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Design of Robot Manipulators and Functional Classification of Medical Robots

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Abstract— **This paper intended to conduct research based on medical robotics, which fundamentally couple information to enhance the performance of human abilities significantly, in this case, surgical interventions, rehabilitation, or simply helping differently-abled people perform daily tasks. This research work aims to comprehend principal concepts in medical robotic designing, analysis, and real-time control of robotic systems within the context of medical applications. Extensive research on telerobotic systems and their applications in robot-assisted minimally invasive surgery/telesurgery is a major aspect of this research. The core aspects focus on the application, functionality, and theoretical aspects of interactive robotic technologies in medicine. Surgical, physiotherapy, and neuro-rehabilitative robotic systems are significant outlooks of medical robotics. Technological aspects, such as instrumentation, mechanisms, imaging, and simulation, were conducted using MATLAB and Webot software. Simulations using software usage was focused on designing robotic medical models and differentiated using functional classification. Three-dimensional robots with better dexterity and degree of freedom were simulated using Webot software. This research work proposes new approaches of augmented reality aiding medical surgeries whereby three-dimensional visualization of organs is detailed as the future of medical applications. Robotic Kinematics and algorithms are studied in detail when designing these robots on CAD/CAM. Comparative studies based on already implemented medical robots were also conducted. The functionality, drawbacks, ethical issues, and consents of patients are comprehended in detail in this research.**

Keywords— **Tele-robotics; neuro-rehabilitative robotics; functional classification; medical robotics.**

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I. INTRODUCTION

Artificial intelligence has revolutionized and transformed the role of a doctor in the field of medicine. This has brought about a drastic change in the health sector with the new emerging technologies and fast-paced equipment's. Introduction to robotics is a prime sector of artificial intelligence. It analyses diagnosis with utmost accuracy making doctors' life much easier. The advent of medical robotics has brought about a paradigm shift in therapy and surgical procedures. The medical field is reconsidering replacing standard procedures with robots. These robots can perform various tasks such as creating lab reports, hospitality, and even helping doctors perform surgeries. There is always a limitation for human beings, as they would not be able to reach every patient on time. Hence to combat their workload, mechanized robots can make every hospital pace much faster to address the patients effectively and efficiently. This paper would bring approaches of robotic design suitable to the medical field and how it can be implemented in different sectors of a hospital [1].

Medical Robots can be designed with different components depending upon the specification of usage and the medical field its associated. They can be characterized and differentiated in terms of forms and construction. The fundamental units used in designing a medical robot are Controller Unit and Manipulator [1]. The Manipulator is the most important part of a robot as it decides the degree of freedom of the arms and legs of the robot. It primarily helps to perform actions. This unit has various sensors joints and is called the driving system of a robot or effector.

The sensor system primarily helps motion in the robot, along with that they gather other data such as camera images and data acquisition of distances from the patients. Once the information is gathered, it is sent to the controller unit for robotic actions. A medical robot is usually controlled using consoles, joysticks, or remotes, which perform function synchronously. The process of controlling robots in this manner is called telemanipulation control. Any design robot change can be altered using this method, whereby the robot's programming language can be altered for other desirable movements and functions [1], [2].

Robotic parts can be classified into two main parts. *Effectors* are devices that control, including legs, arms, wings, and fins. The controllers cause effective action of the effectors. *The actuator* comprises devices that usually include electric motors. They control the degree of freedom of the effectors. They determine how many degrees of freedom a robot can effectively perform a task when programmed. Usually, robots have 6 degrees of freedom. Three are used for translation among the axis, and three are used for rotation and orientation purposes [2].

Robot manipulators are studied using two concepts. *Kinematics*: The study of Kinematics helps design the robot manipulator's controller. *Dynamic study*: This study is conducted to understand the robot's behavior. It identifies dynamic factors which affect the system behavior [3]. A robot has been programmed in a way to perform various tasks. They have been designed with a brain, body, power supply, actuators, controllers, sensors, and manipulators. These parts coordinate to act. The brain coordinates the robot's actions. Actuators perform total robot body motions based on the electrical parts. Sensors give commands in the form of robot information, and the power supply ensures all the parts of the robot are supplied with power [2], [3].

II. Materials and Method

This section focuses on methods, design, and materials used for simulation purposes. This dissertation discusses the proposed framework, design considerations, and software methods. An insight to CAD modeling of robotic simulation along with augmented reality operational procedures are comprehended using various mathematical factors of medical robotics [4].

A. Proposed Framework

The process of simulation follows a framework of procedures. The first step involves loading the robot on MATLAB. Different robotic models are available in the interactive rigid tree tool. This tool helps to design different robotic models with distinct functionality. The second step involves adding constraints or programming motions to each effector, such as legs, arms, or waist. Once programmed, the third step involves running the program to perform the motion. A similar robotic model was simulated on Webot software, where we used nodes to physical input designs of the robot as the first step. The second step involves programming using any convenient language such as python or C programming. The third step involves running the program for robotic motion [4].

B. Design Considerations

Two main software used in this project are

1) MATLAB: This tool is used for designing the autonomous robotic device. This software has a robotic system toolbox that helps to simulate different robotic models with functional comparison [4].

2) WEBOT: This 3D software is used to design a multi-axes robot model, which performs motion like a real-time hardware model. The robotic devices are created like a 3D CAD model, which can be mechanically implemented [5].

3) *System Design Factors:* A system is designed based on three main factors, which are important for design consideration [4][5].

- *Stability*: A system to be stable should always have a bounded input and bounded output.
- *Robust*: Any external disturbances should not affect the system output. Hence any system should always be robust to any external noise.
- *Reliability*: This factor decides the life expectancy of a medical robot and how many performance hours it can withstand to act.

C. CAD Modelling of Robots

Computer integrated systems are used in surgical planning. The patient's basic information, such as diagnosis, has been fed into the system from the consultation. This includes the anatomy of the patient, past diagnosis and history, image evidence such as x-rays CT scans. Depending on this information, preoperative planning for surgery has been decided. The accuracy of this information is a key factor before proceeding with surgery. Hence, a computer model of the patient is being generated, known as the surgical CAD/CAM [6].

D. Teleoperation Control Robots

Many Robots are teleoperated and have hands-on control mode. The major disadvantage of this method is that operating this mode requires large bulky equipment, and the surgeon cannot control the robot with any console form. These robots perform mechanized fixed work accurately [6].

Surgeons should always have access to these mechanized robots, which is a major limitation in teleoperated robots [6]. Though they eliminate human error and define greater precision, they only perform an already programmed task with no combat methods to emergencies. The major advantage of teleoperation control robots is their dexterity and flow of motion [6].

E. Augmented Reality Operational Procedures

Augmented reality display 3D visualization of the affected organ. This helps a surgeon touch the affected area with a robotic arm and view the body's internal organs. The new invention of laser pointers helps in surgical procedures immensely. Augmented reality changes the perspective of relying on X-rays and CT scans which have to be done on a prior basis by the patient. This consumes much time, resulting in a 2D visual image [7], [8].

- Mainly, it focuses on visualizing the patient's internal organs using robot manipulators.
- Robots designed should have a software system linked with hardware to perform certain tasks [7], [8].
- MRI compatible robots usually have a two-interface system as it uses an image-guided diagnosis. Fig 1 shows the surgical process using augmented reality.

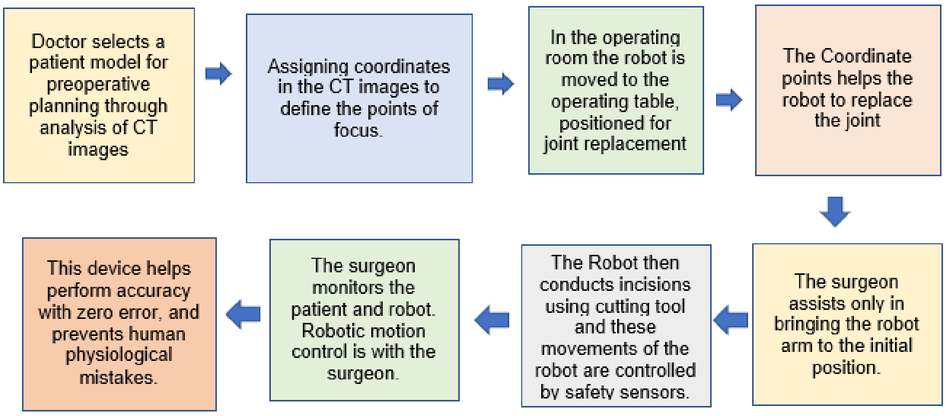

Fig. 1 The augmented surgical process using robotics

F. Dynamics and Kinematics behind Robot Control

1) Direct Kinematics (Forward Kinematics): The main principle behind Robotics is the study of Kinematics. This study mathematically drives robots according to how we want to design. Forward Kinematics deals with the calculation of the position of the end effector. These end effectors are usually joints, which can perform the motion. Kinematics determined the position, speed, velocity, acceleration of each joint. When designing robots, the factors of Kinematics and its constraints should be kept in mind during design considerations [9].

2) Inverse Kinematics (Reverse Kinematics): Inverse Kinematics usually conducts reverse motion, and joint values are attained for given end effector values. This study is important for path planning for trajectory. It gives importance to preventing meaningful events such as avoidance of collision, Preventing repeated motion due to computer error [9].

3) Direct Dynamics of Robots: This study helps in the calculation of accelerations. This factor depends on applied external forces. Direct Dynamics helps to conduct computer simulations [9].

4) Inverse Dynamics of Robots: This dynamic helps to improve the calculation of actuator forces. Actuators usually include electric components such as sensor and piezoelectric components. These calculations help in administering end effector movements [9].

5) Links and Joints in a Robot: Robots are made of several links, mainly input and output links. One link can produce only 1 degree of freedom always. Links are interconnected by joints and are the most vital aspects of constructing a robot. They are rigid segments of a robot that are moved when joints are in motion [10].

G. Robotic Motion Classification

1) Radial Transverse: The forward and backward motion in the Y-axis direction is known as Radial Transverse. The Retraction of the robotic arm always be radial. Fig 2 depicts the number of links that form a joint in a manipulator [11].

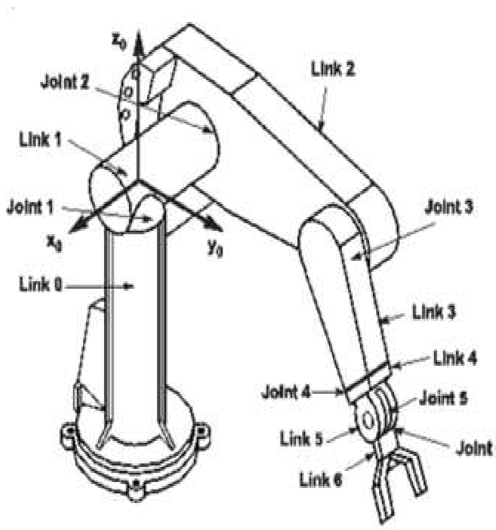

Fig. 2 Links and Joints of a manipulator

2) Rotational Transverse: This is the motion around the X-axis, which is always rotational. Rotational motion and radial motion are the only two kinds of movements for the architectural design of robots [12].

H. Types of Joints used in Robots

There are different types of joints used in a robot. They are listed below:

1) Linear Joint: These types of joints perform sliding and translational motions. Telescoping mechanism and piston are the two ways. For achieving linear motion, the two links of the joint should be in parallel axes [12].

2) Orthogonal Joints: The output and input links of the joints move at right angles. They help in the rotational motion of joints [12].

3) Twisting Joint: This joint provides twisting motion between the output and input links of the joint. The output link here is dependent on the input link. This is similar to revolving joints.

4) Revolving Join: This joint has the output link orthogonal or perpendicular to the rotational axis. At the same time, the input link could be parallel to the rotational axes.

I. Dynamics of Robotic Motion and Mathematical Concepts

Robotics are characterized by many mathematical concepts involving linear algebra, calculus, and matrices. A robot is assigned a particular coordinate system once designed. Fig 3 depicts the coordinate system of a manipulator [13], [14]. In order to perform the action, each robot changes its coordinate system, according to the command program. Fig 3 explains three important parts of a robot manipulator arm: Head, Base, and Piece.

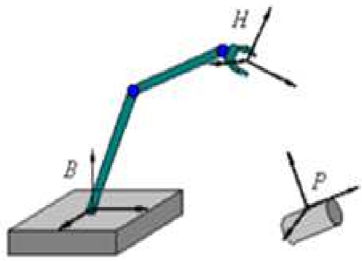

Fig. 3 Coordinate system of a robot manipulator

The systems are integrated so that any changes in these three coordinates systems change the orientation of the robot. Every Orientation and position can be accurately computed using mathematical analysis. Usually, matrices are used for calculation purposes to obtain the endpoints of the head, base, and piece. Fig 4 Interprets the transformation matrix, and Fig 5 depicts the calculation of endpoints using transformation matrix [13], [15]

$$\begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

Fig. 4 Interprets transformation matrix for calculation of endpoints

$$\begin{bmatrix} 0 & -1 & 0 & -4 \\ 1 & 0 & 0 & 5 \\ 0 & 0 & 1 & 2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} = \begin{bmatrix} -4 & -4 & -5 & -4 \\ 5 & 6 & 5 & 5 \\ 2 & 2 & 2 & 3 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

Tranformation matrix

Fig. 5 Interprets calculation of endpoints by using the transformation matrix

III. RESULTS AND DISCUSSION

A. Types of Medical Robots used in MATLAB Simulation

1) Surgical Robots: These robots are used in minimally invasive robotic surgeries. The first implemented surgical robot is the Da Vinci System. This robot mainly focuses on conducting or assisting surgical procedures with a doctor. This robot has been introduced in specialized fields such as urological and gynecological surgical procedures [15], [16]. Fig 6 displays the simulation model of a surgical robot designed on MATLAB.

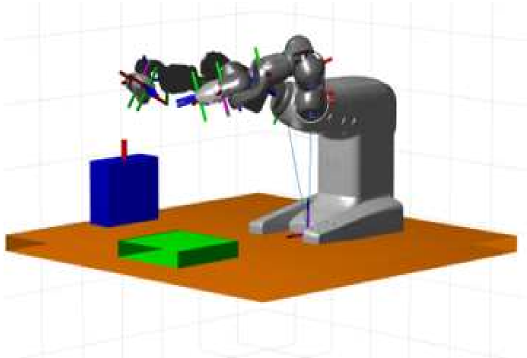

Fig. 6 Surgical Robot Simulation

2) Care Robots: This type of robot is used for support in all purposes, such as physiotherapy. These robots also help elderly and disabled patients by assisting them in conducting their daily routines. Care robots also act as a telerobot where they remind patients to take their medications on time and provide emotional support and counseling to people lacking human interaction. They assist nurses in taking blood tests, checking the patient's temperature, and delivering medications on time. The implemented care robot in Japan is known as Paro [16]. Fig 7 displays a simulation of a care robot with interactive markers assigned to the effectors.

Fig. 7 Care Robot Simulation

3) Hospital Robots: Due to Covid 19, most hospitals require disinfection regularly. These robots are designed to disinfect hospital devices and various medical equipment. A robot called Xenex can disinfect a patient's room in twenty minutes. This robot has been implemented more effectively after the rise of the pandemic [17], [18]. Fig 8 displays the design of a sterilizing robot simulated on Webot.

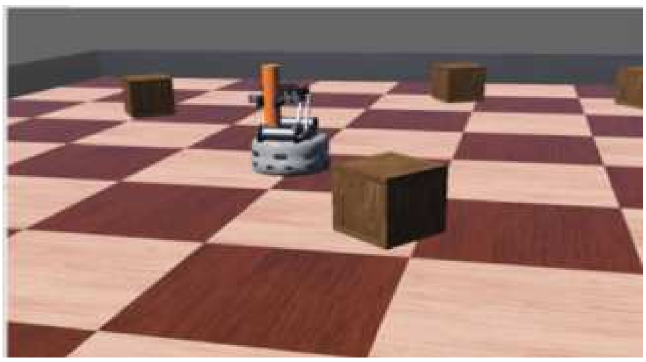

Fig. 8 Simulation of a Sterilizing Robot

B. *Automated Understanding of Human Behavior*

There should be personalized robots that understand and recognize patients' emotional states. Emotions have been identified by speech or vice signals. The robot would observe facial expressions and acquire that data to store in the system. To understand emotions, the system requires perception. The robots can identify physiological data such as fatigue, tiredness, emotional imbalance etc [19]. To identify these factors, there are devices such as wearable sensors, wireless devices used for data transmission [19]. These devices help diagnose, treat, and prescribe the right medicines.

C. *Robot Assisted Recovery and Rehabilitation*

Patients are provided with personalized monitoring and coaching system. They also have wearable sensors, cameras, and other means by which robots perceive information. Using Neuro-rehab robots can help stroke rehabilitation and recover other traumatic brain injuries [20]. Instead of many often-labor-intensive therapists, robots deliver the same therapy. The doctor needs to provide only external supervision for setting up the device. The devised robots can also measure the patient's progress following the treatment [21]. The device always works according to the patient's need; if the patient encounters prolonged pain, the patient can communicate with the robot. The robot is programmed to understand the patient's language and stop the device from functioning temporarily [21].

D. *Image-Guided Intervention for Analyses of Various Factors*

- Mainly, it focuses on visualizing the patient's internal organs using robot manipulators.
- Robots designed should have a software system linked with hardware to perform certain tasks.
- MRI compatible robots usually have these two-interface system as it uses an image-guided diagnosis [22].

E. *Personal Care for Special Needs or Determined People*

There are differently abled children or congenital issues for kids where many treatments can be done [23]. The robots are designed in a different way, such as:

- Autonomous walkers
- Autonomous wheelchair

These devices provide ease to the patient as well as a mechanical aid to the people who cannot walk or conduct routine activities [23].

F. *Robotic Neurorehabilitation*

Physiotherapy requires two people minimum to assist a patient with various therapies. The problem arises when there are shortages of people, where the whole process becomes time-consuming. Robotic therapists come to great help due to their increased dexterity and productivity. Robots can save time and help monitor and control various joints' speed to perform a task better. These same robots can be used in rehabilitation, too [24].

The robots can perform the following tasks:

- Spinal injuries
- Cerebral injuries
- Brain accidental injuries

Neuro-rehabilitative robotics primarily focuses on optimizing a person's well-being in society. The mental well-being of a patient is focused on when introducing these robots. People in this world face cognitive and physical difficulties; hence, rehabilitation systems become necessary to treat such patients. Neuro-rehabilitative systems focus on implementing a few important systems [24].

- Systems designed to help differently abled people in their day to day lives and activities.
- Systems crafted and designed in such a way, ameliorates the cognitive and emotional functions of the brain.
- Systems to assist in physiotherapy, for people who underwent surgeries.
- Efficient Prosthetic devices used in surgeries [25].

G. *Rehabilitation Process*

1) Assessment: The first step involves collecting data from the patient whereby the history of the patient's diagnosis is collected, and different problems, factors and severity of the impairment are measured before the curation [25].

2) Impairments: The patient's joints and muscles are assessed further to investigate the cause of the impairment. The primary cognitive functions are tested, such as movement, balance, memory, response to a stimulus. The impaired parts need to be investigated if it has an influence over neuro-related functions [25].

3) Activity: A therapist could assess the improvement of the patient and the response to rehabilitation techniques. According to their improvements, the therapist could review and advise what changes can be made to their lives [26], [27].

4) Participation: This is the most important factor of physiotherapy, whereby patients are supposed to participate in activities assigned to them. There would be activities related to memory balance where all these senses can be evoked with such mental activities performed. These activities help people recover from stroke and other health conditions [27], [29].

H. *Treatment Planning of Neurological Department*

Rehabilitation treatment involves the SMART rule, which [28] is as follows:

- Specific
- Measurable
- Achievable
- Relevant
- Time-limited

The treatment plan assigned could include the following:

- Different kinds of approaches can cure disabilities specific to the patient [29].
- New strategies developed to maximize the productivity
- Approaches that address the patient to bring social well-being.
- Sufficient Counselling to emotionally down patients.

I. *Specific Methods for Intervention*

These methods focus on many prescribed therapies such as [30]:

- Speech Therapy
- Cognitive Behavior Therapy

- Language Therapy
- Treatment specific for Depression and Anxiety
- External Stimulus Treatment such as environmental change for the patient's mental well-being.

J. Evaluation of Improvement

Based on the SMART objectives defined above, the patient's condition is compared. If the patient has shown sufficient improvement from a clinical point of view, only then the patient could be discharged. At some times, none of these treatments work, so patient-centric customized approaches are taken as treatments. These are usually used in diseases such as Parkinson disease and Alzheimer [31].

K. Behavioral Therapy

Cognitive Behavioral Therapy is a treatment for patients with the following [31]:

- Anxiety
- Stress
- Depression
- Post Traumatic Disorders
- Cognitive disorders

SAR is a new robotic technology that assists users using interactive social tools. This robot can understand every possible emotion communicated by the patient. Socially Assistive Robots (SAR) are therapeutic for many disorders for children, too [31].

L. Surgical Robotics

The most successful surgical robot implemented today is the Da Vinci surgical robot. It has a teleoperation mode controlled by the surgeon and a sub slave robot that operates on the patient. It performs every form of the abdominal procedure with utmost precision, but the system generally lacks the fact that it is too bulky for convenient usage [32], [33].

M. Minimally Invasive Surgeries

This term is a very important aspect as concerned with surgery. A minimally invasive surgery means lesser time for hospitalization for the patient. At the same time, it involves less scarring and incision on the skin. This type of surgery reduces the risk of blood loss and excessive infection [33].

N. Robotic Surgical System

The surgeon makes tiny incisions in the desired part of the body which has been diagnosed with a problem. The doctor inserts the robotic system with a camera in the body. The surgeon then sits down with a console connected to a computer that visualizes the internal organs [34]. He would be able to zoom the suspected parts and stop the robot motion [34]. The magnified image can be viewed with great resolution and clarity on the computer.

Depending upon the console's control, the robot translates this to precise motions inside the body [34]. There are places where surgeons manually cannot reach, whereas robots have greater dexterity to perform tasks accurately. The robot then performs the suturing of incisions to complete.

O. Benefits of Robotic Surgery

- High-Resolution images can be visualized
- Better accessibility to areas where a surgeon's hand cannot reach [35].
- The patients could recover at a faster rate
- No manmade errors during the surgery
- Loss of blood is less as incisions are precise.

P. Ethical Issues and Consents

Ethical systems need to be constructed when designing a robot. Many doctors quarrel about the fact that robots always have an emotional deception when contacting a patient. Security is of major concern to patients as people often lack a trust factor when robots are administered to each patient [10]. Robots should be kept in surveillance all the time while performing any kind of surgery. The doctor should not misuse the operating console. At the same time, the doctor should be well trained to use the console. Many people in the professional field often debate the exploitation of robots. Such manipulation can risk the lives of patients, and at the same time, the credibility of such hospitals is seriously affected.

There are more political propaganda of hospitals using the wrong technology. They believe that digital transformation from doctors to robots could not bring adequate healthcare treatment to patients. Emergency situations cannot be administered by robots, which are again a concern to people. The wrong treatment would lead to fatalities Patients in such a situation refuses to give consent because they believe that their life is at risk at the hands of a robot. Businesses often do not want to invest in medical robotics, because of consents and complications associated with patients' refusal. Unemployment could be rampaged when robots are introduced into the health sector. The profession as a whole would seem to be irrelevant in the future. Stakeholders and investments in robotics are huge, and the contemplating facts are whether they are necessary or managed by professional doctors.

IV. Conclusion

Robotics in medicine is the most revolutionary discovery that set a benchmark for the health sector. When many in-patients are present, robots can handle them for long hours without any stress and strain. Doctors can handle many situations without any hassle and can ensure the administration of all patients for effective diagnosis and treatment. Though consents and ethical issues seem to be a concern, with the onset of Covid 19, the field of AI has increased in its scope tremendously. Patients in the future need to get used to such digitalization so that the healthcare sector can also see massive development. This paper intended to support and implement the new prospects of medical robotics in the field of artificial intelligence. The eight simulations gave a comprehensive understanding of the software implementations of robots, which are very real in nature. These simulations can be implemented using constructive equipment in real time. Patient-effective analysis is more accurate than professional doctors, handling an emergency. If we look at the boon of this new invention, the points to share are many. Though existing, the cons of this new field are comparatively less compared to the advantages of medical robotics.

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