A Review on Medical Robots and Underwater Robots

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***Abstract*—Medical robotics technology, by integrating advanced technologies into healthcare practices, has emerged as a pioneering field that fundamentally transforms healthcare delivery. With the rapid progression of robotics, artificial intelligence, and machine learning, the application of medical robots holds tremendous prospects across various healthcare domains. One of the most critical applications of medical robotics is in the realm of surgical procedures. Robots equipped with precision instruments empower surgeons to execute intricate surgeries with heightened accuracy and control, thereby reducing the margin of error significantly and enabling more precise diagnostic assessments. Additionally, robots have also found application in underwater operations. Intelligent biomimetic underwater robots serve as high-tech equipment that can assist or even substitute for humans in accomplishing a diverse array of tasks. They hold significant application value in fields such as marine research, oceanic exploration, and marine environmental conservation.**

I. Introduction

This article will cover robots technologies from three aspects: Medical robots, Human Scale Tele-operating System, Biomimetic Underwater Microrobots. As an innovative intelligent medical device, surgical robots demonstrate the ability to perform complex surgical procedures in the cavities, blood vessels, and densely populated nerve regions of the human body. They offer advantages such as precise positioning, minimal surgical trauma, reduced risk of infection, and faster postoperative recovery. These attributes meet the need for high-quality medical care and help better address the global problem of under-resourced healthcare due to an aging population. In addition, these difficult surgeries place high demands on the skills of doctors. In addition to upgrading the robot itself, a complete operating system needs to be designed to simplify the entire surgical process, reduce the difficulty of the operation, and improve the safety of the operation [1]. At the same time, underwater robots represent cutting-edge robotic systems designed to operate in underwater environments, primarily for maritime rescue operations. Given the underwater dangers and harsh conditions, human divers face limitations in terms of diving depth. At the same time, the application of underwater robots is emerging in various fields, such as oil exploration, geological survey, scientific research, aquaculture, underwater ship maintenance and cleaning, recreational diving, urban pipeline inspection, etc. Therefore, the development of robotics in these fields has received extensive attention around the world. Here are the main content of the three aspects of the article:

- Robotics System for Minimally Invasive Surgery
- Human Scale Tele-operating System
- Biomimetic Underwater Microrobots

II. Robotics System for Minimally Invasive Surgery

Minimally invasive surgery (MIS) is a surgical technique that minimizes the number and size of incisions needed to perform a procedure, offering several benefits over traditional open surgery. This approach results in shorter recovery times, reduced pain, and a lower risk of infection [2]. Robotics systems have emerged as significant advancements in MIS, enhancing surgical precision, visibility, and control.

A. Da Vinci Surgical System

The da Vinci Surgical System (DVSS), developed by Intuitive Surgical and FDA-approved in 2000, is a leading example in this field, as depicted in Fig. 1. It consists of an operator console (master system), a vision cart (control system), and a patient cart (slave system) [3].

During surgery, a surgeon operates from the console, while an assistant helps with instrument insertion at the patient cart. The surgeon views the surgical field through the vision cart and manipulates the robotic arms and instruments remotely. These instruments are inserted into the patient through small incisions, allowing for precise, minimally invasive procedures.

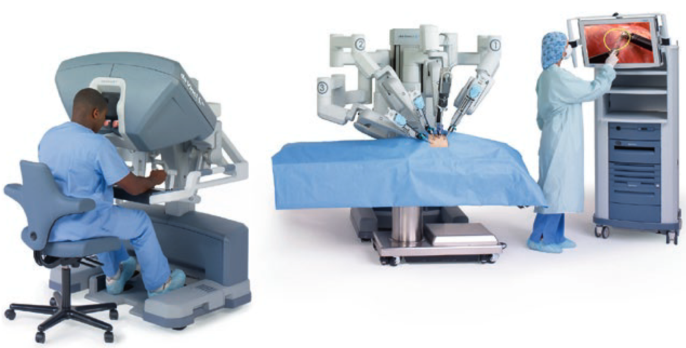

Fig. 1. Layout of Da Vinci Surgical System

The DVSS is renowned for its:

- Enhanced dexterity and precision.
- 3D high-definition vision.
- Minimally invasive nature, leading to fewer complications.
- Potential for telesurgery capabilities.

However, it also has limitations such as high cost, long training time, and the absence of tactile feedback [4].

B. Soft Magnetic-Actuation-Based Haptic Interface

Recent research explores the feasibility of a soft magnetic-actuation-based structure (SMAS) for robot-assisted vascular interventions. This system utilizes magnetorheological (MR) materials, which alter their physical properties in response to magnetic fields, providing real-time haptic feedback crucial in vascular surgery.

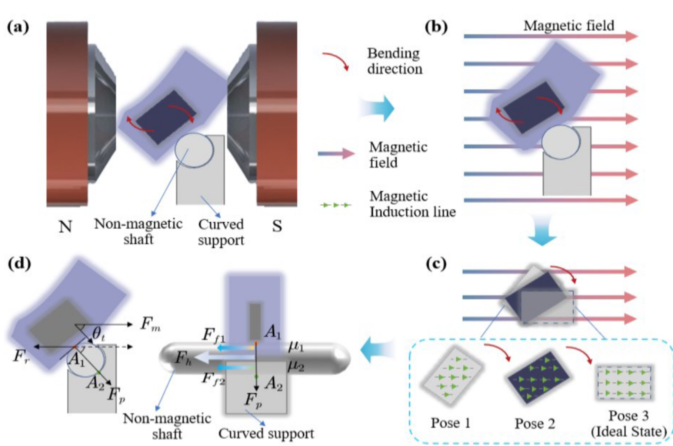

Fig. 2. Soft Magnetic-Actuation-Based Haptic Interface

The interface comprises a solid MR block and silicone skin. The MR block, responsive to magnetic fields, and the silicone skin, providing flexibility and tactile feel, are key components. In a magnetic field, the MR block can rapidly change from a fluid-like to a solid-like state, enabling quick bending actions essential for tactile feedback [5].

This technology offers several advantages over traditional robotic systems:

- **Enhanced Haptic Feedback**: Adjustable haptic feedback is vital in surgeries involving delicate vascular structures. Surgeons can feel the resistance and forces exerted by the instruments, enhancing control and safety.
- **Flexibility and Responsiveness**: The interface's rapid response to magnetic field changes allows for real-time feedback adjustments, a crucial feature in dynamic surgical environments.
- **Safety in Vascular Interventions**: The ability to sense and respond to force feedback is essential in vascular surgery. This system provides detailed feedback on the forces exerted during surgery, reducing the risk of damage to sensitive vascular structures.

C. Comparative Advantages and Future Perspectives

Comparing the DVSS and the soft magnetic-actuation-based haptic interface reveals distinct advantages in specific contexts. While the DVSS offers broad applications, unparalleled precision, and advanced visualization capabilities, the magnetic haptic interface excels in providing real-time tactile feedback, essential in vascular and other delicate surgeries.

The future of robotic systems in MIS is promising, with ongoing advancements aimed at overcoming current limitations. The integration of tactile feedback in systems like the DVSS could further enhance their applicability. Moreover, the development of more cost-effective and user-friendly robotic systems could make MIS more accessible, benefiting a larger patient population.

Both systems represent significant steps towards improving surgical outcomes and patient care. As technology advances, it is anticipated that robotic systems will become more integrated into various surgical fields, offering safer, more precise, and less invasive treatment options.

III. Human Scale Tele-operating System

A remote micro-operation system refers to a system capable of conducting minute-scale operations through remote control. Typically, such systems encompass precise mechanical devices, sensors, control units, and remote operation interfaces. Designed to enable operators to manipulate and control tiny-scale targets from a distance, this system is commonly employed in fields requiring high precision and minute-scale operations, such as minimally invasive surgery, laboratory procedures, and nanotechnology.

Currently, the majority of vascular interventional surgical robots available in the market possess limited functionalities, primarily catering to the function of wire propulsion. However, in vascular interventional procedures, especially in neurointerventions, surgeons typically require the collaborative operation of multiple guidewires and catheters, along with repeated catheter manipulations for contrast imaging to observe instrument positioning and vascular conditions [6]. Due to the inability to achieve multi-instrument collaborative operations, existing vascular interventional surgical robots lack broad compatibility across various vascular intervention procedures, encompassing both imaging and treatment. They have limited active participation time during surgeries, requiring bedside team collaboration, thus preventing surgeons from effectively avoiding radiation exposure.

At present, one of the more complete is Aibo Medical's vascular interventional surgical robot designed based on the modular concept, which can meet the collaborative operation control of multi-catheter guidewires, complete composite actions such as pushing, rotating, pushing + rotating, etc., and adapt to neurointervention, coronary intervention, peripheral intervention and other surgical methods. At the same time, the surgical robot is easy to disassemble and assemble, which can effectively shorten the preoperative preparation time and meet the needs of high-speed operation in China. The following figure is a schematic diagram of the framework of the system.

Fig. 3. Schematic diagram of the system

A remote micro-operation system typically comprises the following components: precise mechanical devices, sensors, control units, a remote operation interface, and communication equipment. Precise mechanical devices encompass various precision mechanical apparatuses, tools, or operating devices employed for executing minute-scale operations, such as miniature surgical tools, micro-manipulator arms, or micro-operating instruments. Sensors are utilized to acquire diverse data pertaining to operational targets, such as position, direction, pressure, force, among others. The control unit, often constituted by computer systems or controllers, is responsible for receiving sensor data, processing information, and generating corresponding control commands to ensure the accuracy and stability of operations. The remote operation interface provides operators with a platform for remote interaction with the system, allowing them to send instructions and receive operational feedback through the interface. Lastly, communication equipment is used to establish a remote communication link between operators and the system. This can entail wireless or wired communication devices, ensuring real-time control by operators and receipt of feedback information.

Currently, remote micro-operation systems offer significant potential for advancement. Future research can explore several key areas. Firstly, advancements in automation and intelligence are paramount. These systems should demonstrate higher autonomy and intelligent decision-making capabilities to reduce reliance on human intervention. Secondly, exploring multi-mode operational capabilities is crucial. Allowing a single operating system to adapt across diverse scenarios enhances system flexibility and applicability. Additionally, improvements in sensor technology are pivotal to enhance the system's precision sensing and control. Employing more effective control methodologies will enable more accurate operations on minute-scale targets. Lastly, focusing on real-time feedback and interaction will elevate system usability, enabling operators to intuitively grasp the system's operational status and make real-time interventions, thereby enhancing operational efficiency and accuracy [7].

IV. Biomimetic Underwater Robots

The vast oceans harbor abundant biological resources, mineral deposits, and energy. Human activities such as production and scientific research in underwater environments are becoming more frequent. The demands for underwater tasks are increasing, surpassing the capabilities of manual operations in terms of cost, safety, and efficiency. Underwater robots, as highly technological equipment capable of underwater movement and certain perception abilities, play a crucial role in marine research, development, and environmental protection. These robots can assist or replace humans in performing various tasks underwater. They are essential in marine rescue operations, especially in harsh and dangerous underwater conditions where human diving depth is limited. Additionally, in military conflicts, unmanned ground vehicles, drones, and unmanned vessels are proving increasingly effective, highlighting the significant role of unmanned combat platforms in future modern warfare. Furthermore, underwater robots find applications in areas such as petroleum development, geological surveys, scientific research, aquaculture, underwater vessel maintenance and cleaning, diving entertainment, and urban pipeline inspections, contributing to a rising market. This part will introduce biomimetic underwater robots from the following aspects- underwater soft robots, application prospect and development trend.

A. Underwater Soft Robots

Soft robots are robots made of flexible materials, such as polymers, elastomers, hydrogels, particles, which can use a number of different drive modes, including pneumatic, electric, chemical. And their motion can be fast or slow. In addition, bodies of soft robots are typically made of soft or expandable materials, such as silicone rubber, that can deform and absorb most of the energy generated by collisions. It is worth noting that the soft materials used in the robot can play a role in the drive part, and not just for aesthetics or protection. Soft robots that can work underwater are called soft underwater robots.

Compared with underwater rigid robot, underwater soft robots have great have advantages in observing Marine lives. Current autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs), which are made of rigid materials, are electrically driven and conventional rigid underwater vehicles. By equipping AUVs and ROVs with underwater manipulators that are in turn capable of performing specific tasks, such as underwater pipeline inspection, sample collection, data monitoring and so on, these underwater vehicle operating systems are called unmanned underwater vehicles (uuv). The underwater rigid robots have a stable structure and precise transmission with a certain degree of freedom, so they can be programmed to precisely control the rotational or translational motion of each joint. However, due to the high elastic modulus of the rigid material, the rigid underwater robot has a hard appearance and poor environmental adaptability, which is easy to cause damage to Marine organisms when it comes into contact with them. The traditional underwater jet propulsion method will cause great disturbance to the underwater environment and affect Marine life. In addition, the traditional underwater rigid robot is difficult to operate in the narrow underwater space due to the existence of control, transmission, drive and other mechanical parts. What's more, the hard and bulky shell used by conventional submersibles makes it difficult for submersibles to integrate into the Marine environment and dive into relatively complex terrain, which is not conducive to clear observation of Marine life. Comparison of some rigid and soft underwater robots and their speed and size are shown in Fig.4 and Fig.5 [8].

Type	Cable/ Cableless	Energy supply	Representative robots	Mess [g]	Velocity [m s^{-1}]	Size [mm]	Range [h]	COT [J Nm^{-1}]	Depth [m]	Reference
Underwater rigid robots	Cableless	Ni–MH battery	Boxfish-like robot	3100	0.404	400 × 140 × 142	5.00	1.9	Water surface	[300]
		LiPo battery	BIKI V1.0	1200	0.500	272 × 110 × 181	2.00	0.5	60	[301,302]
		LiPo battery	SPC-3 UVV	46 000	1.15	Diameter 210, Length 1600	16.7	0.04	NA	[303,304]
	Cable	DC/AC power supply	Gladius Mini	2500	2.000	383 × 223 × 137	4.00	0.4	100	[305]
		DC/AC power supply	Single-motor-actuated fish	597	0.58	Length 345	NA	6	NA	[306]
		DC/AC power supply	Tensegrity fish robot	102	0.23	Length 400	NA	8	Water surface	[307]
		LiPo battery	PowerRay	3800	1.500	465 × 270 × 126	4.00	NA	30	[308]
Underwater soft robots	Cableless	LiPo battery	Electroionic robotic fish	90.3	0.135	220 × 93 × 40	3.25	0.43	Water surface	[55]
		LiPo battery	Piezoelectric fish using MFC actuator	NA	0.075	Length 243	0.50	NA	Water surface	[223]
		LiPo battery	Multiflexible robotic fish	1670	0.822	Length 504.5	NA	0.3	30	[88]
		LiPo battery	Robotic octopus	2680	0.0986	Diameter 160, Length 380	1.0	1.48	NA	[309]
		LiPo battery	FEDORA	230	0.0032	8 circularly arrayed actuators Each width 50.8, Length 76.2	2.7	35	0.15	[22]
		LiPo battery	IPMC robotic cownose ray	119	0.007	210 × 85 × 50	NA	240	0.9	[310]
		LiPo battery	HASEL	170	0.02	Diameter 160	1.0	1.62	NA	[311]
		LiPo battery	Jennifish	380	0.03	Diameter 210	NA	20.5	5	[317]
		LiPo battery	Finbot	125	0.122	100 × 60 × 25	2.00	8.2	0.91	[86,312]
		LiPo battery, DC/AC power supply	Tunabo	306	0.4	255.3 × 49.2 × 67.8	6.0	2.83	0.20	[313]
		Combustion gas	Copebot	2000	1.6	Diameter 150, Height 200	NA	NA	Water surface	[91]
		Ni–MH battery	Cyro	76 000	0.09	Diameter 1700	3.0	1.11	NA	[314]
		DC/AC power supply	UEC Mackerel	NA	0.0258	Length 180, Width 20	NA	0.08	Water surface	[315]
	Cable	LiPo battery	Mariana soft robot	245	0.052	Body length 115, Wingspan 280, Tail length 105	0.75	80	10 900	[15]
		DC/AC power supply	ART	9000	Flapping 0.0833 Padding 0.0655	960 × 358 × 32	NA	Flapping 3 Padding 4.3	Water surface, underwater.	[8]
		DC/AC power supply	Madeleine	24 400	0.74	Length 780	NA	0.3	1.00	[224]
		LiPo battery (PRC)	Microrobot using IPMC actuator	1.45	0.007	57 × 10 × 7	NA	240	Water surface	[58]
		DC/AC power supply	RoboJelly	240	0.0 3	Diameter 164	NA	231	NA	[220]
		DC/AC power supply	Robotic water beetle	22.65	0.117	Length 95, Max span 155	NA	25.5	Water surface	[331]
		DC/AC power supply	Underwater walking robot	356	0.025	Diameter 250, Height 100	NA	NA	0.48	[316]
		DC/AC power supply	HAMR	1.6	0.028	40 × 20 × 20	NA	10.9	Water surface, underwater.	[11]
		DC/AC power supply	OCTOPUS	3000	0.050	Center rigid body diameter 40, Robot diameter 100	NA	1.8	0.02 (Submerged)	[17]
		DC/AC power supply	DE-driven eel larva	150	0.0019	220 × 50 × 1.5	NA	5	Water surface	[64]

Fig. 4. Comparison of Underwater Rigid Robots and Underwater Soft Robots

Although soft underwater robots have many advantages, they face plenty of challenges, which makes them develop slow relatively. The challenges come from the following aspects:

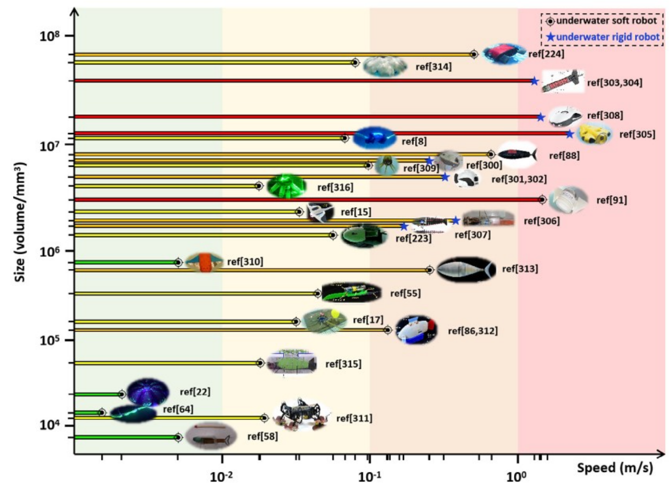

Fig. 5. Comparison of the Speed and Size of Various Underwater Rigid Robots and Underwater Soft Robots

- Materials. Soft materials are essential for the development of high-performance soft underwater robots. The new soft robots currently being developed have higher requirements for advanced manufacturing technologies such as 3D/4D printing.
- Modeling. Soft robots are continuum robots, which means that they have more degrees of freedom, greatly increasing the complexity of kinematic modeling and control. In addition, due to the uncertainties caused by the complex flow disturbance in the underwater environment, ocean currents and low visibility, the simulation results are quite different from the actual experimental results.
- Sensing. Due to the uncertainty and complexity of the underwater environment, traditional sensing technologies, such as acoustics, optics, electromagnetism, etc., have certain application limitations in the underwater environment, and most of the traditional sensors can not be directly applied to the underwater environment. Therefore, it is necessary to re-develop flexible sensors adapted to soft underwater robots.

B. Application prospect

Biomimetic underwater robots have been widely used in many fields, including ocean engineering, port construction, offshore oil, maritime law enforcement and forensics, scientific research and naval defense, to complete underwater search and rescue, exploration and salvage, deep-sea resources survey, submarine pipeline laying and inspection and maintenance, underwater archaeology, power stations and DAMS and dam inspection and other work. At present, the market demand for underwater robots is divided into two types: observation and exploration type and operation type. The observation model is equipped with underwater television and photographic equipment for regular observation and inspection of specific underwater targets; For different requirements, the operation type can also be equipped with forward-looking sonar, side-scan sonar, undersea mapping, undersea profile and other equipment and various manipulators for simple underwater operations.

Zero casualties are the choice in the future war, so the status of unmanned weapon system in the future war is paid more and more attention, and its potential combat effectiveness is more and more obvious. As an important part of the unmanned weapon system, the biomimetic underwater robot can be based on the surface ship or submarine, and complete the environmental detection, target identification, intelligence collection and data communication in the underwater space of tens or hundreds of miles, which will greatly expand the combat space of the surface ship or submarine. Autonomous biomimetic underwater vehicles, in particular, can more safely enter dangerous areas controlled by the enemy, and can stay in the war zone in an autonomous way for a longer period of time, which is an effective force multiplier. More importantly, in the future war, the ”network-centered” combat idea will replace the ”platform-centered” combat idea, and the biomimetic underwater robot will become an important node of the network center station and play an increasingly important role in the war. At present, countries focus on the application of mine countermeasures, anti-submarine warfare, intelligence collection,surveillance and reconnaissance, target detection and environmental data collection.

C. Development Trend

In the future, biomimetic underwater robots will develop in the following directions:

- Development towards Long Distance
  There are three technical obstacles to the long-range development of biomimetic underwater robots: energy, long-range navigation, and real-time communication. Various available energy systems currently under study include primary batteries, secondary batteries, fuel cells, heat engines, and nuclear energy. The development of autonomous biomimetic underwater robots using solar energy, which need to float to the surface to recharge onboard energy systems, is a notable new development. And the energy available is limitless.
- Development towards Abyssal Sea
  The ocean area with a depth of more than 6,000 meters accounts for 97% of the total ocean area. Therefore, many countries have set the development of 6000 water depth technology as a goal. The United States, Japan, Russia and other countries have developed 6000 meters of UUVs. The Woods Hole Oceanographic Institution of the United States has developed a deep-sea exploration vehicle ”ABE” that can stay at the bottom of the sea for a year at a depth of 6,000 meters. In 1993, Japan developed the ”Trench”, a deep-sea unmanned submersible with a working depth of 11,000 meters.
- Development towards Intelligence
  Increasing the intelligence level of biomimetic underwater robots' behavior has been the goal of scientists in various countries. However, because the current artificial intelligence technology can't meet the needs of the intelligent growth of biomimetic underwater robots, it is necessary to introduce human intelligence into biomimetic underwater robots, which is the idea of monitoring biomimetic underwater robots. Not relying entirely on the intelligence of machines, but relying more on the intelligence of sensors and people, is an important development direction in the future, and the biomimetic robot is an advanced biomimetic underwater robot based on sensors. The development of multi-robot collaborative control technology is also an important aspect to increase the intelligence of autonomous underwater vehicles.

V. Conclusion

The development of robotics, apart from its widespread industrial applications, has gradually gained public attention in other fields, particularly in biomedical engineering and underwater robotics. Vascular intervention robots represent an organic fusion of surgical robotics and vascular intervention techniques. These robots manipulate interventional surgical instruments, operating in environments unfavorable to physicians. They precisely locate themselves using medical imaging and execute continuous actions without tremors. Additionally, rehabilitation robots are currently in their initial stages, displaying certain deficiencies in personalized design and human-machine interaction. There exists a considerable gap between their current state and the expected outcomes, necessitating ongoing research efforts.Meanwhile, advancements in intelligent control technology, underwater target detection and recognition, as well as navigation techniques in underwater biomimetic robots, have made notable breakthroughs. These robots can find ample application in underwater resource exploration and might potentially contribute to future warfare.In summary, the prospects for robotic research in these domains are highly promising. Continuous research endeavors have the potential to enhance our quality of life, reduce surgical risks, and mitigate hazards associated with underwater operations.

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