Review:

Development Timeline of the Autonomous Underwater Vehicle in Japan

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In 2020, the autonomous underwater vehicle (AUV) has already become a vital part of deep-sea research. There is a long history of R&D of AUVs that dive into the deep sea, where radio waves cannot reach, thus making remote control difficult so that no help can be provided, which implies that careful and adequate preparation is necessary. Their successful development has been based on the accumulation of experience and achievements contributing to the remarkable results that no other system can produce. The aggressive R&D of Japanese AUVs started approximately 40 years ago. This paper looks back at this history and introduces various Japanese AUVs.

Keywords: AUV, submersible, history, R&D, Japan

1. Submersibles

Submersibles that endure high water pressure and submerge in the deep sea, where radio waves do not reach, can be categorized in the following three groups.

(1) Manned submersibles or human occupied vehicles (HOVs), which include submarines.

(2) Remotely operated vehicles (ROVs).

(3) Autonomous underwater vehicles (AUVs) or unmanned underwater vehicles (UUVs).

Although Japan does not have nuclear submarines, it builds and operates normal (non-nuclear) submarines and is on a different political route from that of the submarine powers, the United States and Russia. With respect to submersibles for scientific research, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) built the manned submersible Shinkai 6500 [a] in 1989, which can dive to depths of 6,500 m and conducted more than 1,500 dives until 2017. The Japanese technology for construction and operation of HOVs for scientific use is considered to be at the world's top level.

Twenty-five years after the development of ROVs in the US, which began in the early 1960s with the CURV [1], JAMSTEC developed the large heavy-duty ROV Dolphin 3K. Then, JAMSTEC constructed the ROV KAIKO [b], which could dive to the full depth of the ocean and succeeded in reaching a depth of approximately 11,000 m in the Mariana Trench in 1995. Despite the success of KAIKO, JAMSTEC purchased the ROV Hyper Dolphin from Canada as a successor of Dolphin 3K and operated it for a long time. After KAIKO, Japan has not developed a work class heavy duty ROV for civilian use.

Small size ROVs (low cost ROVs), which do not require cranes for the launching and recovery operations, have been developed across the world since the late 1980s. For example, Mitsui Engineering and Shipbuilding Co., Ltd. (MES) developed the commercial ROV RTV-100 for shallow water use.

Recently, small ROVs became known as "underwater drones" and many products are now available worldwide. However, unfortunately, no Japanese company is making successful products in this market.

The Applied Physics Laboratory of the University of Washington started R&D on AUVs, beginning with the SPURV in the 1950s [c]. Seven SPURVs were built by 1979 based on R&D expenses from the US Navy. CNEXO (now IFREMER) of France developed the 6,000 m class AUV Epaulard in the early 1980s and succeeded in research diving to her maximum depth. Undoubtedly, they have made important contributions to the history of AUV R&D.

Forty years ago, the computer technology was not as developed as it is today, and thus, it is difficult to say that these vehicles were autonomous. It may be appropriate to call them as unmanned untethered submersibles or automatic underwater vehicles.

In Japan, an unmanned submersible called the OSR-V ($W = 2{,}900$ kg) was constructed in 1974 with funds from the Japan Society for the Promotion of Machinery. Dive tests were conducted, but she did not realize any specific work. The project was terminated after the tests. The major reason why this project was not successful is that OSR-V was designed only as a technological curiosity without defining a clear purpose for diving.

In 1979, the first symposium on the unmanned untethered submersible technology (UUST) was held at the University of New Hampshire, and AUV researchers from all over the world gathered and discussed their visions

Fig. 1. PTEROA150 ($L = 1.5$ m, $W = 220$ kg) before diving in Suruga Bay.

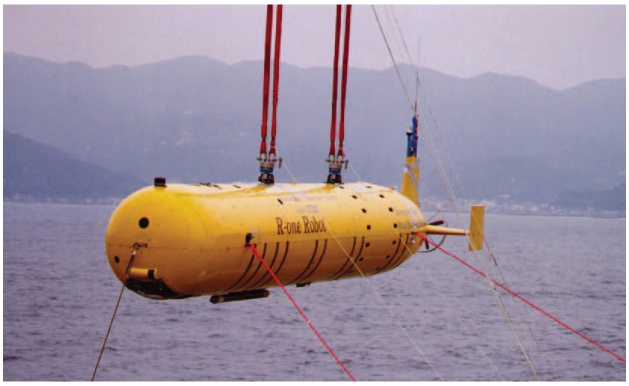

Fig. 2. R-one Robot ($L = 8.2$ m, $W = 4{,}300$ kg) hanging from the R/V Kaiyo before diving to the Teishi underwater volcano.

Fig. 3. r2D4 ($L = 4.2$ m, $W = 1{,}600$ kg) submerging to the Mariana Trough.

on AUVs. Eight years after the first UUST symposium, in 1987, R&D of a full-scale AUV was started in Japan as the PTEROA Project [2] of the Institute of Industrial Science (IIS) of The University of Tokyo.

2. Development of the Japanese AUV in the Period 1980–2000

2.1. The Cruising AUV

The concept and general features of the cruising AUV, which goes forward at approximately 3 knots or more and obtains information of the undersea environment and seafloor, are easily understood by non-specialists because it looks like a high performance torpedo or unmanned submarine. It is well recognized that the mainstream of the early AUV R&D in the world focused on the development of cruising AUVs.

In 1986, the IIS announced the PTEROA Project, embarked on AUV development, and then succeeded in the sea trial of the AUV PTEROA150 (**Fig. 1**) in 1990 [3]. The major objective of the PTEROA150 Project was the development of an AUV able to observe mid-ocean ridge systems. After this four-year project, the IIS continued the development of cruising AUVs such as the R-one Robot [4] (**Fig. 2**) and r2D4 [5] (**Fig. 3**, conf. to Section 3.1). Thus, the IIS became the center of the Japanese AUV R&D.

In 2004, the AUV r2D4 surveyed a submarine volcano, North West Rota 1 [6], which is located off the coast of Rota Island and belongs to the Mariana Islands, and reached the initial goal of the IIS's AUV R&D.

The AUV R-one Robot, which was developed as a joint research with MES, is a largescale model equipped with a closed diesel engine as its energy source for long endurance. In 1998, she succeeded in continuous autonomous diving for 12 h along the Kii Channel. After this event, the IIS and MES teams repeatedly performed long-term tests off the coast of Monbetsu, Hokkaido, and improved the capability and reliability of the software. In 2000, this AUV dived for a survey of a submarine volcano, the Teishi underwater volcano off Ito City [7], and acquired high-resolution side scan sonar images that showed the detailed configuration of the knoll. It should be noted that this dive event was carried out in the year 2000, when the world's expectations for AUVs significantly increased. An important aspect of the IIS's AUV R&D is that its software is based on the reliable software built for development of the R-one Robot. In other words, when a new AUV hardware is completed, it is possible to carry out autonomous test dives immediately, in the actual sea, to verify its reliability. Then, the AUV can be used for scientific research activities. Consequently, the new IIS's AUV could quickly demonstrate its significant advantage.

KDD (now KDDI) developed the Aqua-Explorer for submarine cable surveys, and it carried out diving tests in 1992. Then, together with the Kokusai Cable Ship

Fig. 4. Aqua-Explorer 2000 ($L = 3.0$ m, $W = 300$ kg) on the deck of the R/V Kairei.

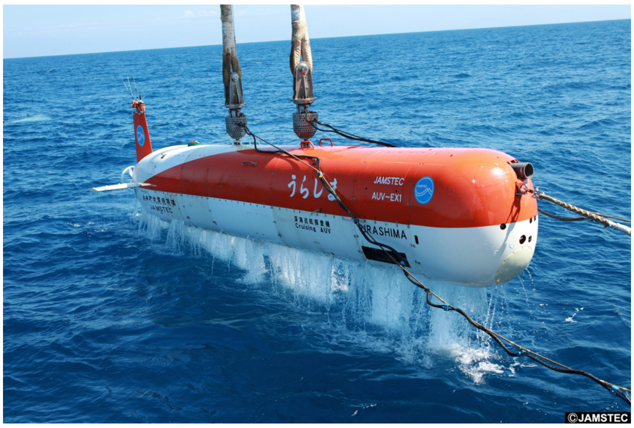

Fig. 5. Urashima ($L = 10$ m, $W = 7{,}500$ kg) provides a payload of 63 kg.

Co., Ltd. (KCS), they constructed two pairs of vehicles, the Aqua-Explorer 2 (AE2) and the Aqua-Explorer 2000 (AE2000, **Fig. 4**) and used them in the field as practical vehicles.

Besides their main task, the AUV AE2000 is involved in a whale tracking project in collaboration with the IIS taking advantage of her medium size. In 2000, off the Zamami Islands in Okinawa Prefecture, she succeeded in approaching humpback whales autonomously, as close as a few meters [8].

However, unfortunately, it became clear that the use of AE2000 and AE2 for submarine cable surveys did not necessarily improve the efficiency. Thus, they were no longer used. In 2011, two AE2000 were transferred to the IIS and became known as the AE2000a and AE2000f, which were modified for observation of hydrothermal vent and cobalt-rich manganese crust fields. At present, they frequently dive fields at depths from 1000 to 2000 m and are acquiring useful data for further subsea mine development.

In 1998, JAMSTEC began development of a large-size cruising AUV, Urashima [d] (**Fig. 5**), equipped with a fuel cell as an air-independent energy source. This vehicle succeeded in diving along a cruise distance of 317 km in 2005. However, the equipment for handling hydrogen (fuel) and oxygen (oxidizing agent) is very heavy, and JAMSTEC recognized that the fuel cell system is not always suitable for AUV applications. JAMSTEC dismantled the fuel cell power system and replaced it with lithium-ion batteries which are used for the HOV Shinkai 6500. Subsequently, the AUV Urashima is being used for seafloor and water column surveys. By taking advantage of her large size, it is possible to mount observation equipment with a heavy weight and large volume.

In earlier times of Urashima operation, the acoustic communication link was frequently used to send the status of the AUV to the support vessel, leaving many decisions to the operator on board. Therefore, a high degree of autonomy was not necessary for the vehicle. After repeated diving and improvement, her autonomy has gradually improved to a high level.

Kawasaki Heavy Industries, Ltd. (KHI), utilizing its submarine technology, developed the AUV Marine Bird, which can be docked in an underwater station, and succeeded in a docking demonstration in shallow water in 2004. However, after the event, KHI suspended subsequent development of the AUV during a period. In 2013, KHI launched a new project and is developing an AUV that can survey underwater pipelines. In 2017, sea trials were conducted, such as automatic docking and contactless underwater charging in the waters of Scotland, UK.

2.2. The Hovering AUV

The cruising AUV dives with high speed, and thus, considering her maneuverability and to avoid an unexpected collision, she cannot approach at close range (some meters) a seafloor with complicated topography. However, to capture high resolution video images of the seafloor, an AUV is expected to be able to approach the seafloor as close as possible. She should move freely back and forth, left and right, and up and down, even at the expense of high-speed movements, and should not be concerned with the complex irregularities of the seafloor. The hovering AUV is designed to comply with these requirements.

The history of the hovering AUV began in 1992, when the IIS developed the versatile test bed AUV Twin-Burger [9] (TB, **Fig. 6**). TB was designed to facilitate the development of software and to accomplish the high autonomy. TB was equipped with the multi-task CPU Transputer, so that it was possible to process the data from many sensors in real time. Today, multiple processing is commonly used; however, thirty years ago, this was a very difficult task for a small size computer. By being equipped with Transputers, it was possible for the TB to analyze video images in real time. If the data processing ability of the AUV is low, it can be operated as an automatic machine, not as an autonomous one, as mentioned in Section 1. Since 1990, the power of the CPU has dramatically and continuously improved. It has become pos-

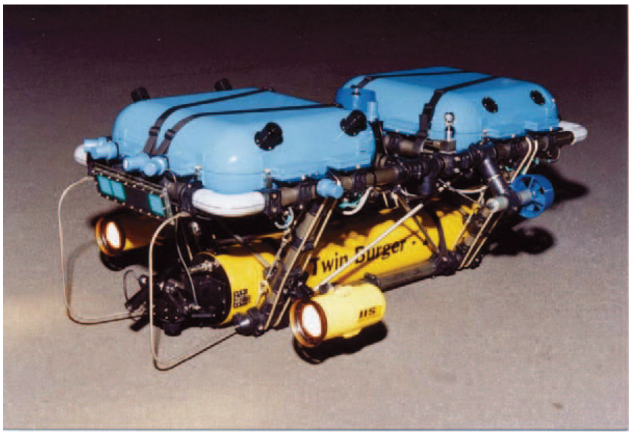

Fig. 6. Twin-Burger ($L = 1.54$ m, $W = 120$ kg) is equipped with 14 transputers.

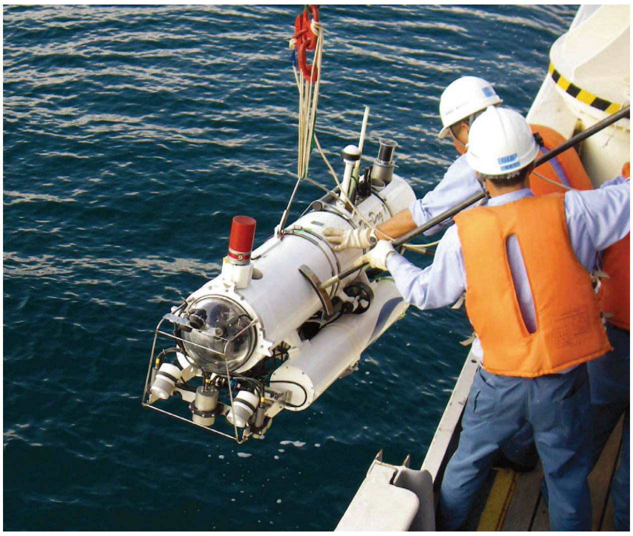

Fig. 7. Tri-Dog 1 ($L = 1.85$ m, $W = 170$ kg) is still active in shallow waters.

sible for AUVs to acquire a high level of autonomy by processing a large amount of sensor data and determining the next actions based on them. The AUV moves in water, and therefore, its electronics should be installed in a pressure-resistant container. It means that lighter and smaller devices are preferable. It should be emphasized that the development of compact and high-performance electronic devices and sensors is essential for the development of a practical AUV. The Transputer was one of the best choices of CPU for the AUV at the time. Although the TB was designed as a test bed, and could dive only in a pool depth, she opened a new world to the AUV.

After the TB, the IIS developed the 100 m-class hovering AUV Tri-Dog 1 (TD1, **Fig. 7**), which demonstrated a mission in fully autonomous mode in 2000 [10]. The TD1 went around three cylinders, orbiting them one by one while keeping a distance of 1 m and facing them in a direction perpendicular to the surface of the cylinder. This behavior showed the significant advantage of the hovering type of AUV. She has no umbilical cable, and hence, she can go around pipes and pillars without worrying about entanglement, which is a critical risk for ROVs. After this, TD1 succeeded in observing a tube worm area (100 m in depth) in Kagoshima Bay and acquired many photographs of the tube worm colony, which were combined in one wide mosaic covering the whole area [11].

Fig. 8. ALBAC ($L = 1.4$ m, $W = 45$ kg), a glider built in 1993.

2.3. The Glider AUV

The IIS developed a glider AUV, ALBAC [12] (**Fig. 8**), and succeeded in realizing a round trip to a depth of 300 m and observing a water column in Suruga Bay in 1995 [13]. The ALBAC was a precursor to the gliders that have been developed worldwide. However, the function to change the buoyancy was not sufficiently developed, and thus, ALBAC could accomplish only one round trip in a dive. Unfortunately, the IIS did not develop successors of the ALBAC.

2.4. Navigation and Operation

Two critical technologies for the successful R&D of an AUV are 1) the self-position recognition technology and 2) the operator-based technology to find out where the AUV is. The former is the basis of navigation. In the sea, where GPS cannot be used, an alternative system for recognition of the AUV position is essential. How accurately the AUV should recognize her own position depends on her mission; in the case of the hovering AUV for hydro-thermal vents survey, it is of one meter or less, but for the glider AUV, the required accuracy can be of some kilometers. The latter is not necessary if the operator has the confidence that his/her AUV will work in a perfectly autonomous mode, but usually this cannot be expected. To be on the comfortable side, the operator wants to know where the AUV is.

A cruising AUV requires a highly accurate inertial navigation system (INS) for long-distance and long-term diving. Usually, a hybrid system associated with a doppler velocity log (DVL) is configured to improve the accuracy. The AUV R-one Robot was implemented with a ring laser gyroscope (RLG) developed for the STOL airplane

ASKA by the National Aerospace Laboratory of Japan. It was the most accurate gyroscope at the time, but it is quite large. In the middle of the 1990s, the accuracy of the fiber optical gyroscope (FOG), which can be downsized, was improved and can compete with that of the RLG. Thus, a small size INS was available for AUVs in the 2000s. The AUVs r2D4 and Tuna-Sand of the IIS were equipped with iXblue's FOG Phins.

The major system for detecting the location of an underwater target is the acoustic positioning system, which is classified in three categories: long baseline system (LBL), short baseline system (SBL), and super short baseline system (SSBL). By placing a transponder in the vehicle, the operator on board can find the location of the AUV by the SSBL. In the middle of the 1990s, the SSBL had problems owing to its poor accuracy, frequent errors, and missing data. The operator was often terribly anxious on the support vessel, as he/she could not know for a long period of time where the AUV was or was given false reports of the location. However, in the 2000s, the iXblue's SSBL GAPS appeared and showed high reliability, including the cancellation of the disturbance caused by motion of the support vessel, which became possible by introducing Phins as a gyroscope. The frustration of the operator considerably decreased.

3. Development of the AUV in the Period 2000–2010

3.1. Observation and Use of Cruising AUV as a Practical Vehicle for Deep Ocean Surveys

In 2003, the IIS completed a 4000 m-class medium-sized AUV, r2D4 (**Fig. 3**), in two years and immediately operated it off Sado Island and then off Ishigakijima Island. From launching to recovery, she cruised in full autonomous mode except for receiving several position-update commands from the support vessel. She was equipped with an interferometry sonar as her main observation sensor, and her main task was to make a detailed topographic map of the seafloor. Until 2010, she dived into the Northwest Rota 1 submarine volcano, Myojin and Bayonnaise knolls in the Izu-Ogasawara archipelago, Yonaguni No. 4 knoll in the Okinawa Trough, the rift valley in the Indian Central Ridge, and so on. She realized detailed topographic maps of the hydrothermal vent field and sometimes found hydrothermal plumes. However, in 2010, she was lost during her second voyage to the Indian Ocean. The IIS did not construct a successor, but received two Aqua-Explorer 2000 from the KCS and improved them for further observation of the seafloor.

After the fuel cell was replaced with lithium-ion batteries, JAMSTEC's Urashima dived to the hydrothermal area off Hatsushima Island in 2006 and the Iheya site in the Okinawa Trough in 2007. As a result of these achievements, the advantages and availability of the AUVs are now well recognized by scientists. Then, in 2009, JAMSTEC made an open call for the use of

Fig. 9. Tantan ($L = 2.16$ m, $W = 180$ kg) surveyed Lake Biwa, the largest lake in Japan.

Urashima. The large body of Urashima can be equipped with large and heavy payloads. Therefore, she can carry the observation equipment commonly used in ordinary subsea observation. Moreover, she can also take care of multiple measuring instruments at the same time.

3.2. Aggressive Use of the Hovering AUV: From Tri-Dog 1 to Tuna-Sand

TD1 was used to observe the Kamaishi Bay breakwater (in 2004) and to survey the distribution of a tube worm colony in Kagoshima Bay (from 2005), as mentioned in Section 2.2. She demonstrated that the hovering AUV is a useful platform to realize a mosaic of photographs of the seafloor. In the case of the Kagoshima dives, scientists had not known the overall feature of the colony because of the high turbidity. However, she worked even when surrounded by bubbles of methane seeping from the seafloor and approached the colony close enough to take photographs.

The maximum diving depth of the TD1 is 110 m, which was decided based on the maximum depth of Lake Biwa, which is the largest lake in Japan. Lake Biwa supplies fresh water to the population of the Kansai area, and thus, water quality management is an important task for the local government. The IIS, in collaboration with MES, developed the AUV Tantan (**Fig. 9**) for the Lake Biwa survey in 2000, which was operated by the Lake Biwa Research Center [14]. After evaluating the performance of Tantan, three Tantan class vehicles were built for the dam lake survey.

The IIS developed the 2000 m-class hovering AUV Tuna-Sand (**Fig. 10**) in 2007 as a more advanced vehicle than the AUV TD1. In 2010, she surveyed the methane hydrate zone in the Sea of Japan at a depth of 1000 m, and provided seafloor mosaics showing a huge number of red snow crabs (**Fig. 11**). As the red snow crab is an important marine resource, this survey caused a shift of paradigm in the method of surveying benthic aquatic resources. Subsequently, in collaboration with the Fisheries

Fig. 10. Tuna-Sand ($L = 1.1$ m, $W = 240$ kg) is the first Tuna-Sand class vehicle constructed in 2007.

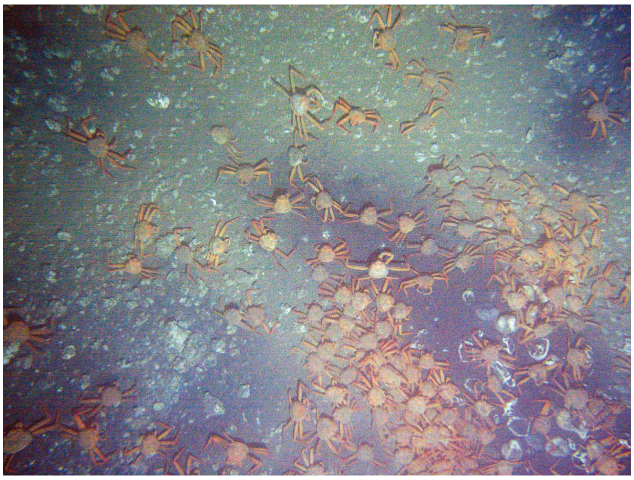

Fig. 11. Photograph of a red snow crab colony on a methane hydrate area acquired by the autonomous underwater vehicle (AUV) Tuna-Sand at a depth of 1,000 m.

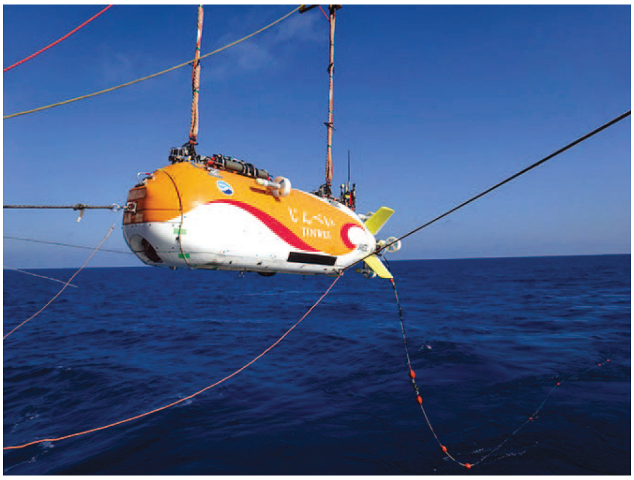

Fig. 12. Jinbei ($L = 4$ m, $W = 1{,}700$ kg) is a newly developed cruising AUV.

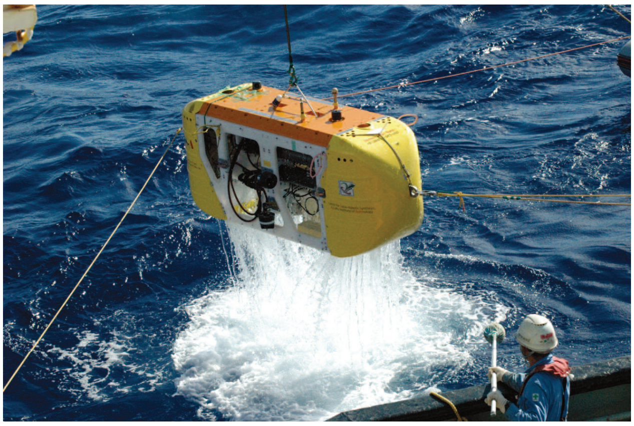

Fig. 13. BOSS-A ($L = 3$ m, $W = 600$ kg) was designed for surveying a cobalt-rich manganese crust.

Research Agency, the IIS surveyed the rock fish and snow crab in the Sea of Okhotsk using the Tuna-Sand and other AUVs.

4. Development of the AUV Since 2010

4.1. Development of Practical AUVs

The IIS introduced two Aqua-Explorer 2000 AUVs. It installed an interferometry sonar in one and a high-altitude video image measurement system developed by the IIS in the other. Thus, they were reconfigured to AE2000a and AE2000f, suitable for hydrothermal vent area surveys. In 2017, the IIS team of Prof. Blair Thornton participated in the voyage organized by the Schumit Ocean Institute [e] with two AE2000, Tuna-Sand and Tuna-Sand 2 AUVs (see Section 4.3). A detailed three-dimensional image measurement of the sea floor, with an area of 12 ha, was performed. In 2012, the AUV AE2000a also succeeded in submerging under the sea ice off Monbetsu in the Okhotsk Sea.

JAMSTEC built three UAVs, Jinbei [15] (**Fig. 12**), Yumeiruka, and Otohime, in 2012. The first two are cruising AUVs that can be deployed together, and the last one is a hovering AUV. After debugging the software, Jinbei was offered for public use from 2015.

IHI Corporation has developed a system that consists of a cruising AUV and an unmanned surface vehicle (USV). In 2014, the USV succeeded in following the AUV in Kagoshima bay. Based on this achievement, IHI put emphasis on R&D of AUVs. As a result, IHI sold two cruising AUVs to the Japan Coast Guard, which equipped the survey vessel Heiyo, in service since 2020, with these AUVs.

The IIS invented an acoustic device for measuring on-site the thickness of a cobalt-rich manganese crust and developed a specialized hovering AUV, BOSS-A (**Fig. 13**), in 2015. BOSS-A was deployed to promising crust

Fig. 14. Smith Caldera dive. Three AUVs (AE2000a, AE2000f, and Tuna-Sand) successfully dived together.

Fig. 15. Three Tuna-Sand class AUVs, Tuna-Sand, Hobalin ($L = 1.2$ m, $W = 270$ kg), and Tuna-Sand 2 ($L = 1.4$ m, $W = 380$ kg), surveyed benthos in the Sea of Okhotsk.

seamounts such as Takuyo No. 5. The IIS is also conducting a large-scale survey with the Japan Oil, Gas, and Metals National Corporation (JOGMEC) using BOSS-A, AE2000f, and an ROV to obtain data useful for estimating endowments [16].

4.2. Multiple-AUV Operation

The simultaneous operation of multiple AUVs allows effective use of the valuable and expensive ship time. Owing to typhoons and the seasonal high winds around Japan Islands, the sea conditions are often very harsh. Therefore, operation of multiple AUVs is highly valued by the organizations conducting marine resource surveys. The IIS co-deployed three AUVs simultaneously, i.e., AE2000a, AE2000f, and Tuna-Sand, in 2012 at the Smith submarine caldera in the Izu-Ogasawara archipelago and surveyed the caldera bottom (**Fig. 14**). This deployment was the first multiple-AUV operation in Japan. Since then, the IIS has been observing benthic fish continuously with two or three hovering AUVs (**Fig. 15**) and is surveying the hydrothermal vent and cobalt-rich manganese crust areas with a cruising AUV, a hovering AUV, and an ROV.

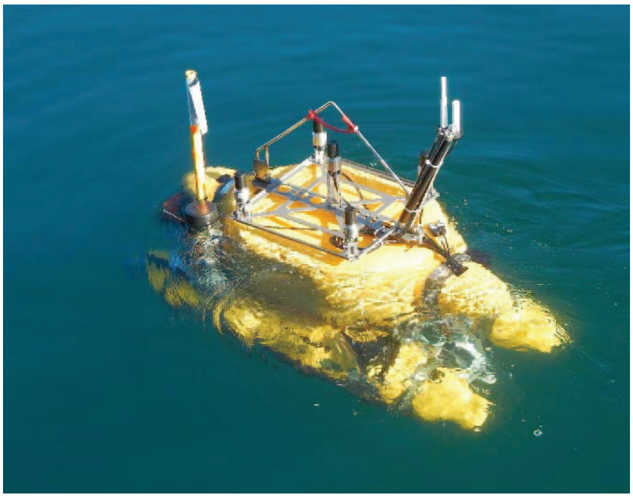

Fig. 16. Hovering AUV Tri-TON 2 ($L = 1.4$ m, $W = 300$ kg).

In the early 2010s, Prof. Maki of the IIS developed two hovering AUVs that improved the TD1, named as Tri-TON and Tri-TON 2 [17] (**Fig. 16**), and is conducting R&D on the coordinated behavior of these tree vehicles.

In the national project Cross-ministerial Strategic Innovation Promotion Program [f] (SIP), which started in 2014, simultaneous operation of multiple AUVs was one of the major targets of technological achievement. Four new cruising AUVs and one hovering AUV, named Hobalin [18] (**Fig. 15**), were built. A semi-submersible USV was added to support them. Thus, a multi-AUV operation infrastructure (the AUV team) was organized by 2017 and operated for exploration of subsea minerals.

The Team Kuroshio, which was organized by JAMSTEC, the IIS, the Kyushu Institute of Technology, and others, constructed two 4,000 m-class AUVs (AUV-NEXT and AE-Z), and a USV (ORCA) and competed for the Shell Ocean Discovery XPRIZE that started in 2015. Unfortunately, the team missed the first place, but won the second place [g]. The Team Kuroshio competed with its own AUV, whereas the team that obtained the first place used a commercially available AUV. In XPRIZE Round 1, the IIS's AE2000a and AE2000f were the main players. In Round 2, unfortunately, the multiple AUV operation was not successful, but AUV-Next carried out a dive survey for 23 h, and cruised 135 nautical miles.

4.3. Improving the Hovering AUV to Something More Sophisticated

By modifying the AUV Tuna-Sand, the IIS has developed the Tuna-Sand 2 [19] (TS2, **Fig. 15**), which can sample objects on the seafloor by using a hand attached to the bottom of the vehicle. In general, it is very difficult to develop a fully autonomous pick-up task for a specific object on the seafloor because the AUV should independently decide what object will be obtained. She may pick-up something that does not make sense. There are two solutions for this problem. First, after acquiring a mosaic photograph of the entire survey area, the operator selects the object that the AUV should fetch and provides the vehicle with its coordinates and image. Then, the AUV dives to the exact point selected, searches the target by image recognition, and picks it up. Second, the AUV uses AI to select what could be of interest to the operator using video images in real-time, and when she finds the appropriate object, she sends the image to the operator on the support vessel through the acoustic link. If the operator accepts the proposal of the AUV, he/she sends a command to the AUV to retrieve the object. TS2 has adopted the latter method and is carrying out repeated sea tests to enhance her capabilities.

As mentioned in Section 4.2, the hovering AUV Hobalin, part of a multiple AUV team, was manufactured in 2015 by the SIP based on TS and is under service. In 2019, IDEA Consultants, Inc. [h] introduced the Tuna-Sand-class AUV named Youzan and is using it for environmental surveys. In this way, almost 30 years after the development of the TB, the hovering AUV has been developed successfully in Japan. As it can have various advanced functions taking advantage of the hovering function, further R&D of the sophisticated hovering AUV is expected.

5. Closing Remarks

As aforementioned, R&D of the AUV has had a long history (**Fig. 17**). It is expected that the AUV, which is being increasingly diversified and will obtain a higher degree of autonomy as R&D progresses, will reveal the unknown deep sea.

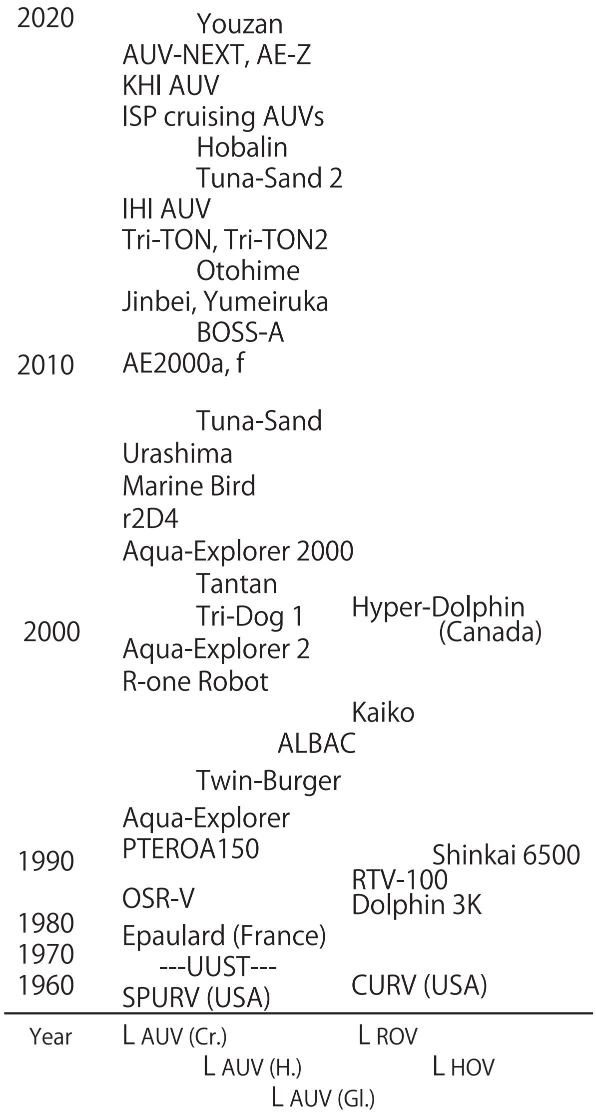

Fig. 17. Timeline of the AUV development in Japan and some important vehicles (including remotely operated vehicles and a human occupied vehicle).

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