Swimoid: A Swim Support System using An Underwater Buddy Robot

[Full Paper]

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ABSTRACT
In the field of sports and athletics, it is important for athletes to recognize their own performance by themselves to gain skills effectively. Although swimming is a popular life-long sport all around the world, it is difficult for non-professional swimmers to understand how they swim. In other sports such as baseball, golf and dancing, mirrors are utilized to examine the players ' form. However, it is difficult to use the mirror for this purpose when it comes to continuous sports such as swimming, running and cycling. To solve this problem, we propose a buddy robot that has an ability to recognize, follow, and present information to the swimmer. We developed a swim support system called "Swimoid ". The buddy robot can swim directly under the user, and present information through the display mounted over the main body. To follow the user, we utilized image processing techniques on the footages captured by two cameras mounted on the front and rear of the robot. Swimoid can augment the user ' s ability underwater environments in two different ways. First of all, Swimoid enables swimmers to recognize their swimming form in real time. Secondly, Swimoid could allow coaches on the pool side to give instructions to swimmers. These two functions are for improving swimming techniques. However, we also believe we can use the buddy robot for a different purposes, such as entertaining novice swimmers and we implemented a game function to get familiar with water using the touch interaction with a swimmer. As a result of user tests, we confirmed this system works properly. Finally, we measured our contribution in the research field by comparison with related works.

Categories and Subject Descriptors
H.5.m. [**Information Interfaces and Presentation (e.g. HCI)**]: Miscellaneous

General Terms
Design

Keywords
Sports Assistance, Swimming, Autonomous Underwater Vehicle, Underwater Human-Robot Interaction

1. INTRODUCTION
There are a lot of different kinds of sports, and everyone on earth involve in sports and anyone could be involved by either playing or watching. It is well known that playing sports is necessary for us humans to keep healthy, both mentally[1] and physically[2]. Some surveys[3, 4] conducted at several countries show swimming is very popular sports all over the world. To be sure, the age affects physical performance[5], swimming is widely-recognized as a lifelong sport, so you can swim for your whole life for fitness, recreation and fun. Thanks to the characteristics of water there is little chance of injury and people who aren't able to do other activities because of their heart conditions or chronic back problems can participate in.

On the other hand, the characteristics of water make swimming more difficult than other sports done on terrestrial environment. For example, humans aren't able to breathe underwater. Because of that, swimmers need to practice and gain breathing technique at first. Poor breathing technique can easily cause a wide variety of the problem on the swimmer's stroke. In order to swim efficiently, it is essential to master proper swimming techniques to reduce water resistance. To gain proper swimming stroke technique, people should know how they swim and understand the difference between ideal strokes. This ability is generally called "self-awareness" or "self-monitoring" and we use the term "self-awareness" in this paper.

A previous study[6] indicates that athletes use mental imagery of their performing form for improving their performance skills. It also shows people who are able to understand correctly how they perform can learn sports skills more quickly than others do[7]. It is also said that eminent athletes can imagine their performing form from the perspective of an external observer as if they are watching themselves as the spectators in the stands. However, it is difficult for non-professional athletes to imagine their form vividly by themselves due to the lack of experience.

Sports can be classified into two categories depending on the position of the player, weather if it moves constantly (continuous) or not (non-continuous). In continuous sports such as swimming, running, or cycling, the position of the players moves continuously while the player repeats the motion. On the other hand, in non-continuous sports such as baseball, golf, and dancing, the position of the player remains mostly fixed. In non-continuous sports, people use mirrors while training to check whether their performance is right or wrong. However, when it comes to continuous sports, it is hard to check their performance by the use of mirrors. This is because players move constantly without interruption, making it difficult to remain in front of an fixed mirror. To overcome this problem, a quad-copter and head-mounted-display are used in the previous study[8] to give visual feedback to a runner.

Swimming obviously belongs to the category of the continuous sport, so it is difficult to check swimmer's stroke by the use of mirrors. As we previously mentioned, underwater environment is a harsh environment for human beings. According to the book published by Japan Swimming Federation that is an official organization in Japan, the swimmer is difficult to recognize their stroke because swimmer's face is often below the surface of water.

In short, swimmers should check their stroke but it is difficult. We want to solve this problem, but there are not many studies conducted in this area.

Recently, there has been rapidly increasing in research about the development of ROVs (Remotely Operated Vehicle) and AUVs (Autonomous Underwater Vehicle) [9]. They are now playing a crucial role in the underwater activity[10] such as a seafloor exploration and an inspection of bridges, dams or pipelines and environmental monitoring. However, those underwater robotics technologies have not been used for underwater sports yet.

2. RELATED WORKS

This study belongs to two research domains; UHRI (Underwater Human-Robot Intearction) and swim assistance systems.

2.1 UHRI

HRI (Human-Robot interaction) is a complicated problem even in a terrestrial domain, and most of existing studies in this field have been mainly performed overland. Us humans mainly live on dry land, but we also do considerable amount of activities in water and underwater. For example, we swim in pools and dive under the seas. Because of that, research on UHRI is important to perform underwater activities.

Some studies have already been conducted in the field of UHRI. Compared to the existing studies about HRI in terrestrial domains, the biggest problem of UHRI is that many communication channels available in the terrestrial domain become unavailable underwater. Recently, many studies use some cameras mounted on robots as a visual communication channel. The existing studies may be classified into two categories (Figure 1): giving instructions to robots from human (Figure 1a) or tracking human (Figure 1b).

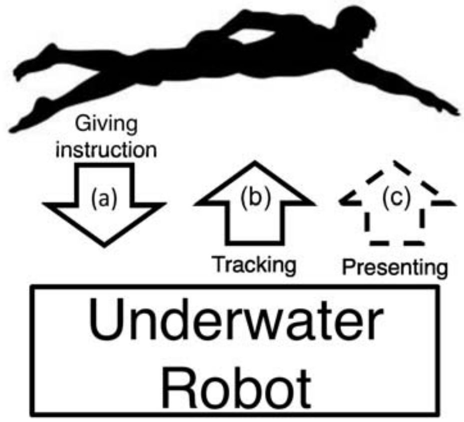

Figure 1: Underwater HRI: three types of the interactions: (a) giving instructions to robots from human (b) tracking human using some sensors mounted on robots (c) giving out information to human from robots

However, although the method of giving out information from robots to users is one of the important topic in the research field of HRI in terrestrial domain, the method that is available underwater (Figure 1c) has not yet been fully investigated .

2.1.1 *Giving instructions*

The objective of these studies shown in the Figure 1(a) is to give instructions to robots from human in various ways.

A previous study[11] has shown the availability of using visual markers (2D bar codes) to transmit commands to an underwater robot. Another study[12] uses gesture detections to communicate between divers and a robot. Also, the work described in [13] depends on LEDs mounted on a diver's hand for diver-machine interface.

All of them use cameras mounted on robots as a communication channel.

2.1.2 *Tracking Humans*

Tracking human in underwater environments is also an essential topic in UHRI. [14] presents an algorithm for underwater robots to follow divers by detecting periodic motion.

2.2 Swim assistance systems

There are several studies or products to support swimmers while training. These can be classified into two general groups: analyzing swimmer's stroke and presenting information.

2.2.1 *Analyzing swimmer's stroke*

There are a lot of studies or products to analyze swimmer's movement underwater. They can be classified into two categories: infrastructure-based and wearable-based.

Since early times, studies that analyze swimmers' stroke utilizing some cameras mounted on the bottom of the pool have been conducted[15]. We categorize these studies as an infrastructure-based method because the cameras used in these research are mostly fixed on the bottom of the pool.

However, non-professional swimmers have been impossible to use these systems because infrastructure development is required to use these systems due to the cost of installation. There is also another problem that the process of digitization is necessary to recognize swimmer's stroke from a video footage. Recently, motion-capture system[16] that is available underwater is developed and utilized to recognize swimmers' stroke more precisely, and the process of digitization is done almost automatically. However, it is still necessary to install some cameras to use underwater motion-capture system. It makes difficult for non-professional swimmers to use and the range of an available area is restricted.

On the other hand, several systems[17, 18] that recognize the swimmer's movement using the wearable sensors such as accelerometer mounted on swimmer's body have been conducted recently. We categorize these studies as a wearable-based method and this method allows us skip the step of digitization.

2.2.2 *Presenting information*

As we previously described in Section5.1, LEDs embedded with the swimming goggle, vibration motors installed on the swimmer's body and speakers in the swimming cap are used to convey the information to the swimmer from the coach. However, those devices can transmit only limited information.

And also an underwater HMD(Head Mounted Display) is used to present information underwater [19]. In the article[20], the augmented reality application using the handheld underwater HMD for the diver is proposed. However, as noted previously, many communication channels available in the terrestrial domain become unavailable underwater. In previous projects, the underwater HMD is connected to the computer using the cable. Because of that, the movement of the swimmer is restricted.

3. SWIMOID

We developed a swim support system called "Swimoid" to solve swimming-related problems. One of the function in Swimoid enables swimmers to recognize their swimming stroke and gain self-awareness. To make this system, we develop an underwater robot (Figure 6) with a display that has the ability to follow the swimmer. This is so named because the features of this robot are similar to those of the buddy system in diving. The buddy robot has an ability to swim directly under the user by the use of two cameras mounted on the both the front and rear of the main body (shown in Figure 2).

Figure 3 shows a system overview. The buddy robot has a control computer, some sensors and batteries inside of the main body and it can work autonomously. However, this

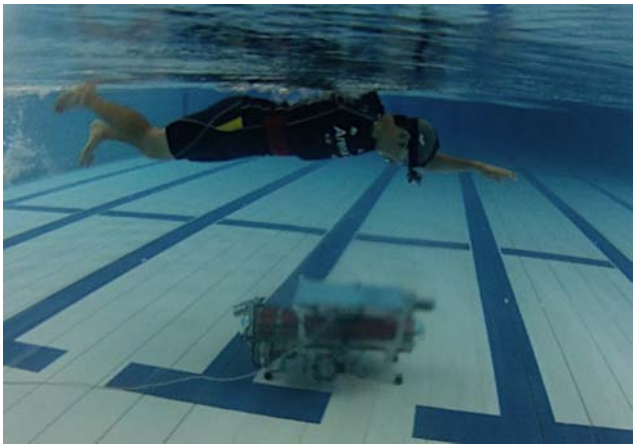

Figure 2: Swimoid: a swim support system using an underwater buddy robot. Swimoid's buddy robot can swim directly under the user.

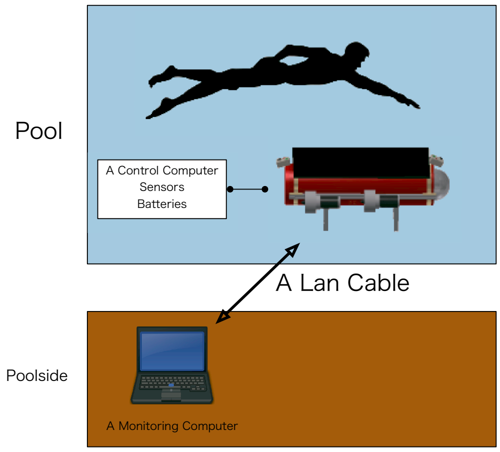

Figure 3: System Overview

robot tethered to the monitoring computer at the poolside via a LAN cable due to safety concerns.

Simply put, Swimoid consists of the hardware of the buddy robot that moves along with the swimmer, control software that recognize and follow the user by the use of image processing techniques. It also has two functions for improving swimming techniques; self-awareness(Figure 4) and coaching(Figure 5)). Moreover, we implemented a game function for novice swimmers. We will give a full detail of system configuration later on this paper.

4. SELF-AWARENESS

Figure 4 shows a self-awareness function that enables swimmers to recognize their swimming form. Those images are captured by the camera mounted on a swimmer's head.

4.1 Background

As we previously mentioned, self-awareness is an important skill to develop sports skills. However, it is difficult for non-professional players to imagine their performing form

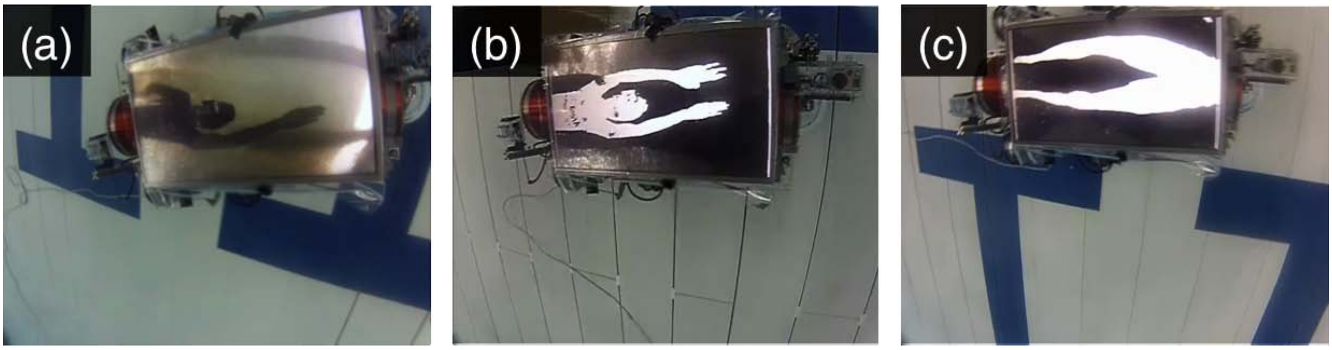

Figure 4: Self-awareness Function: (a) The swimmer is utilizing the frontal camera to check the movement of his arms in front crawl. (b)This captured image is binarized to be easily recognizable. (c)The swimmer is utilizing the rear camera to check the movement of his legs in breaststroke.

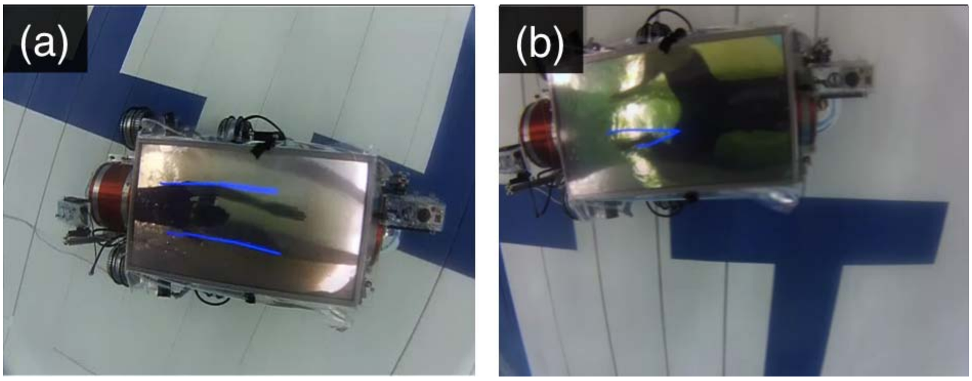

Figure 5: Coaching Function: (a)The coach draws two lines that suggest the swimmer to move one's arms straightforwardly.(b)The coach gives instruction that the knees stay close together.

vividly. Moreover, underwater environment makes this problem more complicated.

4.2 Feature

This function enables swimmers to recognize their swimming form in real time by the captured image from the cameras and displaying this image on the display.

The swimmer in Figure 4(a) uses the frontal camera to check the movement of his arms. We also implemented the function that binarize capturing image to recognize the swimming form easily. The swimmer in Figure 4(b) uses banalized image to do the same task in Figure4(a) . Swimoid's buddy robot has two cameras, therefore swimmers can choose which camera to use. It is considered highly beneficial for the swimmer because there are many swimming styles, and each style has different attention point. For example, the movement of arms (pull movement) is important in front crawl and the movement of legs (kick movement) is vital to swim efficiently in breaststroke. Figure 4(c) shows the user uses the rear camera to check the movement of his legs.

By using this function, swimmers can recognize their swimming form in real time.

5. COACHING

Figure 5 shows the coaching function which enables the coach to instruct the swimmer in real time by drawing some shapes.

5.1 Background

Generally, voice is commonly used to communicate between the swimmer and the coach. However, it is difficult for the swimmer to understand what the coach is saying because of noises and reflection.

Moreover, it is hard for non-professional swimmers to correct their stroke by the spoken command from the coach, and the coaching technique that watches a video footage given by a underwater camera after they swim is widely used.

In the recent study[21], some devices installed on the swimmer's body are used to give instructions. LEDs embedded with the swimming goggle, vibration motors installed on the swimmer's body and speakers in the swimming cap are used in this study. However, those devices can transmit only limited pieces of information.

5.2 Feature

To solve this problem, we implemented a coaching function by the use of buddy robot. The coach on the poolside can observe the swimmer's performance remotely on the monitoring computer and instruct the swimmer by drawing some

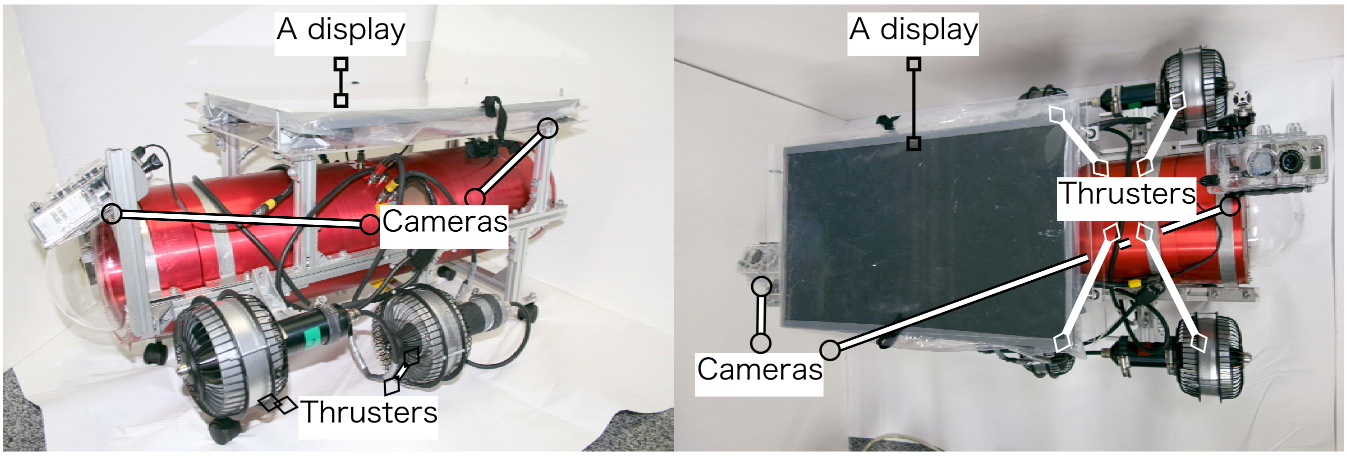

Figure 6: Swimoid's buddy robot: The small size AUV has two cameras, 22-inch display, and four thrusters.

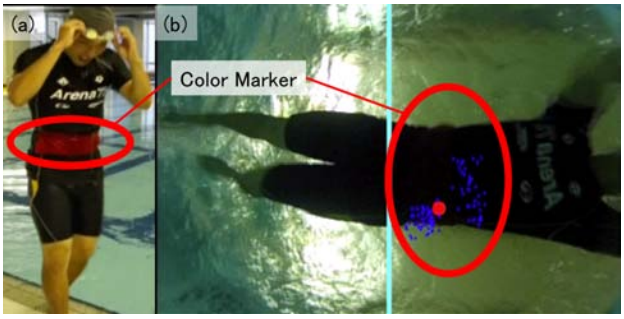

Figure 7: Swimmer tracking: Two cameras mounted outside of the main body in an upward direction are utilized to recognize and track the swimmer. (a)A discriminative color marker (b)Particle filtering algorithm applied to captured image

shapes. The shapes drawn by the coaches is rendered on captured image and the swimmer can recognize instruction from the coach visually and in real time. In the Figure 5(a), the coach draws two lines that suggests the swimmer to move the arm straight. In Figure 5(b), the coach instructs the swimmer to keep the knees close together in breast strokes to decrease the water resistance.

6. SYSTEM CONFIGURATION

The buddy robot which is used in Swimoid is shown in the Figure 6. We used existing small size AUV that was developed by another laboratory in our university as the base of our robot. Our robot is 42 centimeters tall and 58 centimeters wide and has a depth of 96 centimeters. Main body of our robot is a cylindrical metal container, and its maximum cruising depth is expected to be 10 meters. Some devices such as a notebook computer, batteries and electric circuits are stored in this container. This robot has four thrusters to gain the propulsion and four wheels. Original AUV that we used as the base of our robot also has four thrusters but two of them are utilized to control it vertically. However, in our use case scenario within the swimming pool, we figured that vertical maneuvering is unnecessary. Thus we installed wheels to increase its horizontal stability. As mentioned earlier, this robot has also 22-inch display over the main body and two cameras on the front and rear of the main body. This robot tethered to the computer at the poolside via a LAN cable due to safety concerns.

6.1 Swimmer Tracking

As already stated, we used two cameras that are attached to front and rear of the main body for swimmer recognition and tracking. In this research, we implemented a color extraction and particle filtering algorithm for swimmer tracking (Figure 7 (b)) . The notebook computer that is located internally in the main body processes these calculations. The system requires the subject to wear a discriminative color marker (Figure 7(a), in this research, discriminative color is red) . The captured image data contains noise that is caused by some environmental factors. Particle filtering algorithm enables noise-robust tracking by observing time-series data, and it estimates the current and subsequent states of the tracked object. We use this tracking data to control the robot's front-back direction only, because swimmers commonly swim in a direct line parallel with lane ropes. We used an electronic compass to control horizontal direction of our robot.

7. GAME

We have already introduced two functions (self-awareness and coaching) that are for improving swimming techniques. We also believe we can use the buddy robot for a different purpose, and we developed an entertainment function (Figure 8) for novice swimmers to get familiar with water.

7.1 Background

As we previously mentioned, humans can't breathe underwater. Because of that, many people, especially young people, have fear of water[22] and which may develop fear toward swimming.

To remove this fear, games that require children to dive and fetch items from the bottom of the pool are used in many swim classes. People can get used to water in an enjoyable format.

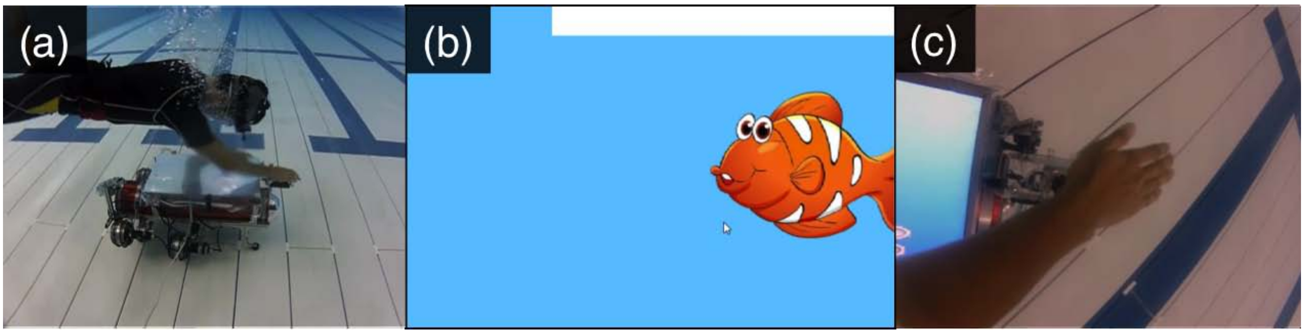

Figure 8: Game Function: (a)Touch interaction using the camera (b)The view of the function (c)The user's view

7.2 Feature

We introduce a touch interaction (Figure 8(a)) to develop this function. In order to achieve this interaction, we use the camera as an input device. When user touches a camera mounted on the buddy robot, the system can recognize and respond.

Figure 8(b) shows one of the characters that appears as an enemy. These characters appear at a random interval and scroll on the display at a random speed. Therefore, the user need to submerge their face in water to know when to touch. When the user touches the camera when there is a enemy shown on the display, the users would get points. Of course, if the user touches when the character isn't displayed on the screen, the point that the user has already gained is decremented.

8. DISCUSSIONS AND LIMITATIONS

In this section, we measured our contribution in the research field by comparison with related works. And also we attempt to discuss the limitation of the current prototype.

8.1 User Study

We also tested the proposed system by recruiting a swimming coach as a test user. He is good at swimming and has an experience to teach children swimming. The images used in this paper are shot in the experiment. We confirmed this system works properly by this test and by the test user's comments.

8.2 Comparison

As we previously stated, this study belongs to two research domains; UHRI and swim assistance systems. In short, we contribute each research domain respectively. In UHRI domain, we invent a robot-based way to present information to the swimmer. On the other hand, in swim assistance systems, we invent some functions that support swimmers and swimming activities using the buddy robot.

Although there are a lot of studies in the research field of UHRI, the method of giving out information from robots to users has not yet been fully investigated in underwater environments. On the other hand, some non-robot-based studies that present information to the swimmer have already been conducted. However, these non-robot-based methods still have difficulties. The method using the LEDs, the vibration motors, the speakers can only transmit limited information. And the method using the underwater HMD may solve this problem, but it restricts swimmer's movements because of its cable. To solve this problem, we use the buddy robot to present information to the swimmer that an underwater display mounted on buddy robot that can follow the swimmer are used. The swimmer can gain information without restriction of movement.

And also we propose some functions using the buddy robot for swimming activities. Although some studies have already been conducted and they can be classified into two categories; infrastructure-based and wearable-based, the system to use an underwater robot for assisting swimming activities has not yet been investigated. We compared the advantages and disadvantages of the robot-based system we proposed with the existing two methods in Table1.

8.2.1 *Presenting information*

First of all, presenting information to the swimmer using the infrastructure-based method is difficult. For example, installing displays to the whole of the bottom of the pool is feasible but it is unreal due to the enormous cost of installing (Table1(a)).

Some non-robot-based studies that present information to humans underwater using some devices like the underwater HMD have already been conducted in the research field of UHRI. However, this method restrict swimmer's movements due to the cable that connects to the computer (Table1(b)).

On the other hand, we proposed robot-based method. One advantage of our method over the wearable-based method is that there are fewer restrictions on what kind of devices mount (Table1(c)). The robot can carry heavier devices than the swimmer do. In this study, we mounted a 22-inch display on the robot.

8.2.2 *Analyzing Swimmer's Stroke*

The infrastructure-based technique using the fixed camera or underwater motion-capture system has been used to analyze swimmer's stroke. As we mentioned, the process of digitization is inevitable to analyze swimmer's stroke by the use of the camera, and the range of an available area is also restricted (Table1(d)).

Table 1: Comparison with existing methods (◯:Good, △:Not so bad, ×:Bad)

	Presenting information	Analyzing swimmer's stroke	Cost of installation
infrastructure-based [15, 16]	× (a) (Installing displays is unreal.)	△ (d) (Digitizing and the range of an available area)	Expensive (g) (Construction is needed.)
Wearable-based [17, 18]	△ (b) (Restricting swimmer's movement)	◯ (e)	Inexpensive (h) (Construction is not needed.)
Robot-based	◯ (c)	× (f) (Making digitization more complicated)	Relatively inexpensive (i) (The robot is a little expensive yet.)

On the other hand, the wearable-based method can solve these problems, and it enables analyzing swimmer's stroke more precisely (Table1(e)). Previous study[23] that compared infrastructure-based method with wearable-based method indicates the wearable-based method is superior to infrastructure-based method in several respects. It also indicates the wearable-based method will hold a important place in years to come.

We didn't implement a function that analyze swimmer's stroke using the camera that is installed to the buddy robot. In robot-based system, the process of digitization may become more complicated because both a camera and a subject (a swimmer) move (Table1(f)).

8.2.3 *Cost of installation*

The infrastructure-based method may be the most expensive (Table1(g)) because the construction is needed to install some devices underwater. On the other hand, the wearable-based method is most inexpensive (Table1(h)).

The robot-based method is inexpensive compared with the infrastructure-based. However, the robot is a little expensive yet (Table1(h)).

8.3 Limitations

We observed following problems with this system during the test run. It is difficult for the user to observe the display for a long time due to the limitation of breathing capacity. The technique which recognizing the cycles of user's breathes may eliminate this problem.

We attached the display over the main body of the robot, it causes two problems. First, it makes difficult to control the robot because of increasing water resistance. We'll try to make the robot smaller in order to solve this problem. Second, it also makes the batteries running out fast because the LCD display requires a measurable amount of power. Our robot could run only for an hour.

9. FUTURE WORK

We develop the buddy robot and some functions for the swimmer. However, there is room for further research into some domain.

9.1 Buddy Robots

Our buddy robot is that swimming just under the user and to support the swimmer, but we don't limit the figure, positional relationship between the user and the robot and purpose of buddy robot.

Figure 9: The concept of Buddy Robot: (a)with a swimmer (b)with a diver (c)with swimmers

Figure 9 shows some examples and the Figure 9(a) is our buddy robot for the swimmers. Figure 9(b) indicates the possibility of a diver-robot interaction using buddy robot. We expect that some applications for divers such as safety monitoring application around the diver or giving geographical, environmental and sea creatures' information to the diver are implemented in the near future. Finally, Figure 9(c) shows another shape of buddy robot like a ball. This robot does not have a big display but has some LEDs to communicate with swimmers or divers around the robot. In this case, the robot may be used to entertain people by utilizing light and sound, or it may be used as a safety monitoring device in pools or beaches. We don't limit the style of buddy robot and strongly expect a wide variety of buddy robots will be developed.

9.2 Functions

We develop three functions; self-awareness, coaching and game. We have already described our motivation and how they work. And we recognize there is still plenty room for improvement or enhancement for those functions.

In self-awareness function, the swimmer can only know how they swim, and it is still difficult to use for the swimmer who doesn't know how to correct their stroke. Therefore, we need to improve this function that the users who are without knowledge about swimming can easily use. For instance, the function that recognize user's form automatically and compare to professional swimmer's form and feedback the difference of these forms.

In coaching function, a coach at a poolside has to draw some shapes to instruct a swimmer. However, if the computer can analyze their stroke automatically, the coach doesn't need to give instructions manually any more. Or if the computer has a connection to the network, someone on the internet may give instructions to the swimmer. These technological advancements may revolutionize the way people mastered swimming.

In gaming function, we introduced a touch interaction and used a camera as a gaming input. However, we can only recognize the user is touching now or not. We think inventing the novel way to interact with an underwater robot is interesting topic in UHRI.

10. CONCLUSION

We propose a swim support system "Swimoid" using an underwater buddy robot. Our buddy robot can swim directly under the user. We implemented two functions that are to improve swimmer's skills. Self-awareness function enables swimmers to recognize their swimming form in real time. And coaching function also enables coaches on the poolside to give instructions to swimmers. Both functions can augment the user's ability underwater. Moreover, we implemented game function to get the swimmer to get familiar with water. As a result of user tests, we confirmed this system works properly by the test user's comments. Finally, we measured our contribution in the research field by comparison with related works.

11. ACKNOWLEDGEMENTS

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