Introduction Remote-operated Underwater Vehicle for Inspection of Underwater Structure

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Abstract. Since many dams and bridges constructed in last century are facing serious safety issue resulting from leakage, erosion, and crack, it is increasingly urgent to develop more inspection and repair technologies that can be used for the maintenance operation. This essay introduces the practical application of underwater structure inspection conducted by remote-operated underwater vehicle. The applications include Mullaperiyar dam, Amagase dam, Aqua bridege, and Shorenji dam. And the application skills are summarized in inspecting small leaks of dam in clean water, inspection in turbid water, conducting survey in easy-entangled environment, and operation in flowing water. The advantages of remote-operated underwater vehicle compared with traditional divers are accumulated, and the remaining problem of existing remote-operated underwater vehicle are also summarized. This paper further provides experience of its operation in low-visibility water and stabilizing its position in turbulence, as well as solving the difficulties of getting the cables entangled in easy-winding water. Besides, an outlook is provided for remote-operated underwater vehicle's development tendency in the field of underwater detection and reinforcement, with the purpose of addressing more critical problem in maintaining underwater structure in the future.

Keywords: Remote-operated underwater vehicle, dam, underwater inspection, easy-entangled environment

1. Introduction

Dam is a water conservancy infrastructure that plays an important role in national flood control, water resource allocation, and security of water supplies for production and daily life. As most of the existing dams in the developed and developing countries were constructed in the last century, they might have experienced different levels of failure after a long period of use, which includes structural damage and missing, wear, metal parts corrosion, and cracks. In this case, it is necessary to check the structural condition and safety of operation by conducting maintenance and recondition regularly.

Internationally, underwater inspection techniques can be divided into two major parts, which is manual visual inspection and intelligent monitoring inspection. Manual visual inspection is a traditional method that requiring divers to do artificial visual detection by taking equipment like underwater camera. And this method was largely restricted by the limitation of work condition, short diving depth, and limited operation time [1]. As for the intelligent monitoring method, underwater robots based on defect detection of underwater structure of dam has been recently adopted widely since they were mainly used in military and deep-sea exploration previously. Among these robots, a cable remote-operated underwater vehicle (ROV) is the most adopted type when doing the dam maintenance work, which has excellent engineering application effect, strong working ability and stability, and will continuously being the mainstream techniques of underwater infrastructure inspection.

The early ROV development were generally carried out by America and British armies around 60s of last century, a typical example was the Cutlet developed by British Royle Navy in 1966 that managed to retrieve a atomic bomb lost in the Mediterranean [2]. After grasped the technology background established by military, ROV gradually marched on civil and production industries during 70s to 80s last century, especially in the offshore oil and gas production. Therefore, the technique level of modern ROV adopted in developing sub-sea oil and gas are much higher than most of other fields. For example, a breakthrough in subsea residency capability was just achieved by Oceaneering's Freedom ROV, which could continuously operating under the depth up to 6 kilometers for six months [3]. Currently, the greatest challenge for ROV is its application in the field of deep-sea mining, which may face the threat come from extremely high pressure and temperature, as well as the unpredictable damage on the deep-sea environment. However, the attraction of marine resources still made the mining companies to play the high-stakes gamble, as the Toronto-based mining company Nautilus Minerals just adopted the world's first deep-sea mining ROVs [4].

In water conservancy project, ROV has also been applicated widely in 21st century. HYDRO-QUEBEC is a major hydroelectricity industry in America, which is also the first company to adopt ROV for the maintenance of all its 59 hydroelectricity power stations and 570 dams, then produced a conservative net worth 8 million dollars [5]. Since then, the demand of ROV grow with an exponential extent, and INESC Porto also exploited the market of autonomous underwater vehicle (AUV) to fulfill the requirement from more complex scenarios [6]. While these applications all states that ROV has high efficiency and adoptability to inspect and maintain underwater structure, it is still restricted by the cable and external power supply, which may even become a fragile part when operating in a non-ideal environment.

This essay will first introduce the main composition of ROV and its general operation procedure, then summarize some practical skills for the inspection and maintenance of underwater structures in non-ideal environment. These include inspecting small leaks in clean water, underwater inspection in turbid water, conducting survey in easy-entangled environment, and operating in flowing water. The experience like stabilizing ROV's body in flowing water and seeking small leaks more effectively will also be provided during the practical applications.

2. ROV's Composition and Operation Procedure

2.1. Composition of an ROV System

ROV is a device that replaced human's position in completing underwater operations, especially for underwater jobs with long period, large area, and large depth. It has two major types which is observation type and job type, and based on power range and operation depth, job type of ROV can be further divided into light, middle and heavy types [7]. ROV contains several electric modules in a main mechanical structure to control different units, which usually include a submersible, umbilical cables, and an image system [8]:

1) Submersible: The submersible is a part consist of two LED lights, two color camera for both front and rear views, and several thrustors for horizontal and vertiacal motion. Conventionally there are just two lateral thrustors located on left and right side, HYDRO-OUEBEC applied symmetrical lateral thrustors in every direction of the horizontal plane on its latest produt MASKI+, and produced almost 139% more lateral proplusion compared with its previous generation [9].

2) Umbilical cables: One of ROV's largest advantages is reperesented on umbilical cables, which ensured limitless electric power supplied by mother ship. The cables also allow operator to transmit operation commond to ROV and receive image data took by ROV instantly. But it is still weak and fragile in easy winding environment, as the cables are generally designed with negligable buoyancy.

3) Image system: The optimal image system is the basic component for both observation ROV and job ROV when operating underwater. Its typically designed 180 degrees rotatable, and equipped with wide variable light beams or calibrated lasers to measure the distance and dimension on selected image. As the quality of optimal imaging is largely depend on water turbidity and light source, acoustic image system may be adopted in such poor situation by using scanning sonar.

2.2. Operation Procedure of ROV

1) On-site assembly: First choose an appropriate platform to assemble the ROV. The repacable components like robotic arm, sonar system, and rear-view camera should be chosen appropriately based on the function required to do the underwater job. It is also needed to perform parameter calibration before enter the water.

2) Enter the water: According to the water condition, adopt the simplest mechanical operation which use rope to suspend ROV artificially and lower it down until the level of water surface. This is in order to avoid impact and collision.

3) Swim: After ROV entered the water and leveled off, release the cable gradually. Then use the control unit to drive ROV horizontally to the position just beneth the inspection area.

4) Underwater operation: This is the core of ROV' operation, which is also the most significant part that affects the result. First plan a appropriate route for the inspection process based on the scheduled check plan, during which the cameras should do real-time monitor of the environmental condition. As for the six degrees of freedom motion of ROV, which include go forward, go back, go up, go down, and stay, it should be operated by the control unit. And these commonds can be achieved by just using a vedio game controller with elaborate design [10]. When focusing on the maintenance for a small crack or defect that requires more precise operation, operation buttons may be adopted. Operating buttons are generally used as back-up system with low efficiency but higher precision, which could conduct elaborate operation like cutting, twisting, rust cleaning, and puncture.

5) Coming out of the water: After finished the underwater operation, ROV can just rise to the surface and swim back to shoreside. The cables should also be recovered gragually during this process, and finally the ropes are used to lift ROV out of water. It is also neccesary to do some maintenance for the ROV after each operation.

3. Pratical Application for ROV

3.1. Inspect Small Leaks of Dams in Clean Water

As clean water condition is the ideal environment for the application of ROV in the inspection of dams, the main focus of this part will be how to detect and inspect small leaks. If the total seepage of the dam is slight, the location of leakage points would be unclear and hard to detect. As the area of toe of the upstream panel is large, and the quantities of dirt and debris mixed in the bottom is a lot, the search of leakage points would be more difficult. Therefore it is necessary to understand the quantity problem encountered during the construction of the dam in advance, as well as how does leakage quantity change with water level. The Mullaperiyar dam is composite dam constructed using masonry and lime with 1200 ft. in length and 155 ft. in height, across Periyar river in Kerala. It was constructed during 1887 to 1895 and was commenced to fill the reservoir in 1896, the full reservoir level is up to 152 ft. and total water storage is 443.23 million cubic meter [11]. There were some slight water leakage noticed in the first process of filling the reservoir, so two dam grouting were resorted to address this issue, but the phenomenon happened again as time goes by. In the practical inspection process, technicians partitioned the dam surface into several blocks for inspection, and marked vertical grid with 10 feet interval on it. Initially they scanned at each 100 feet grid as preliminary survey, and then reduced to 50 feet, 20 feet, and gradually 10 feet [11]. The whole process made good use of the advantages of ROV which include long operation period and fast travel speed, also combined the sonar system to carry out positioning, to inspect the leakage points carefully with a stable speed. When it was necessary, sludge would be removed by swing ROV' body reduplicatively.

3.2. Underwater Inspection in Turbid Water

As the water visibility is largely dependent on the water quality, the visibility in the reservoir environment is usually less than 1 meter due to the effect of sediment and other silt, even there is no water pollution [7]. In this case, the video took by the image system of ROV would be dim, which makes optimal positioning hard, so the back-up system which is sonar scanner is adopted in this situation. However, sometimes it is difficult to interpret the range information provided by sonars due to the angular uncertainties, even include some spurious measurement. To address this issue, a Simultaneous Localization and Mapping (SLAM) system was develop which could search point features in the environment, as long as the technicians deployed the required landmarks [12]. The other doable method is to lie ropes on the sea floor to guide ROV to carry out the underwater inspection. The color of the ropes should make a sharp contrast to the turbid environment, and its unique algorithm should support the processing stages which include target enhancement, edge detection, and line detection [13]. If the water is not turbid enough to adopt the sonar scanner, optimal positioning system is also applicable as long as enhance components are equipped. A test was conducted at Amagase dam in 2015, as Amagase dam is a concrete dam with 254m in length and 73m in height which across Yodo river in Kyoto, and it was completed in 1964 [14]. To address the turbid water issue, the experimenters added a turbidity reducing device in front of the camera of ROV which could emit two parallel light beams 5cm apart. During the investigation, they found the structure was in good condition, which represented the feasibility of the turbidity reducing device in the low-turbidity situation.

3.3. Conduct a Survey in Easy-entangled Environment

The surface and both shores of the dam may have deposited a lot of branches and debris during the long period of application, which could add more difficulty to the inspection conducted by ROV. Sometimes the unevenly drug caused by ROV, and the nonlinearly forward motion, as well as the natural varix of the cables, would make the cables easily get entangled in the jungle-like environment. Once the umbilical cables are winded by the branches, ROV will be difficult to get away, and the cables may be damaged or even cut off in extreme situation. In 2016, a site survey of the Aqua bridge in Tokyo carried out by the Tokyo University of marine science was aborted due to several steel wires found on the footing of the pier. The technicians conducted another survey after several months, for which they replaced the tether cable with a thinner and softer one, and performed the survey successfully at last [15]. Despite changing the material of the cable, the other effective strategy is avoiding travel in the easy-winding region. But if it is compulsory, try to move carefully and remove the obstacles beforehand by using robotic arm. And the cable winding recovery mode should be adopted to perform reverse rotation if the obstacles are not removable [16]. To deal with the most serious situation, which the cables are winded and cannot get away, a cable disengaging device was developed which allows ROV to disconnect with the cables actively in this situation, and engage the back-up AUV returning mode to return [16]. The AUV mode will use the terrain and position data recorded before to perform real-time target for its returning route. As AUV mode would consume much more energy, it could only be used for a short period in emergency.

3.4. Underwater Operation in Flowing Water

As the water supply to the urban is necessary sometimes, the dam may be unable to close the gate, in which case, the inspection work may have to be operated in flowing water. A more general situation would be the turbulence. While the ROV is hard to stay steady in one position even it retains some speed on the opposite direction of the flow, the controllability might be out of order when the flow velocity is too fast. In order to stabilize the position, a common strategy is used which the ROV contacts the surface mechanically and maintain a distance to carry out work. Sakagami and his teammates designed a ROV with several contact rods that allows it to attach stable on the surface of the inspected object by the frictional force and thrust force [17]. After several years, they came out with another type of ROV with high position stability. The new ROV is equipped with robotic grippers designed based on Bernoulli's theorem. As Bernoulli's theorem states the pressure drops when the flow is fast, the negative pressure generated in this process can provide pull force for stabilization. They developed a device called negative pressure effect plate to achieve this, while the plate can also perform the function that a simple thruster has [18]. Therefore, the technicians do not need to switch roles actively when launching or leaving the surface, which is an ingenuity. Sakagami and his teammates also conducted a test to demonstrate that the new ROV can get clear picture of the inspected surface in fast flow environment. The experiment was conducted in Shorenji dam in Nabari city, Japan, and the dam is 82m in height, with reservoir area of 1.04 square kilometer and total water storage of 27.3 million cubic kilometers. They chose a strong wind weather, which the wave height was about 0.2 to 0.3m, and the ROV successfully got continuous clear images of the dam in the fast-flow environment [18].

4. Discussion

According to the several inspection and maintenance work conducted by ROV in different environment, the main characteristics and advantages of ROV compared with conventional divers can be summarized as follow:

1) Diving speed is fast and the diving depth is up to 100m, which could satisfy most of dam inspection operation. While divers have to equip diving bell that may spend a lot of time for compression and decompression, ROV are represented to be more efficient than artificial operation while it is also able to curise with constant speed.

2) Able to hover in one position stablily in a given depth and work for a long period, while locking the inspected object automatically. If the environment is flow water, ROV is also able to attach the object and stabilize its position mechanically.

3) When in low-visibility environment, ROV can adopt the sonar scanner as back-up system to recognize and locate the target object. The underwater camera took by divers may be unable to acheieve this.

4) The result and data produced by ROV is usually clear since the information is processed. As the information would be received by the operator and recorded instantly, it is more convenient to conduct analysis work after the survey.

5) ROV's high efficency could also result in financial benefits. The jobs carried out by MASKI, which is the first version of ROV developed by Hydro-Quebec, have totally saved more than 2 million dollars in 2007 [19].

6) As ROV have a limited range of application, the most ideal environment would be clean water, standing water, and water with slow flow rate. When it was applicated in torrent, turbid water, and water with plenty of debris, the operation of ROV might be disturbed a lot. The image system of ROV may not be used in water with low visibility, therefore the sonar scanner is adopted for detection. In flowing water the ROV can not stabilize its body in one position by simply hovering, so contacting the object mechanically through the friction force and pressure is doable. ROV should also avoid operating in environment with many debris in order to preventing the cables from getting entangled, but it is still necessary to prepare solutions for the emergency.

Therefore, ROV still represents more advantage than traditional divers as it is restricted by the limited range of application. In the future, the system of ROV will be improved, as well as the number of accessories carried by ROV will increase, and there will be more types of ROV to address different situation. In this case, the adoptability of ROV will rise to a higher level, and its range of application in inspecting and maintaining dams and other underwater structure will be wider.

5. Conclusion

ROV is able to conduct fast underwater detection over a large area and detailed structural inspection. It also shows higher workability in clean water compared with traditional divers. In the presence of non-ideal environment, ROV can also improve its workability by equipping more functional modules and operating more carefully. For example, ROV can add turbid reducing device or adopt sonar scanner in water with low-visibility. In easy-winding environment, operator should control ROV carefully to pass through the region with many debris to preventing ROV from getting entangled. When opearting in turbulence, ROV can also contact the inspected object mechancially or use the negative pressure effect plate for stabilization if the flow velocity is fast. Besides, ROV can generate and represent result in a more comprehensible way, as well as recording them for future analysis. Despite increasing ROV's adoptability in complex environment, the future work will also focus on adding more inspection function in ROV's system, like the detection of changes in surface temperature, detection of dam's body deformation, and measurement of dam‘s osmotic pressure and leakage. By collating and analysing the inspection data, the condition of the structure can be tracked. Hence the safety of the underwater structure would be ensured and generate more economic and social benefits.

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