm for velocity pressure coupling were used. The features of the flow field and hydrodynamic forces acting on the body and fins were investigated based on the computed results. The governing equations and the method of computation were briefly discussed in the previous studies [11-13]. The computed results were verified by comparing the results with the physical experiments and good agreement, to some extent, was obtained. A simple relationship among the fin's principal dimensions and hydrodynamics was also established using the computed results.

Recently, a CFD computation around a body similar to the physical body of Model-4 was also conducted. The strategies of generating numerical grid and the method of computation were similar to that discussed in the previous study; however, some modifications have been taken into consideration to make the computational model same as real Model-4. The computed pressure distribution on the body and undulating side fins of the Model-4 is shown in Figure 9.

3.2 Motion Simulation

The motion of Model-4 of the Squid-robot using undulating side fins propulsion system was also simulated. In the first study, the braking performance of the undulating fin propulsion system of the underwater robot was investigated through free run experiment and simulation of the quasi-steady computational model [14-15]. The quasi-steady equations of motion were solved using the measured and calculated hydrodynamic forces and compared with free-run test results. Various braking strategies were tested and discussed in terms of stopping ability and the forces acting on the stopping stage. The stopping performance of the undulating fin propulsion system turned out to be excellent considering the short stopping time and short stopping distance. For example, the travelled distance in translation motion with respect to time is shown in Figure 10.

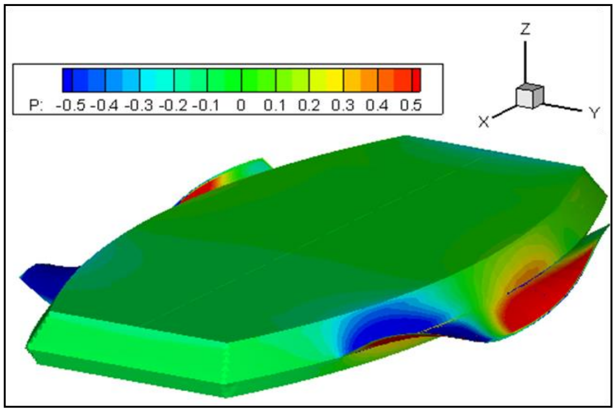


Figure 9 Computation of pressure distribution on model-4 of the squid-robot

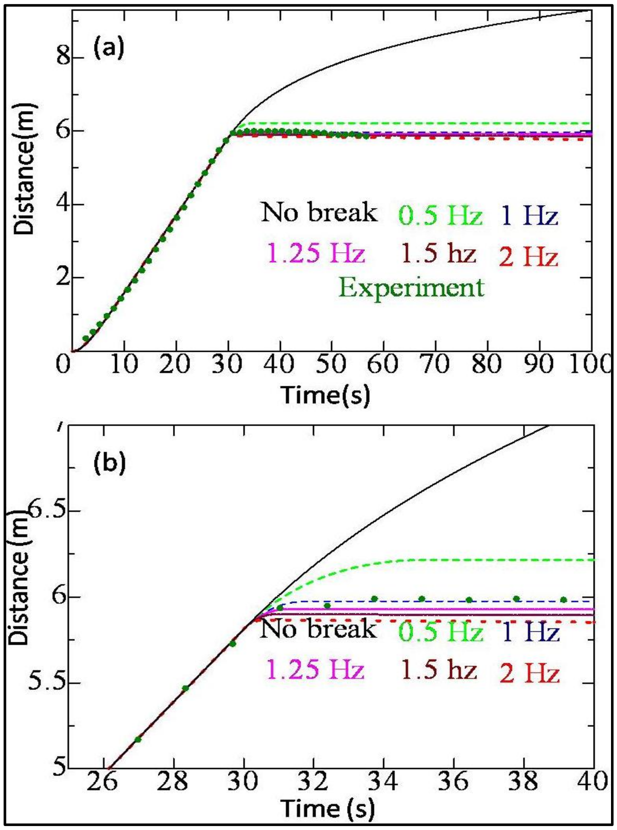
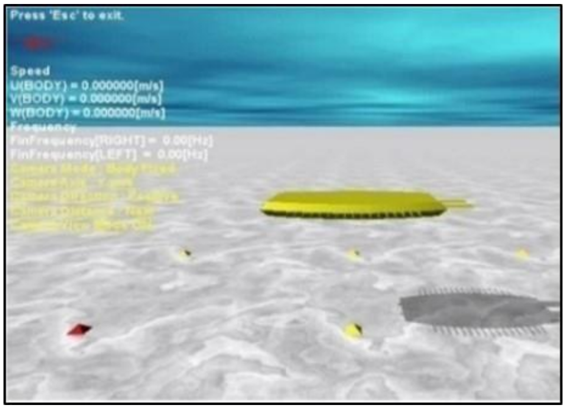


Figure 10 (a) Travelled distance in translation motion with respect to time; (b) Enlarged view near the breaking point

The motion of Model-4 of the squid-robot with two undulating side fins has also been investigated through the simulation of 6-DOF computational model in 3D space with the aim of developing a real-time simulator [16]. The comparison between simulation results and experimental results confirmed the accuracy of the simulation. The real- time handling simulator was developed based on a computational model by using Open Dynamic Engine (ODE) (Figure 11). It was confirmed that the robot in this simulator could move in a similar way as real robot's motion by the same control. The real-time simulator is now used for the training of the operators to increase their skill.


Press 'Esc' to exit.
Speed
U(BODY) = 0.000000[m/s]
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W(BODY) = 0.000000[m/s]
Frequency
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FinFrequency[LEFT] = 0.00[Hz]

Figure 11 Real time simulator of model–4 of squid-robot

4.0 CONCLUSION

The Squid-robot is still under research and development in order to optimize its performance and capability. Though the robot has proved its performance for precise maneuverability and environmentally friendliness in underwater, there is still far away to go to reach the goal. Till now the robots are experimented in the towing tank or aquarium or swimming pool; the performance of the robot in a real environment will be tested soon. The use of autonomous underwater vehicles (AUV's) are expanding rapidly; the demand for improved efficiency is also increasing. The robot will be converted to autonomous in the future to allow for longer missions. The strength of the communication system will be improved for controlling the robot from a far distance that is required for real application. The robot is now using the rechargeable battery for power supply that can work only for few hours; another source of power should be generated for longer mission. Robotic devices are currently being developed to assess the benefits and study the ways of porting mechanisms utilized by fish and other aquatic animals to artificial systems. Under this perspective, engineers working in this area should have a background knowledge of the swimming abilities and performance of fish that provide benchmarks for evaluating our designs and drive further developments. The characteristics and type of color blind has been studied and identified as well as the problem faced by individual that is color blind. A real-time color recognizing system using image processing technique is successfully developed and tested.

A various experiments were performed to test the functionality of the developed application for color deviation and range tests. For the color deviation test, the results showed the deviation on the HSV value of the tested color was small and within an acceptable ranges. The results of the range test showed that the device could recognize color from a range of 20 cm up to 12 m.

Acknowledgement

The Squid-robot is developing under the direct supervision of Professor Yasuyuki Toda, Osaka University, Japan; we are grateful to him.

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