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A Review of Comparing Robotic Arms in Space Station and Medical Applications

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Abstract. This review paper compares robotic arms in space stations and medical applications. It summarizes some similarities and differences between the space station robotic and medical robotic arms. In both fields, robotic arms are indispensable in helping humans explore the world and reduce human burdens. Many kinds of space and medical robotic arms have appeared on the market. In this paper, we compare the space station robotic arms and medical robotic arms from the overall perspective and comprehensively compare the mechanical arms applied in these two fields from the structure, control mode and environmental impact of the mechanical arm, as well as the economic benefits of the two kinds of mechanical arms. Our review can provide ideas and guidance for future research. At the end of the paper, the shortcomings of robotic arms in these two fields are mentioned and suggested working directions are given.

Keywords: Robotic arm, control mode, degree of freedom, micro-gravity, economic benefits.

1. Introduction

The robotic arm is an automatic device composed of joints and connecting rods. It generally has multiple degrees of freedom and can execute instructions in three-dimensional space. It is widely used in industrial, medical, logistics, agriculture, and other fields. The main applications of robotic arms include welding, assembly and handling in industrial manufacturing, surgery and rehabilitation training in the medical field, goods sorting in logistics and warehousing, and automated picking in agriculture. Its advantage is that it can perform repetitive work well, with higher accuracy and efficiency. However, there are also challenges, such as high costs, complex maintenance, and the potential impact on employment. With the progress of Technology, the application range and performance of the mechanical arm will continue to improve, which can bring more convenience and benefits to all walks of life.

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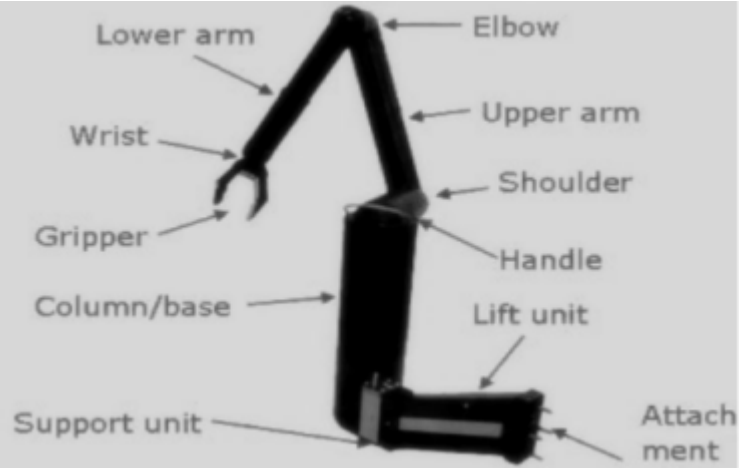


Figure 1: A robotic arm with labels [1]

Space station robotic arms, such as the European Robotic Arm(ERA) [2], are designed to perform in the vacuum of space, executing tasks like capturing satellites, module assembly, and extravehicular support. On the other hand, medical robotic arms, such as the da Vinci Surgical System, are designed for the human body, focusing on precision and real-time interaction in delicate procedures, exemplified by surgery like laparoscopic surgery. The comparison between space station and medical robotic arms is not merely an academic exercise; it illuminates the broader evolution of robotic Technology and its tailoring to specific human needs. Space robotic arms emphasize strength and durability and try to adapt to microgravity and radiation. For medical robotic arms, micron-level precision, safety for the human body, and advanced imaging. Such contrasting demands reflect the specific difficulties in their respective environments.

The current field has fewer review papers, yet it is significant. Our review aims to systematically compare space station robotic and medical robotic arms, exploring their control methods and comparative analysis of freedom, environmental effects and economic benefits. By summarizing insights from existing papers and the latest Technology, we stress the common principles widely applied in these systems and their respective innovations. Such an analysis deepens our understanding of robotic Technology and may provide potential cross-disciplinary lessons.

2. Comparison of space and medical robotic arms

2.1. Control methods of space and medical robotic arms

Most current space station robotic arms are semi-automatic, but they also have some fully automatic functions, and their degree of automation depends on the specific mission and objective. In the space robot arm, the semi-automatic mode is mainly sent by astronauts or ground controllers to control the movement of the robot arm through remote operation. The automatic mode is that the robot arm completes the task independently according to the set program. For example, the International Space Station robotic arm shown in Figure 2 mainly operates in semi-automatic mode [3], and the China Tianhe Robotic arm [4] has high automation capabilities. It can independently complete tasks such as module transfer. The European robotic arm, as shown in Figure 3, which supports semi-automatic and fully automatic modes, is equipped with cameras and computer systems and can perform some operations autonomously without requiring astronauts to be in control all the time.

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Figure 2: International space station robotic arm [5]

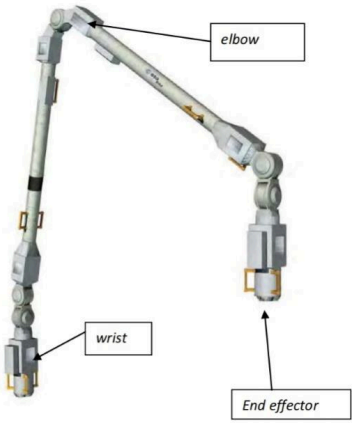


Figure 3: Overall ERA arm architecture [6]

There are three kinds of medical robotic arms on the market: automatic control, semi-automatic control, and manual control. Automatic control relies on advanced algorithms and sensors, without human control, reducing the error caused by human operation. However, this robot arm is weak in responding to emergencies, making it more suitable for work with high repeatability. For example, the CyberKnife radiosurgery system [7], which is mainly used in tumour radiotherapy, has real-time image tracking and automatic adjustment of radiation beam functions. Semi-automatic control allows a robotic arm to filter out hand tremors while giving the doctor complete control over the procedure, ensuring safety and accuracy. For example, in the Da Vinci Surgical system, which is suitable for minimally invasive surgery, the doctor controls the robot arm through the console, combining the flexibility of the robot arm and the doctor's experience so that the surgery is more efficient. Manual control entirely depends on the doctor's experience but also tests the doctor's level. For example, the MAKO orthopedic surgery robot, as shown in Figure 4 and Figure 5 [8], which is used in orthopedic surgery, is planned by the doctor and operated by a robotic arm.

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Figure 4: A view of the MAKO orthopedic surgery robot [9]



Figure 5: The MAKO orthopedic surgery robot [10]

All in all, the application of the space station robotic arm and the medical robotic arm is more semi-automatic control, combining the controller's experience and the robotic arm's flexibility so that people can complete the task more efficiently. Due to the differences in environment and mission complexity, space station robotic arms apply more automatic and semi-automatic control, while medical robots use more semi-automatic and manual control.

2.2. Analysis of freedom (DOF) of space and medical robotic arms

In robotics, "degrees of freedom" represents the number of independent movements a robotic arm can perform. These movements contain translations and rotations. Robotic arms control all points using their degrees of freedom. For comparison, a human arm is controlled by seven degrees of freedom. For example, from shoulder to wrist,7 degrees of freedom enable a wide range of motion. Robotic arms change in DOF based on their application:

3 DOF, as depicted in Figure 6, is a basic translation (up/down, left/right) suitable for simple tasks.

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Figure 6: Schematic diagram of a 3 DOF robotic arm [11]

DOF, as depicted in Figure 7. It includes three translational DOFs and three rotational DOFs. Has the ability to move in six different directions, which are commonly referred to as the six degrees of freedom, and include translation along the x, y and z axes and rotation around these same axes.

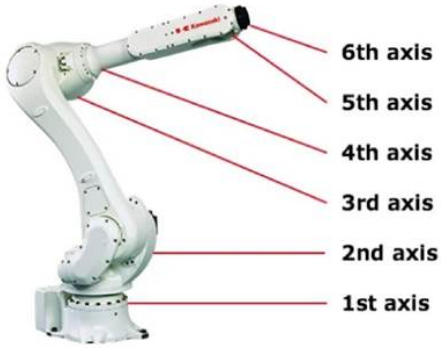


Figure 7: Schematic diagram of a 6 DOF robotic arm [12]

7+DOF, as depicted in Figure 8. A 7+DOF arm introduces redundancy, allowing it to adjust its joint configuration while keeping the end-effector's position fixed. Robots are generally flexible machines that can be applied to many tasks.



Figure 8: A kuka 7-degree-of-freedom arm [13]

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2.2.1. Medical robotic arms

Degrees of freedom in medical robotic arms are critical for assessing motion flexibility and operational precision. There are various types of medical robotics, especially these three, which are widely used in the medical field: minimally invasive surgical robots, rehabilitation and assistive robots and laboratory automation arms. Firstly, in minimally invasive surgery, robotic arms like the Da Vinci Surgical system, as shown in Figure 9, typically have 6-7 degrees of freedom. The EndoWrist is a key system component; it can mimic human wrist movements, offering 7 degrees of freedom and greater surgical flexibility.

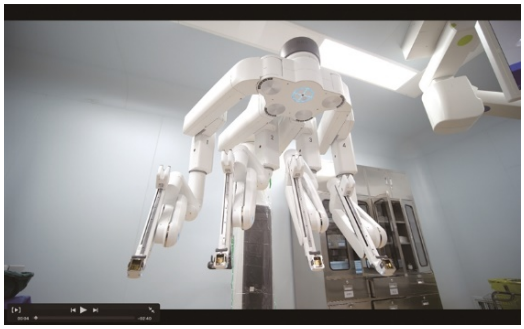


Figure 9: Part of the Da Vinci surgical system [14]

Secondly, these robotic arms usually have 4-6 degrees of freedom for rehabilitation and assistive robots. HAL(Hybrid Assistive Limb) is a powered exoskeleton with multiple degrees of freedom [15]. The lower limb version(HAL3)has at least 4 degrees of freedom, and the full-body version(HAL5) has additional degrees. Clinical evidence supports its effectiveness in improving mobility and functional outcomes, making it a valuable tool in modern rehabilitation practices.

Lastly, laboratory automation arms typically have 3 – 6 degrees of freedom. It can move samples or plates in labs. For example, Universal robots UR5 and UR10 are popular in labs and have 6 DOF suitable for tasks like pipetting.

2.2.2. Space station robotic arms

Application of degrees of freedom is mainly stressed in these fields: Satellite Capture and release, station assembly and maintenance, and astronaut assistance. Canadarm2 on the International Space Station(ISS) has performed outstandingly for all these three parts. It typically has 7 degrees of freedom. This means it can move in 7 independent ways, with three joints at the shoulder, one at the elbow, and three at the wrist, similar to a human arm. This equipment allows it to handle tasks like assembling station parts and berthing spacecraft. Compared to Canadarm(6DOF), the additional degree of freedom enhances Canadarm2's capability to perform delicate operations [16], such as handling orbital replacement units(ORUs) and conducting precise maneuvers. In summary, Canndarm2's 7 DOF provide exceptional flexibility for adapting ISS's complex structure.

2.2.3. Conclusion

Medical and space robotic arms share similar degrees of freedom, usually 6 to 7, to operate in all directions. However, they differ in divided applications. Medical robotic arms have a wide range of degrees of freedom (DOF), typically from 4 to 10, which are determined by the specific tasks they

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perform. On the other hand, space robotic arms, such as Canadarm2 with 7 DOF and Canadarm with 6 DOF, generally maintain a more standardized range of 6 - 7 DOF.

2.3. Environmental effects on space and medical robotic arms

The working environment of space robotic arms and medical robotic arms is very different, resulting in different structures of the robotic arms.

Micro-gravity environment, vacuum environment, and extreme temperature are significant features of space [17]. Their impact on robotic arms is more significant than on Earth. In micro-gravity environments, robotic arms do not need to resist gravity, so they can be designed to be lighter. It can reduce the need for driving force and cause lower energy consumption, but traditional lubrication methods may fail. Leading to increased wear and tear on the joints and components of robotic arms, requiring special lubrication materials and designs. Also, the movement of a robotic arm can easily cause vibrations, which can last for a long time without gravity damping, affecting the accuracy and stability of the operation. Then, in a vacuum environment, the movement of the robotic arm is not affected by air resistance and allows for smoother and more efficient motion. Also, there is no oxygen, dust or other pollutants in a vacuum environment, which extends the service life [18]. There are also extremely hot and cold temperature changes, and heat can only be transferred through radiation, lacking convection and conduction. Thermal management is becoming more complex and requires special thermal control systems to prevent overheating or over-cooling. However, it is very different on Earth. In medicine, the most important is aseptic control technology for medical robotic arms, which work in sterilized and isolated areas. The area must be a sterile Zone, and the parts that come into direct contact with patients or surgical instruments, such as fixtures, puncture needles, and cameras, must be Autoclave (121 ° C+) or disposable. The material must be corrosion-resistant, such as titanium alloy, medical grade stainless steel, and special plastics. The mechanical arm body, motor, cables and other components can not directly contact the patient. It must be isolated from the surgical area through sterile barriers such as sterile covers and isolation membranes. For instance, the Endo Wrist arm of the da Vinci surgical robot is equipped with a disposable sterile sheath, while the robotic arm body is covered with sterile cloth for isolation.

There are many disadvantages to the two fields. The space robotic arm relies too much on preset programs and cannot make changes based on the environment. In the fixed task mode, the current AI of robotic arms is mainly based on prepared programmed instructions. If the task exceeds expectations, such as shape changes due to a vacuum environment or position moves due to gravity, it may be unable to adjust autonomously. Unlike robots on Earth, such as Tesla's Optimus and Boston Dynamics Atlas, space robotic arms do not have adaptability and learning capabilities. Then, visual recognition accuracy is limited. Space robotic arms typically use stereo vision and laser ranging but may misjudge their position in intense light, shadows, and reflections in space.

Regarding the medical robotic arm, there are compatibility issues with disinfection and a risk of cable or interface contamination. Some robotic arm materials, such as specific polymers or electronic components, cannot withstand high temperatures and high-pressure sterilization, such as 135 ℃ steam, and rely on chemical disinfection, such as hydrogen peroxide plasma, which may result in residual toxicity. The cables of external devices, such as cameras and electrocoagulation knives, may damage the sterile area and increase the risk of infection.

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2.4. Economic benefits between space and medical robotic arms

Space station robotic arms' development and maintenance costs are high and low. However, compared with medical robotic arms, even low-cost robotic arms are higher than the average cost of medical robotic arms. Maintenance costs are also very high once the high-cost, high-precision robotic arm fails. However, a highly automated robotic arm also reduces mission costs because it does not require astronauts to go outside the capsule for equipment maintenance, does not require astronauts to operate inside the capsule, and does not require the robot arm to perform tasks autonomously, reducing the cost of support for astronauts to step outside the capsule. For example, Northrop Grumman's MRV robotic arm, as shown in Figure 11 [19], which is used in the satellite life extension mission, costs about $8 million and is installed on the MRV spacecraft to dock and repair communications satellites in geosynchronous orbit, significantly extending the life of the satellite and reducing operating costs, so it is also highly economical. MDA Canada's Space Infrastructure Servicing Arm focuses on geosynchronous orbit satellite servicing [20]. A single SIS Arm costs about $80 million to $120 million. However, it significantly affects the maintenance of geostationary orbit satellites, which can extend the life of satellites by five to ten years and save more than 75% of the cost. Therefore, although a Space Infrastructure Servicing Arm costs relatively high, its return rate is also high in the long run.

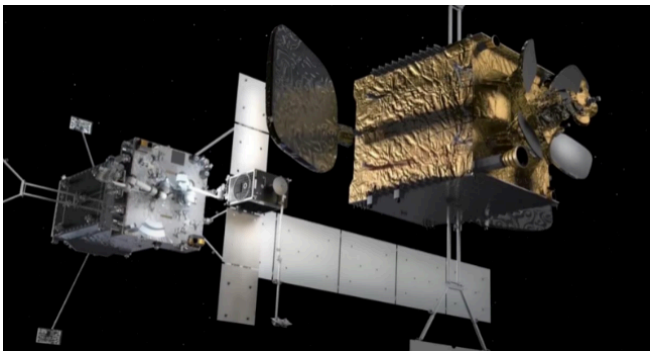


Figure 11: The Mission Robotics Vehicle (MRV) installs a Mission Extension Pod (MEP) onto a client vehicle. On MRV and MEP, the Hall thrusters are located at the ends of the long boom arms shown in the image [21]

Medical robotic arms cost much less than space station robotic arms, but some are still expensive. Relatively low-cost robotic arms, such as the Fourier Intelligent Upper Limb Rehabilitation robot, as shown in Figure 12 [22], cost about 300,000 yuan and have adaptive resistance regulation. It has a good effect on stroke, brain injury, orthopaedic postoperative rehabilitation and children's cerebral palsy rehabilitation. Its return on investment period is around one to three years. Moreover, high-cost medical robotic arms are smarter and more expensive. For example, BrainRobotics smart prosthetics [23], which cost about $1.5 million, support mind control. Using BrainRobotics smart prosthetics, as shown in Figure 13, can reduce the cost of treatment of complications, saving 20,000 to 30,000 yuan per person. Of course, the use of medical robotic arms for treatment does require a high cost; in the future, through large-scale workshop production and research of low-cost materials, to reduce the cost of robotic arms, as reducing the cost of surgery can improve the economic benefits of medical robotic arms.

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Figure 12: ArmMotusEMU 3D upper limb rehabilitation robot [24]



Figure 13: BrainRobotics intelligent bionic hand [25]

Overall, the development costs of the space station robotic arm and the medical robotic arm are high, but the former's maintenance cost is much higher than that of the latter. The short-term economic benefits of a space station robotic arm are limited, but in the long-term, it is good for the country and the people. The short-term economic benefit of the medical robotic arm is much higher than that of the space station robotic arm, and the long-term return is also significant.

3. Conclusion

In conclusion, space robotic and medical robotic arms have a lot of similarities and advantages. The application of space station robotic arms and medical robotic arms is more focused on semi-automatic control, combining the experience of controllers with the flexibility of robotic arms to enable people to complete tasks more efficiently. Due to differences in environment and task complexity, space station robotic arms tend to use automatic and semi-automatic control. In contrast, medical robots tend to use semi-automatic and manual control. Furthermore, referring to DOF, medical robotic arms usually have low to medium degrees of freedom (DOF), while space station robotic arms tend to have high DOF. This difference exists because their tasks require different levels of precision and complexity. However, there is a similarity: both environments use high-DOF robotic arms when handling exact tasks. These advanced systems help complete work efficiently, accurately, and safely, whether in medical operations or space station maintenance. Thirdly, it is different from the single environment of the medical robotic arm, which needs a sterilizable and isolated area and a Sterile Zone. The environment of a space robotic arm has a micro-environment,

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vacuum environment and extreme temperature. The visual recognition accuracy of the space robotic arm is limited. Space robotic arms typically use stereo vision and laser ranging but may misjudge their position in intense light, shadows, and reflections in space.

Also, the automation technology of space robotic arms still needs to be improved because space robotic arms rely too much on preset programs and cannot make changes based on the environment. Then, the research and development costs of space station robotic arms and medical robotic arms are both high, but the maintenance costs of the former are much higher than those of the latter. The short-term economic benefits of the space station robotic arm are limited, but in the long run, it is a good thing for the country and the people. The short-term economic benefits of medical robotic arms are much higher than those of space station robotic arms, and the long-term returns are also significant. Ultimately, we should strive for excellence in improving robotic arms and increasing precision and automation.

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Yiman Li, Yuze Gao and Jiaoyu Zhang contributed equally to this work and should be considered co-first authors.

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