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Review

A role of advanced image data logger systems in marine animal studies

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Abstract—To fulfill information gaps of underwater animal behavior, variety of animal-borne observation systems have been developed in last several decades, which revealed diving behavior, foraging behavior of many endotherms, particularly seals and penguins by providing information on many dive parameters, such as dive depth, dive angles, dive profiles, swim speed, body motion, body postures, ambient temperatures, 3D dive paths and so on. Above advanced animal-borne systems supported us to obtain reliable data both in quality and quantity regarding diving behavior, particularly foraging behavior, which have been hidden underwater for long period. Challenges to reveal foraging behavior of diving animals developed new hypotheses regarding foraging strategies of diving animals. Accordingly it was expected to develop a new tool to examine the hypotheses. A tool to obtain visual information on prey items, distribution and prey capturing events was strongly expected to be developed. Corresponding to above expectation several types of image data loggers were developed in recent years and have been used for variety of research purposes. Here I review the current system of image data loggers and concurrently role of image data loggers in studies of diving animals.

Key words: image data logger, animal-borne camera, Bio-logging, digital still picture Logger (DSL), visual information

Introduction

Space and ocean have long been objectives of our scientific interest. Comparing both objectives, while the space is much far from us, its objective is visible for our naked eyes. On the other hand, ocean particularly underwater world is much closer to us but almost completely invisible. Difference in visibility between space and ocean has brought us significant difference in the way of challenge to explore them as objectives of our scientific curiosity. Because human beings have developed scientific ideas and hypothesis based on the visual observation facts. From prehistoric days stars of space might have been observed with scientific interests and raised questions "why" based on observation facts, and in order to test hypothesis and ideas we developed many scientific tools like as telescopes, variety of modern telemeter observation systems and many space vehicles. On the contrary underwater marine science, particularly science on marine living animals has been poorly developed because we did not have any visual observation tools on living animals. This resulted to create many monsters and devils merely by virtual imaginations in deep oceans and even in lakes. Nevertheless challenges have been made to observe living animals by developing variety of sampling gears, which are not direct observation but supported to understand dynamic aspects of living animals, such as vertical movements of planktons and fishes and other marine animals. More direct observation systems are scuba, remotely operated vehicles (ROV), autonomous underwater vehicles (AUV), manned vehicles and acoustic remote observation systems. However use of those systems for study on marine mobile animals is often limited by depth, duration and mobility. Thus these systems still provide short advantages in study of marine animals that move widely in ocean space. In studying foraging behavior of marine mammals for example these technologies often provide only fleeting glimpses of highly mobile species (Davis et al. 1999).

To obtain information from mobile animals in 3-dimensional ocean spaces unique technique specified to study on the diving behavior of endotherms has been developed. Animal-borne observation system, so called "Bio-logging" is a data collection system by the animal-borne micro instruments, which was initially developed as a time depth recorder (TDR) revising a kitchen timer in order to measure swimming depth of Antarctic seal (Kooyman 1965). The TDR succeeded to visualize diving behavior of seals in the dive profiles, providing 2-dimensional view of movements. Technique of Bio-logging has further progressed in accordance with development of digital micro-electronic technology and enabled us to measure many variables of animal behavior and ocean environments such as swim speed, body motion, body angle, 3-dimensional swim path, water temperature, water conductivity and so on (Sato et al. 1994, Hakoyama et al. 1994, Minamikawa et al. 2000, Otani et al. 2000, Tanaka et al. 2001, Sato et al. 2002a, Mitani et al. 2003, Naito 2004). These bio-loggers provide information on the utilization of ocean space by animals and support to visualize animal behavior and their environment. However real visual information with images was very much limited and development of such instrument was strongly required to understand complexity of marine living animals. Recent development on still picture and video loggers may play a new role in obtaining visual information from mobile animals in 3-D ocean spaces. Here I report recent results of development of the camera loggers and the new role of these instruments in animal and ocean science.

Type of image-loggers

In 1990's ambitious attempt of developing image-loggers to obtain underwater images from animal's points of view have been made, and several types of animal-borne image-loggers have been developed. The research results using those have been reported in recent years. As seen in Table 1, systems of the image-loggers were 3 types, a video camera, a still picture camera, and a video-still convertible camera. The animal-borne video camera was first made by Marshall (1998). He developed the video camera system named "Crittercam", which is an integrated video camcorder combined with data-logging system engineered in streamlined housing (Marshall 1998). The crittercam system was about 10 cm in diameter and 20 cm in length and has capabilities of data sampling control on time, salt-water immersion, depth and temperature by on board micro-computer. The three hours video tape employing standing mode can record behavioral events over days or even weeks using discrete sampling. He used the crittercam on 22 species (Field experiments: 7 pinnipeds, 2 cetaceans, 5 sea turtles, 5 sharks, Laboratory test: green turtle, hippopotamus and American alligator).

Following Marshall (1998), Davis et al. (1999) used video system to study feeding behavior of Weddell seals in Antarctica. System is similar to the crittercam and the size of torpedo-shaped housing is 35 cm in length and 13 cm in diameter and is pressure-rated to a depth of 1000 m. They attached LED light source to use in deeper waters. Two types of still picture camera were developed by Naito and National Institute of Research Group cooperated by Little Leonard Co. Ltd (Sato et al. 2002b, Sato et al. 2003, Watanabe et al. 2003, Takahashi et al. 2004). One has light source for flush and is designed for the study of deep diving animals and the other designed for smaller animals has no flush light. There are no explanations about reasons for selection of the system of image-loggers, video camera and still picture camera. However comparing the both systems, video system, it is clear that video system needs much larger housing. A convertible

Table 1. Animal-borne cameras used for diving animals.

References	Type of camera (cm)	Height (cm)	Width (cm)	Length (cm)	Weight (g) in air	Weight (g) in water	Recording capcity	Light source	Resolution (no. of pixcel)	Other parameters	Animal
Marshall 1998	Video	about 10 in diameter		20–30	2000		3 h			Depth, Temp	22 species
Davis et al. 1999	Video	13 in diameter		35			6 h	LED (850 nm)		Depth, Audio, Acceleration[2]	Weddell seal
Ponganis et al. 2000	Video	9 in diameter		25	1000	0	6 h	LED (850 nm)		Depth	Emperor penguin
Hooker et al. 2002	Still & Video	5.5	8.5	10.5	700	200	30 min–6 h	31 LED (820 mW at 735 nm)	640×480, 160×120	Depth	Fur seal
Sato et al. 2002b	Still	52 in diameter[1]		23[1]	3400	1600	700 images	Flush (guide no.32)	510×492	Depth	Weddell seal
Takahashi et al. 2004	Still	2.1 in diameter		13.8	73		1280 images	No light source	510×492	Depth	Chinstrap and Adélie penguins

1) Two same size housing for camera and flush.
2) Separate set.

system (Hooker et al. 2003) is designed to obtain high-resolution still pictures and low resolution motion pictures depending on the research purposes. All the systems were developed independently according to their own research purposes and there were no universal image-logger system that can cover every purpose.

Regarding the size of the loggers, the present systems are still large compared with other animal-borne loggers and might have affected the normal behavior of the seals if it is used for long duration. At first stage of development of image-loggers, as there were no alternation methods, such large system was allowed to use. All types of image loggers listed in Table 1 are equipped with flush light system, mostly arrayed LED around lens except one video and one still picture logger and the battery package for light source inevitably made systems large. Thus these systems were limited to use for only larger animals, such as seals and whales and none was used to the marine diving birds, except emperor penguins. Although major reason for large size of image data loggers was mostly due to the battery size for flush light, effort in down sizing of the system was made in the still picture logger. While down sizing of the system as a whole is required, at the same time development of low power flush light system is required. In development smaller systems the use of lower light imaging sensor will be a one of key techniques. Discussion about utility of the video system and still camera system will have no meaning, because the still picture camera will increase the data processing speed up to several frames per a second while video system will increase resolution and both will have same function. Future development of image data loggers will promise to improve data quality and will provide more information in marine animals and in environmental studies. Particularly miniaturization of image data loggers will be used to smaller animals such as fishes, squids and others.

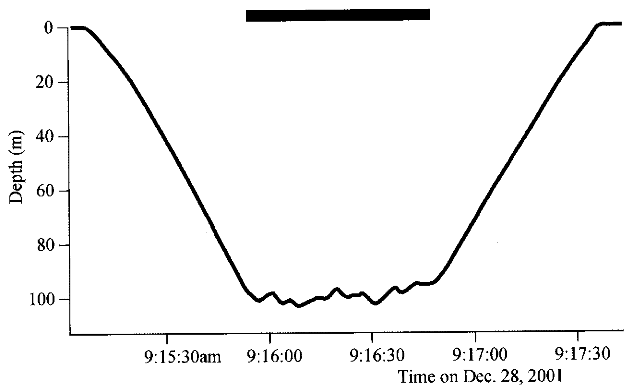

Fig. 1. Typical dive profile of an Adélie penguin (A. Takahashi & Y. Naito unpublished data). Zigzag movements are observed at the bottom time, which is indicated as a horizontal black bar.

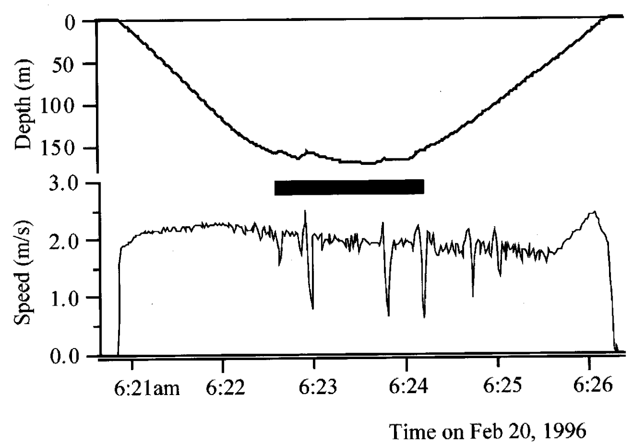

Fig. 2. Swim speed and dive profile of a king penguin (K. Sato and Y. Naito unpublished data). Horizontal black bar indicates bottom time of the dive. Penguins changed swim speed abruptly during bottom time, which indicated that penguins pursued their prey.

Present situation of image data loggers used for diving animal studies

There were potential demands for the animal-borne image logger since variety of electronic TDR has been developed in 1990's, which revealed the foraging dive behavior of many seals and penguins. Dive profiles of most diving animals are usually separated into three segments, descent phase, ascent phase and bottom phase, suggesting descent as transit to foraging depth, ascent as transit towards surface to breath. During the bottom phase, unique pattern of vertical movements composed of several up and down zigzag movements (ZZM) could be observed. It is generally believed that the bottom phase corresponds to the prey searching and capturing time during dive at depth (Le Boeuf et al. 1988 for northern elephant seal, Chappell et al. 1993 for Adelie penguin, Fig. 1). Much interest has been focused on the ZZM and effort to clarify ZZM in relation to prey-capture behavior. New smaller depth and swim speed data loggers (PDT) and 2-axis acceleration with depth and swim speed data loggers (PD2GT) developed by National Institute of Polar Research and Little Leonard Co. Ltd. from 1990's have revealed new aspect of dive profiles, particularly about bottom time. According to Sato et al. (2002a) propulsive swim speed of Adelie and king penguins was about 2 m^{-1} and they abruptly changed swim speed during bottom time, of which timing seemed to correspond with ZZM, suggesting that penguins had pursued preys (Fig. 2). Further direct observation that ZZM at the bottom time corresponds to prey capturing behavior was shown by the esophagus temperature method, which detect timing of prey capture by measuring sudden temperature drops caused by swallowing of cold preys (Ropert-Coudert et al. 2000). Thanks to new advanced techniques and enthusiastic effort to reveal the ZZM and bottom time events, penguins apparently pursued and captured preys at the ZZM events during bottom time. However in the case of seals, which often shows same dive profiles at ZZM during bottom time, neither abrupt changes of swim speed nor acceleration have been observed by these new loggers. To examine bottom time events of seals it is expected to develop image data loggers to detect the foraging events during diving and to assess the prey items.

Davis et al. (1999) first used the animal-borne video camera system to study the underwater foraging behavior and reported the scene of prey capturing by Weddell seal beneath the fast ice in Antarctica. As the reason for use of the video image logger in study on underwater foraging behavior, they described that in contrast to the research on the foraging behavior of the terrestrial mammals less is known about the foraging behavior of marine mammals, primarily because they are so difficult to observe underwater. They used two data logger systems combined together. One is the video camera system, which recorded time, depth, swim-speed, compass bearing (separately housed and connected by the cable) once per a second and ambient sound continuously. The other is the accelerometer to record flipper stroke frequency. They reported that in 57.4 h of video recording several encounters between seals and their prey were recorded, three out of which were midwater interactions with Antarctic cod, which grow to 165 cm in length and 77 kg in weight. They described capturing behavior that involved details of 3-dimensional dive paths by seals, angle to approach, flipper movements, swim speed and other locomotion. Although they described the detail of prey capturing behavior underside of fast ice that the video camera recorded, none was reported about relation between prey capturing and ZZM at bottom time of seal dive profiles. According to them depths of prey encounter by seals were very shallow compared to the normal dive depth (100–350 m, 741 m maximum, Davis et al. 1999). Sato et al. (2002b) used Digital Still picture Loggers (DSL) to study foraging behavior of Weddell seal around Japanese Antarctic station in 1999. The DSL provided several thousand images taken from the seals' perspectives every 30 s. Weddell seals sometimes stretched their necks to capture fish and other prey-like objects that were encountered near depth of 300 m (Sato et al. 2002b, Fig. 3). Using image processing software, a 'prey index' was calculated for each image according to brightness ratio of the prey-like objects (Watanabe et al. 2003). Watanabe et al. (2003) suggested different result from Davis et al. (1999) that significantly larger amount of prey were distributed at deep bottom area of dive profiles (250 m–350 m), which may correspond to ZZM of bottom time (Fig. 4a). Mitani et al. (2004) reported unique result about the foraging strategy of Weddell seals in the region of McMurdo Sound using the digital still picture loggers together with 2 data loggers, PD2GT (23 mm in diameter 90 mm in length) for recording 2-axes acceleration, depth and temperature and 3MPDT (24 mm in diameter, 189mm in length) for recording 3D geomagnetic fields intensity, rotation rate of propeller and temperature manufactured by Little Leonardo Co. Ltd., Tokyo. They reconstructed 3 dimensional dive paths and compared with prey distribution along the dive paths. Seals went to deeper foraging areas straightly and returned to the breathing holes directly but moved randomly

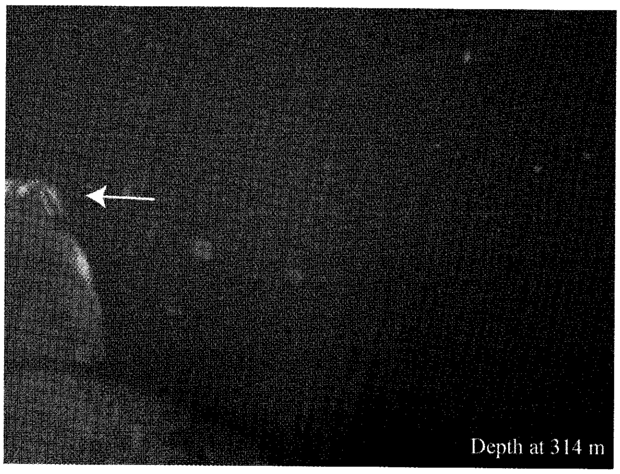

Fig. 3. Animal-borne still picture logger seized the instance of capturing prey, provably *Pleuragramma antarctica* by Weddell seal (modified from Sato et al. 2002).

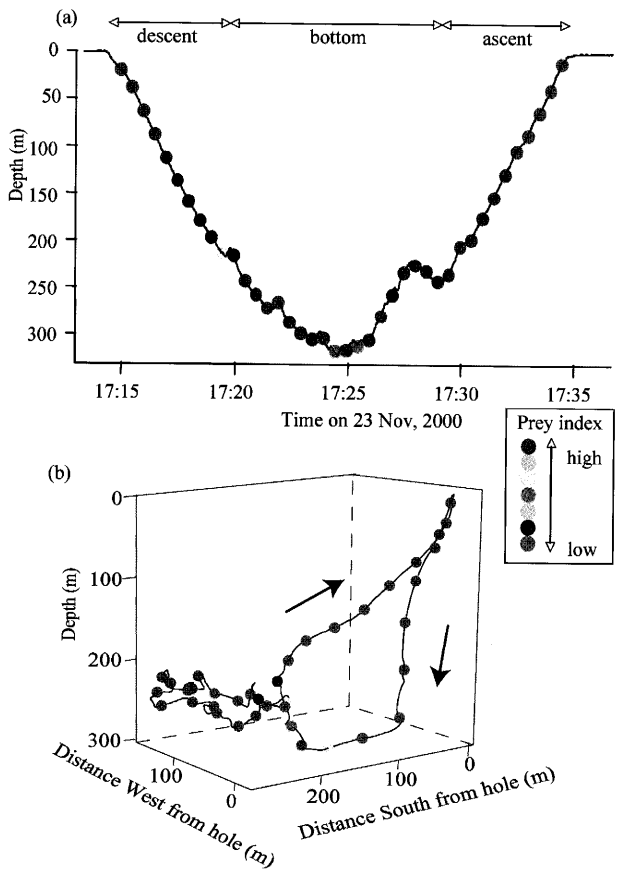

Fig. 4. a) Time-depth profile and b) 3D profile of Weddell seals in relation to prey distribution (modified from Watanabe et al. 2003 and Mitani et al. 2004). Circles on the dive profile represent the moment when an image was taken. The color of the circle represents the prey index. Arrows indicate swimming direction of the seal (b).

at bottom foraging areas where prey distribution increased. Mitani et al. (2004) indicated about foraging strategy that physiologically restricted seals maximized foraging time at deeper foraging areas by minimizing transit time between the foraging area and breathing holes (Mitani et al. 2004, Fig. 4b). As above research results demonstrated, here I conclude that image-loggers had a new role to investigate how seals explore deep ocean for their preys.

By the quite same reason as Davis et al. (1999) and Watanbe et al. (2003), the image data loggers were used for emperor penguins and Antarctic fur seals. Ponganis et al. (2000) used the image data logger named Crittercam to emperor penguins to evaluate foraging diving behavior better and to identify prey items as very little is known about the foraging strategy and feeding behavior of emperor penguins under the ice. They reported that penguins with the camera system showing significantly shorter dives than non-camera birds (21–35% shorter) foraged successfully (80% of 91 dives greater than 1 min dive duration). Video images showed penguins fed prey species as sub-ice fish *Pagothenia borchgrevinki* and successfully captured in 77% of 128 ascents.

Hooker et al. (2003) reported that studies of the diving behavior of marine mammals are limited by our inability to comprehensively assess an animal's behavior beneath the water, and the simultaneous acquisition of images of the prey encountered, together with records of diving behavior will allow researchers to more fully investigate the nature of subsurface behavior. They used their custom-made video-still convertible image loggers to assess the diving behavior of Antarctic fur seals. According to their results, an average 8.5% of still pictures out of 8,288 images of 5 deployments showed krill (*Euphausia superba*) while half of the images were empty. They also used video mode and obtained 18 movies (7,598 frames). Two of them obtained recognizable images of krill and other 16 movies often showed krill swarms and other seals. Although their experiment was very preliminary and their new image data logger has not brought much of new insights into foraging behavior of Antarctic fur seals, they concluded that in terms of seal behavior, such camera footage can provide unique insights into the functionality of dive types and the detail of fine-scale foraging behavior. They also referred that not only for the seals but the system could be applied to a wide variety of marine mammal species, and is likely to dramatically improve our current ability to interpret subsurface behavior.

The use of image loggers is still limited in study of subsurface foraging behavior, however above results promise at least that image data loggers are effective in identifying the prey species (or prey type) and timing of prey capturing in relation to 2D or 3D dive profiles. To improve the image logger systems for further studies of foraging behavior it is strongly desired to give strong light emission in darkness of dive depths simultaneously. As seals and penguins are sensitive to normal light and thus it is required to use infrared light that causes to limit the camera sight to close area 1–2 m due to absorption rate of infrared in ocean. Strong light power needs larger battery pack, which on other hands makes difficult to miniaturize image logger systems. This is reason that image logger systems are not used to smaller animals. Development of further miniaturized image data loggers equipped with low power light emission system is strongly expected.

Image data loggers were used for other purposes. One is to identify interaction between individuals and the other is for visual new findings, which were not known to us. To examine the mother and pup interaction under water, Sato et al. (2003) deployed accelerometers both a mother and pup of Weddell seals simultaneously and also deployed the digital still picture logger. They found that swimming activities of both a mother and pup were well synchronized when they were near surface depths. However when a mother dived deeper than 50 m such synchronized swimming was not observed. They also examined this unique interaction visually by using still picture loggers and suggested that a mother and pup swam keeping close distance to contact each other. Takahashi et al. (2004) also studied underwater social behavior of penguins. They used a smaller digital still picture logger (Table 1) on Chinstrap and Adélie penguins at Signy Island (Fig. 5), Antarctica without attaching any light sources. They obtained 7,387 underwater pictures from 2,140 dives. From the analyses on these pictures they showed that penguins were closely associated with each other in less than 2 m in 44.4% of 266 pictures and penguins swam in the same direction in close visual contact with other birds at depth. They also suggested that the primary reason for swimming in groups might be related to factors other than foraging: e.g. predator avoidance.

Another use of image data logger is so much unique that phenomena found by the image data logger has not been expected before hand. Hooker et al. (2005) used video, acoustic and conductivity loggers and observed bubble emission that Antarctic fur seals exhaled, which were consistently observed during 50–85% of ascent from more than 8000 dives from 50 seals. They interpreted the bubbling by the seals as physiological function underlying in diving animals with air in lungs. They suggested that fur seals descent with full lung air stores, which implies face to the physiological consequences of pressure at depth, and also indicated that the regular and predictable ascent exhalations could function to reduce the potential for a precipitous drop in blood oxygen that would result in shallow-water blackout. Giving the digital still camera system on the back of Weddell seals, Watanabe et al. (2006) also found a unique phenomena under side of Antarctic shelf ice. They reported that seals often visited under side of shelf ice at about 150 m deep and took photos of isopods

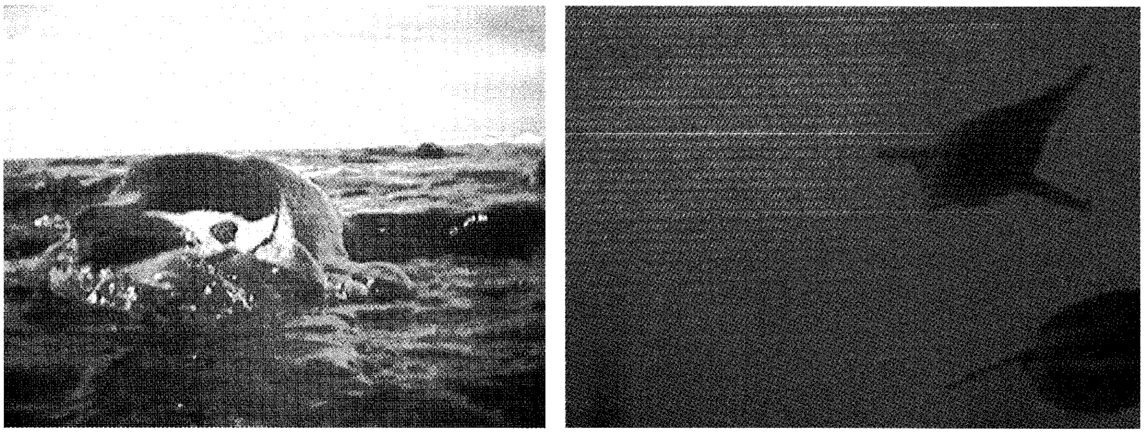

Fig. 5. Images obtained from digital still picture loggers attached to the back of penguins (A. Takahashi and Y. Naito unpublished data).

colonies hugging down beneath the under surface of crystal ice suggesting a new rich fauna including preys for seals under surface area of the Antarctic shelf ice. This unique colonies has not been reported as it is technically difficult to operate ROV keeping close distance to the under surface of shelf ice.

Future study

Major technical subjects of image data logger facing at present are establishing data compression system within loggers and low power flush system. Higher resolution camera requires the larger memory size, which almost automatically require large battery size. To achieve mega pixel resolution while keeping smaller camera size it is evitable to employ data compression system within CCD or CMOS modules. Current available techniques may allow us to realize small high-resolution camera, which may load almost 10 K mega resolution photos in the logger. This may allow us to take high-resolution photos at a high-frequency interval; several flames per a second for example. Second goal for the picture loggers to solve is more difficult. There are no available techniques on low powered flashlight. Infrared LED as light source might be a proper technique for low powered flashlight, but it still needs large battery power for flash and will limit photo numbers. Therefore some devices are expected to control photo timing; command by depth, body angle and body motion for examples. It is also expected to use camera system combined with acoustic censors for detection of target objectives.

Image data loggers if remarkable down sizing was achieved, the techniques will promise dramatic increase of new information and enlarge the utility of image data loggers, because it means that we obtain animals' view in the ocean where most of things have long been invisible to us. Thus not only for study of animal foraging behavior it will provide much useful information to us, such as environmental assessment, habitat use, distribution of preys and organisms, stock managements and so on. Image data logger techniques will be utilized to other optic observation, which will be strong tools for micro- analyses of chemical components of the ocean environment and also for physiology of marine animals, much of which are not studied yet.

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