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Overview of Robotic Applications in Biomedical Domain

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Abstract

Robotics is widely applied across various fields, including manufacturing, transportation, medicine, defense, space, and agriculture, with significant contributions to the biomedical domain. Its applications in healthcare include surgical robots, soft robots, companion robots, and sanitation and disinfection robots. Soft robots play a crucial role in diagnosing diseases, detecting tumors, and delivering drugs inside the human body. Additionally, they support patient rehabilitation, enhance social and physical well-being, and assist medical professionals in performing complex surgeries, disinfection procedures, and hospital supply transport. The rapid growth of robotics in healthcare is primarily driven by advancements in Artificial Intelligence, which continue to enhance robotic capabilities and efficiency. This paper provides an overview of the fundamental concepts and technologies in robotics, explores different types of robots, discusses the development process, and examines their applications in the biomedical field.

Keywords: Robotics; Biomedicine; Robotic Operating System; Surgical Robots; Soft Robots.

Introduction

Advancements in robotic technology have provided guiding paths for care at the cellular level, and the same will become reality in the coming years, thus enhancing the level of diagnosis, prognosis, and treatment [1-3]. Robots, which are autonomous or semi-autonomous machines capable of sensing, processing information, and performing tasks with minimal human intervention, have found significant applications in healthcare. Robotic applications in health care, a sector within the broader medical domain—which encompasses all healthcare-related fields such as diagnostics, treatment, rehabilitation, and patient care—help improve the efficiency of surgeries carried out through less invasive, precise, and targeted actions and provide radiotherapy to cancer patients with less human intervention [4, 5]. Medical robots, specifically designed robotic systems that assist in medical procedures and healthcare operations, play a crucial role in surgery, rehabilitation, diagnostics, and patient support. Companions or rehabilitation robots help patients return to their normal lives in less time. The objective of this study was to provide an overview of the basic concepts and technology involved in robotics, the process involved in developing a robot, and different robotic applications in the biomedical domain.

Basic Concepts and Technologies Involved in Robotics

Basic concepts and technologies involved in robotics are represented by Robot Operating System (ROS), actuators, sensors, computer vision and image processing, embedded systems, robotic hardware, artificial intelligence and robotics and modelling and controlling robots.

Robot Operating System (ROS) is an open-source middleware for the development of robotic systems. It includes a comprehensive set of libraries, tools, and algorithms [6]. The primary platform is Ubuntu owing to its flexibility and user-friendliness [7].

Actuators are devices that convert energy into physical motions, and can be linear or rotary based on movement type [8]. In the field of robotics, actuators are critical components that enable the movement of robot joints. They are typically classified into three primary types: hydraulic actuators, which utilize pressurized fluids to generate motion; pneumatic actuators, which operate based on compressed air; and electric actuators, which convert electrical energy into mechanical motion. Each type of actuator is characterized by distinct features, including their power sources, efficiency, control mechanisms, and suitability for various robotic applications, thereby influencing their selection based on the specific requirements of the task.

Sensors are devices that measure physical properties in an environment, enabling a robot to perceive and interact with its surroundings [9]. These sensors detect a wide range of stimuli, such as temperature, pressure, proximity, force, and light, and convert these measurements into signals that can be processed by the robot's control system. Examples of commonly used sensors in robotics include infrared sensors (IR), which detect obstacles by measuring the reflection of infrared light; ultrasonic sensors, which use sound waves to measure distance to objects; accelerometers, which measure changes in velocity and orientation; and vision sensors, such as cameras, that allow robots to interpret visual information. Sensors are essential for robots to perform tasks autonomously, as they provide real-time data crucial for decision-making and interaction with the environment [10].

Computer Vision and Image Processing enable robots to analyze digital images and videos in order to extract meaningful information. This capability allows robots to perform complex tasks with high accuracy [11]. These tasks include object recognition, where robots identify and classify objects within their environment; motion tracking, which involves monitoring the movement of objects or people; facial recognition, enabling robots to identify and interact with individuals based on their facial features; and scene reconstruction, where robots create 3D models of their surroundings from visual data. Computer vision plays a vital role in enhancing the robot's awareness, enabling it to interact effectively with its environment and make informed decisions [12].

Embedded systems in robots include either microprocessors or microcontrollers enable communication between hardware components and sensors and control movement and interaction with the external environment [13]. Real-time embedded systems used in the biomedical field include computer systems that interact with sensors, actuators, and input and output interfaces [14].

Robotic hardware includes microprocessors or microcontrollers, sensors, actuators, and electric motors that transform electric energy into mechanical energy for the movement and rotation of components, communication devices that transfer data between input and output devices, and control devices that control all the hardware components of the robot [15, 16].

Artificial intelligence (AI) systems reflect the ability to perform tasks such as learning, problem solving, and decision-making by processing data [17]. When AI is integrated into robotics, it enables the decision-making capabilities of the robot, which in turn improves the performance of the robot [18, 19]. Artificial intelligence-enabled robots use computer vision, sensors, and machine-learning techniques to process large amounts of data gathered from the external environment and make decisions at a faster pace, mimicking human capabilities [20, 21].

Robot modeling is classified into two major approaches: kinematic modelling and dynamic modelling. In kinetic modelling, general kinematic equations are used, and controllers tend to develop more easily [22, 23]. Dynamic modelling involves controlling the torque and forces where controllers will be more accurate but also complex and prone to errors.

The process of developing fully functional robots consists of identifying a need, designing the structure of the robot, developing a prototype, integrating-hardware and software components, and testing and deploying robots in the actual environment [24]. The initial phase starts with the design phase, which is accomplished using software tools such as Fusion360, SolidWorks, and Catia, which helps us to visualize the structure of robots and simulate their movements. The structure of the robot can also be visualized by feeding the output from the aforementioned software tools through 3D printing technologies. The second phase involves simple to complex programming using languages such as C++ and Python, which helps communicate with the hardware [25]. In the third phase, software is integrated in the robot embedded systems that contain microprocessors or microcontrollers to perform the desired operations. The fourth phase includes the assembly of control devices and boards to receive the process, send the data, and control various robotic hardware components. Once the robot is developed, it needs to be tested in the actual environment to see if the desired goals are met, and any deviation or error to be recorded and rectified during the test phase. After the successful deployment of the robot, its function was monitored regularly for any improvement or correction in the course of action [26].

Classification of Robots

Different types of robots, such as pre-programmed robots, autonomous robots, remote-controlled robots, and augmented robots, have been developed to perform specific tasks:

a. **Pre-programmed robots** perform specific, repetitive tasks in controlled environments [27, 28]. Examples of such robots include robots in automated production lines and robots that are used to provide radiation for treating tumors in cancer patients.

b. **Autonomous robots** perform tasks with little or no human intervention by interacting with the external environment on their own through AI capabilities. Autonomous vehicles and cars are examples of autonomous robots [29]. A Smart Tissue Autonomous Robot (STAR) is another example of an autonomous robot used in the medical field that performs surgery with the help of computer vision, machine learning, and robot controls [30, 31].

c. **Tele-operated robots** are robots that carry out tasks based on the control given from remote places, such as space robots and tele-operated surgical robots, wherein the surgeon performs the surgery on the patient from a remote place through a surgical robot [32, 33].

d. **Augmented robots** are fitted to parts of the human body, such as arms or legs, which help the user carry out tasks with ease and accuracy, such as surgical robots and prosthetic arms or legs [34, 35].

Robots can be categorized according to their degree of autonomy, application domain, structure, and functionality. It can be classified as industrial, service, medical, military, or space robots based on their functionalities. While service robots carry out non-industrial duties like housework, customer support, and security monitoring, industrial robots are mainly utilized in production and assembly lines for jobs like welding, painting, and material handling. Robots are divided into four structural categories: soft robots, humanoid robots, mobile robots, and articulated robots. Mobile robots include wheeled, legged, or airborne robots made for navigating in a variety of situations, whereas articulated robots include rotating joints and are frequently employed in automation.

While soft robots, which are composed of flexible materials, are employed in sensitive activities like medicinal applications, humanoid robots are designed to resemble humans in look and movement, making them appropriate for human interaction. From an application standpoint, robots are used in space exploration, healthcare, agriculture, logistics, and defense, each of which is suited to particular operating requirements. Robots can have three different levels of autonomy: teleoperation, semi-autonomy, and full autonomy. Semi-autonomous robots occasionally need human input, teleoperated robots are completely controlled by human operators, and fully autonomous robots use artificial intelligence to make decisions without human interaction. This classification offers a foundation for comprehending the wide range of robot applications and capabilities across multiple domains.

Robotic Applications in Biomedical Domain

Different types of robots find applicability in biomedical domain (Figure 1).

Surgical Robots

Advancements in Artificial Intelligence and computer vision enable surgical robots to assist surgeons in performing minimally invasive procedures with high accuracy and speed. Surgical robots are usually divided into autonomous and tele-operative robots [36-38]. Surgical robots with robotic arms, computer vision, and embedded Artificial Intelligence techniques can assist surgeons in performing laparoscopic operative procedures through smaller incisions. It also helps surgeons to predict and analyze the surgical environment and provides constant feedback to surgeons regarding the actions performed. Surgical robots are used for specific orthopedic surgical procedures such as knee or hip replacements. When operating on soft tissues, surgical robots perform with great accuracy and ease and also reduce complications during surgery. One of the widely used commercial surgical robots is the da Vinci robot, which has assisted surgeons in performing nearly 12 million surgeries during the last three decades [39,40-43].

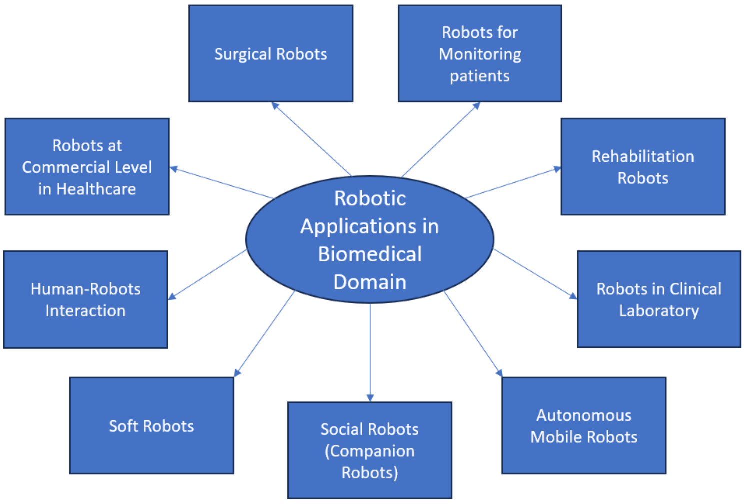

Figure 1. Different types of robot applications in biomedical domain

Robots for Monitoring Patients

Robots help clinicians monitor the status of chronic patients, thereby reducing manual intervention. It helps patients recover from chronic diseases or severe injury through constant monitoring and tracking of their progress until they reach normal levels of physical operation and capabilities [44-46]. The DR Spot robot from Boston Dynamics helped clinicians measure vital signs during the COVID 19 pandemic and reduced exposure to infections at the Brigham and Women's Hospital [47].

Rehabilitation Robots

Rehabilitation robots help overcome disability through assistive devices such as AI-enabled wheel-chair, artificial limbs and organs, prostheses, and exoskeletons. It also helps elderly people perform their routines with more comfort [48-51]. Examples of rehabilitation robots include the University of Michigan's SepaRRo—Semi-Passive Rehabilitation Robot, which helps to guide the patients' intended motion through controllable breaks, and The Activities of Daily Living Exercise (ADLER) therapy robot, which helps patients to recover after stroke through physical and neurological rehabilitation [52,53]. In addition, a wearable robot helps avert freezing of gait in patients with Parkinson's disease [54].

Robots in Clinical Laboratory

Robots in laboratories help automate repetitive and time-consuming processes. This helps us handle hazardous substances and chemicals. It also helps us perform clinical laboratory testing with greater speed and accuracy [55]. ESSERT robotics used in clinical lab settings perform lab sample movements within laboratory machines, testing and data acquisition of the sample, and handling reagents.

Autonomous Mobile Robots

Autonomous Mobile Robots help simplify routine tasks and carry out tasks with consistency and the desired level of accuracy in the areas of delivering medicines and specimens, automating ordering of monitoring stock level, and ordering of materials at the right time [56]. AMRs also help the hospital environment to be free of infections and maintain cleanliness at all times. AMRs fitted with sensors, 3D cameras, and Artificial Intelligence capabilities can be used to plan collision-free navigation within a hospital environment [57,58].

Soft Robots

Soft robots are one of the most discussed recent advancements in the biomedical field and will take some years to achieve their full objectives, as some of the challenges with respect to the safety of the human body need to be addressed [59,60]. Soft robots can be used in any environment, including the human body, unlike traditional robots, which are best suited to work in specific environments such as industrial settings and flat surfaces. Soft robots are made of flexible materials and do not contain rigid joints compared to traditional robots. Soft robots are designed such that when they are inside the human body, they do not cause damage to human cells or other parts of the body [61]. The successful design of soft robots depends on modelling their behavior, controlling and inducing their movement, and fabricating the robots with suitable materials [62,63]. The current challenges lie in providing a power source for its operations, free movement, and the trade-off between the size of the robot and its functionality. In addition, the types of fabrication materials used to satisfy different constraints with respect to human muscles, such as density and stress

Human – Robots Interaction

Robots are used to facilitate communication between healthcare workers and patients, record data, alert emergency staff, in an emergency and monitor patient status [64]. A rapid increase in the number of robots in the health-care domain occurred during the COVID-19 pandemic outbreak.

Robotic Application at Commercial Level in Health Care

The actual application of robotics is possible only when it reaches commercial-level applications [65,66]. Table 1 provides details of some commercial robotic applications in health-care. The costs range from $6000 USD (PARO Therapeutic Robot) for individual-assisting robots to $1.25 million USD (Xenex Germ-Zapping Robot) or $2 million USD (da Vinci ® Surgical robot) for those used in hospitals.

Conclusions

Robotics has significantly advanced the biomedical field, revolutionizing various healthcare applications such as surgery, rehabilitation, diagnostics, and drug delivery. Surgical robots have enhanced precision and minimally invasive procedures, while rehabilitation robots have improved mobility and recovery for patients. In diagnostics, robotic systems enable early disease detection and real-time monitoring, and soft robotic technologies are paving the way for safer drug delivery and personalized treatments.

The integration of robotics in healthcare has led to increased efficiency, accuracy, and patient outcomes, reducing human error and enabling more consistent medical interventions. The rise of artificial intelligence, computer vision, and machine learning has further enhanced robotic autonomy and adaptability. However, challenges such as high costs, accessibility limitations, regulatory hurdles, and ethical concerns regarding human-robot interaction need to be addressed for broader implementation.

Looking ahead, advancements in AI-driven automation, miniaturization, and bio-hybrid robotics are expected to drive the next wave of innovations in the biomedical domain. Future research should focus on improving robotic decision-making, enhancing patient safety, and developing cost-effective solutions to make these technologies more widely accessible. Moreover, interdisciplinary collaborations between engineers, medical professionals, and policymakers will be crucial in shaping the future of robotic healthcare applications.

Table 1. Commercial robotics applications in health care.

Name of the robotic application	Company	Description	Follows Medical Device Regulation (MDR)
da Vinci ® Surgical robot	Intuitive Surgical	The robot gives the 3D vision and control to Surgeons and performs surgical incision with precision	Yes
Vicarious Surgical's Robotic System	Vicarious Surgical	Help surgeons helps to conduct minimally invasive procedures through a console and arms	Yes
Robot "IRIS 3200 UV-C	Infection Prevention Technologies	It uses Ultra Violet light to disinfect the whole room in lesser time	No
Xenex Germ-Zapping Robot	Xenex Disinfection Services	Hospital cleaning robotic system which clears infectious bacteria through Ultra Violet rays	No
PARO Therapeutic Robot	PARO Robots	Interactive device acts which help elderly patients with dementia to reduce stress and anxiety	Yes
CyberKnife	Accuray	Robot helps to provide radiotherapy for treating tumors and it also reduces risk of radiation to healthy tissues in the body	Yes
TUG	Aethon inc	Acts as a transport system to supply materials including food items, lab samples and removes waste in the hospital	No

As robotics continues to evolve, its role in transforming medicine and patient care will only expand, offering new possibilities for precision treatment, enhanced rehabilitation, and intelligent healthcare solutions. The future of biomedical robotics holds immense potential to redefine modern medicine, making healthcare more efficient, personalized, and accessible on a global scale.

List of Abbreviations: Not applicable.

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Conflict of Interest: The author declares no conflict of interest.

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