Robotic Arm Concept for Surgery: Integrating of 3D Printing and IoT Technologies

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Abstract

The development of robotic surgery has introduced significant advancements in medical procedures, yet challenges remain in achieving precise control and tactile feedback. This paper presents the design and implementation of a novel robotic manipulator arm, developed using principles from bionic prosthetics and enhanced by modern technologies such as 3D printing and IoT. The proposed system integrates tactile feedback mechanisms and intelligent control features, making it highly responsive and user-friendly for surgeons. The robotic arm's anthropomorphic structure and the use of high-performance micro-motors enable natural and precise movements, closely mimicking human hand functions. Additionally, the implementation of artificial neural networks in the feedback loop enhances movement coordination, accuracy, and speed. This innovative approach promises to reduce the cost of production while significantly improving the efficiency, safety, and effectiveness of surgical procedures. By leveraging IoT technologies, the system offers enhanced connectivity and real-time data analysis, further optimizing surgical outcomes. The advancements presented in this paper represent a substantial improvement over existing robotic surgical systems, providing a valuable tool for modern healthcare.

Keywords

Robotic surgery, robotic manipulator arm, bionic prosthetics, tactile feedback, 3D printing, IoT, surgical technology, precision control, intelligent feedback mechanisms

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1. Introduction

Robotic surgery represents a significant advancement in medical technology, providing unprecedented precision and minimally invasive solutions for complex procedures. Central to this innovation is the robotic human hand, an intricate device designed to emulate the dexterity and functionality of the human hand. The integration of high-performance micromotors is crucial in these systems, allowing for precise control and movement essential for surgical tasks.

Research and scholarly articles have extensively explored the application of high-performance micromotors in robotic surgery, particularly within robotic prosthetics. These studies highlight key advancements and evaluate the effectiveness of these technologies, emphasizing their role in improving surgical outcomes and prosthetic designs. One line of research focuses on the development and implementation of soft robotic hands that leverage 3D-printed components and high-performance micromotors. This approach emphasizes creating functional and cost-effective prosthetic hands suitable for various applications, including surgical procedures. The practical use of 3D printing significantly reduces the weight and cost of these prosthetics while maintaining high functionality [1].

Another area of study involves the development of low-cost anthropomorphic robotic arm prostheses. These systems integrate advanced micromotors and control mechanisms to closely mimic human hand movements with high precision. This research underscores the importance of such technologies in enhancing the functionality and adaptability of prosthetic limbs, making them more accessible and effective for users [2]. Further investigations delve into the kinematics, statics, and dynamics of the human hand to provide a foundational understanding necessary for replicating these movements in robotic systems. Such research is crucial for developing surgical robots capable of performing delicate and precise manipulations, essential for complex surgical tasks [3]. Additionally, systematic reviews of current robotic surgery practices highlight the evolution of these technologies, focusing on the use of high-performance micromotors. These reviews offer insights into the impact of these advanced motor systems on surgical precision and training, showcasing their potential to revolutionize surgical practices. Collectively, these studies provide a comprehensive overview of the advancements in robotic hands equipped with high-performance micromotors and their applications in surgery [4]. They highlight the technological innovations, practical implementations, and significant benefits of these systems in enhancing surgical procedures and improving prosthetic designs.

Robotic surgery requires overcoming several technical and operational challenges to ensure successful outcomes. The key requirement is achieving a high degree of precision in surgical tasks, which is not always possible with manual operations alone [5-7]. This precision includes controlling the movement speed of surgical instruments, their precise positioning, and the force applied during procedures. Any deviation from these parameters can lead to suboptimal results or even complications.

To address these challenges, advanced technical systems are integrated into robotic surgery. These systems act as sophisticated extensions of the surgeon's capabilities, equipped with intricate control mechanisms. These control systems are designed to monitor and regulate the precision of movements, the speed of operations, and the force exerted by surgical instruments. By incorporating such technology, the overall accuracy and efficiency of surgical interventions are significantly improved.

There are currently two primary methods for controlling surgical instruments in robotic surgery:

1. Semi-Automatic Control – the surgeon directly controls a remote telemanipulator to perform the necessary surgical movements. The robotic arms execute the required actions, utilizing manipulators to carry out the actual operation and sensors to monitor and regulate the activities. One of the major advantages of this method is that it allows the surgeon to conduct operations without direct physical contact with the patient. This opens up the possibility of performing surgeries remotely, which can be particularly beneficial in situations where the patient and the surgeon are in different locations. This method enhances the surgeon's dexterity and control, minimizing the risk of human error and reducing the strain on the surgeon during long procedures.
2. Automatic Control – this approach involves the complete automation of routine and repetitive surgical procedures under the control of robots. These robots are pre-programmed to perform specific types of operations with high precision and consistency. The automatic method is particularly useful for high-volume, standard surgical procedures where consistency and repeatability are crucial. Robots can perform these tasks without fatigue, maintaining a high level of precision and reducing the risk of complications. This method also frees up surgeons to focus on more complex and critical aspects of surgical care, enhancing overall productivity and efficiency in the operating room.

The implementation of robotic systems in surgery brings numerous benefits. It significantly improves the precision and accuracy of surgical procedures, reduces the risk of human error, and allows for minimally invasive techniques that can lead to faster recovery times for patients. Additionally, robotic surgery can facilitate remote operations, providing access to surgical care in remote or underserved areas

2. Analysis of Well-Known Robotic Systems for Surgical Procedures: Advantages and Disadvantages

One prominent example of a robotic system used in surgical operations is the Da Vinci robotic-assisted surgical system. This system consists of two main components: the first is designed for the surgeon-operator, and the second is the robotic manipulator, which acts as the executive device. The Da Vinci system is utilized in hundreds of clinics worldwide [6]. One of the robot’s “arms” holds a video camera that transmits images of the surgical area, while two other arms replicate the surgeon’s movements in real time, and the fourth arm functions as a surgical assistant. The surgeon sits at a console that provides a 3D view of the surgical site with high magnification and uses specialized joysticks to control the instruments.

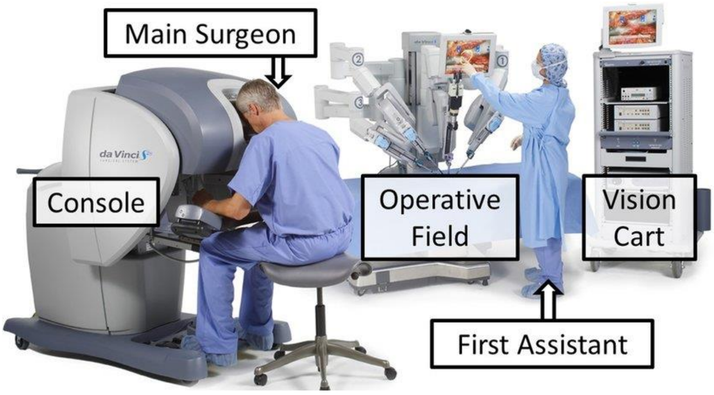

Figure 1. Surgery team with a da Vinci S R surgical robot [6]

Another example is the ZEUS system, which is similar in capability to the Da Vinci system but has several structural differences. The ZEUS system comprises a control console and three manipulator arms attached to the operating table. The right and left manipulators replicate the surgeon's hand movements, while the third, AESOP, is a robotic arm with voice control for navigating the endoscope. The control console features a monitor and ergonomically placed manipulators for controlling the surgical tools. The system allows for the use of both traditional laparoscopic instruments and complex tools with seven degrees of freedom.

Figure 2. ZEUS robotic system; first robotic system to combine instrument and camera control.

In general, robotic surgery offers several advantages, including minimal postoperative pain, reduced risk of wound infection, decreased need for blood transfusions, rapid recovery, and a short postoperative period. Additionally, robotic surgery minimizes the risk of complications common in traditional surgery and provides an improved cosmetic outcome due to the absence of large postoperative scars. It is worth noting that robotic surgeries are considered minimally invasive and can be performed through very small incisions (laparoscopic access), leaving only small marks on the body that heal quickly. Throughout the procedure, the robot remains under the full control of the surgeon and their assistants. The risk associated with the operation is minimized, and the patient typically has no postoperative scars.

Robotic surgery is gaining widespread acceptance globally, as the use of this technology can enable many procedures that were previously considered impossible. The precision, control, and minimally invasive nature of robotic systems significantly enhance the quality of surgical care, making complex surgeries safer and more effective. The advent of robotic surgery marks a significant technological innovation in the medical field, transforming the way surgeries are performed. Systems like Da Vinci and ZEUS not only enhance the surgeon's capabilities but also open new possibilities for complex and delicate procedures. These systems leverage advanced imaging, precise instrument control, and ergonomic designs to facilitate operations that demand high precision and dexterity. The integration of real-time imaging and feedback systems ensures that surgeons have a detailed and magnified view of the surgical site, improving their ability to perform intricate tasks. The use of robotic arms allows for greater flexibility and control, enabling surgeons to operate in tight and delicate spaces with unprecedented accuracy. This technological advancement reduces the physical strain on surgeons, allowing them to perform longer and more complex procedures with ease. Looking ahead, the future of robotic surgery holds even greater promise. Continuous advancements in artificial intelligence, machine learning, and robotics are expected to further enhance the capabilities of surgical robots. AI-driven algorithms could provide real-time assistance, guiding surgeons through complex procedures and predicting potential complications. Moreover, improvements in haptic feedback technology could give surgeons a more intuitive sense of touch, further enhancing their precision and control [8,9].

The potential for tele-surgery is another exciting prospect. With robotic systems, surgeons could perform operations remotely, bringing specialized surgical care to underserved regions and improving global healthcare access. As technology continues to evolve, the scope and impact of robotic surgery are set to expand, revolutionizing the field of surgery and improving patient outcomes worldwide. In conclusion, robotic surgery represents a significant leap forward in medical technology. By combining precision, control, and minimally invasive techniques, robotic systems like Da Vinci and ZEUS are transforming surgical practices and offering new hope for patients. As technology continues to advance, the future of robotic surgery looks incredibly promising, with the potential to make complex surgeries safer, more efficient, and more accessible to patients around the world.

However, this method also has certain drawbacks, with the primary one being the high cost of operations. This is largely due to the high cost of the robots themselves. The use of robotic systems has not been approved for cancer surgery, as the safety and efficacy of this method in such cases have not been conclusively proven. Some of the most significant disadvantages of robotic surgical systems in performing minimally invasive laparoscopic operations include the lack of tactile feedback, the restriction of the surgeon's movements by the technical capabilities of the working instrument, and the absence of three-dimensional imaging, which impairs coordination and reduces maneuverability. Addressing the first two limitations is the main focus of the proposed project. The high costs associated with robotic surgery are a significant barrier to its widespread adoption. These costs stem not only from the initial investment in purchasing the robotic systems but also from the ongoing expenses related to maintenance, training, and disposable instruments. Hospitals and healthcare providers must weigh these costs against the potential benefits of robotic surgery, such as improved patient outcomes and shorter recovery times. Economic considerations play a crucial role in the decision to implement robotic surgery. While the technology has the potential to reduce long-term healthcare costs by minimizing postoperative complications and reducing hospital stays, the initial financial outlay can be prohibitive. This is particularly challenging for smaller hospitals and clinics with limited budgets [10-12].

In the realm of cancer surgery, the safety and efficacy of robotic systems have not yet been firmly established. While robotic surgery offers precision and control, its effectiveness in treating cancer compared to traditional methods remains under scrutiny. The lack of conclusive evidence supporting the use of robotic surgery for cancer treatment means that regulatory bodies have not approved its use in this context. This highlights the need for further research and clinical trials to determine the potential benefits and risks of robotic surgery in oncology. The lack of tactile feedback is a major drawback in robotic surgery. Surgeons rely on tactile sensations to gauge the pressure and resistance they encounter during procedures, which is crucial for delicate tasks. The absence of this feedback in robotic systems can make it challenging for surgeons to perform precise movements, increasing the risk of inadvertent tissue damage. Additionally, the technical capabilities of current robotic instruments limit the range of motion available to surgeons. This can be particularly problematic in complex surgeries requiring intricate maneuvers. Enhancing the dexterity and range of motion of robotic instruments is essential for expanding their applicability and effectiveness in various surgical procedures. The absence of three-dimensional imaging further complicates robotic surgery. Surgeons often depend on 3D visualization to accurately perceive depth and spatial relationships within the surgical field. Without this capability, coordination and maneuverability are compromised, potentially affecting the accuracy of the procedure.

It is known that the anthropomorphic structure of the robotic arm and the use of high-performance micromotors provide natural and precise movements, closely imitating the functions of human hands, and the introduction of artificial neural networks in the feedback loop improves movement coordination, accuracy and speed.

The article [13] presents the results of a qualitative study of a neural network, including discrete and distributed time delays. A method for calculating the exponential decay rate for a neural network model based on differential equations with a discrete delay was developed and applied [14], [15].

When studying the properties of a robotic hand, the direction of using biosensors [16], [17] is promising, in particular for monitoring the health of the elderly or patients with special health needs [18]. An important characteristic [19] of different types of biosensors is stability [20]. Scientific studies [21], [22] provide examples of modeling sensor responses. Numerical modeling in cyber-physical biosensor systems [23-26] is important at the stage of their design.

The proposed project aims to overcome the primary limitations of current robotic surgical systems. By enhancing tactile feedback mechanisms, the project seeks to provide surgeons with a more intuitive and responsive interface, closely mimicking the sensations of traditional surgery. This would enable more precise and controlled movements, reducing the risk of errors. Improving the technical capabilities of robotic instruments is another critical objective. By expanding the range of motion and enhancing the flexibility of these tools, the project aims to offer surgeons greater control and maneuverability, making robotic systems more versatile and effective. Lastly, the project focuses on integrating advanced 3D imaging technologies into robotic systems. This would provide surgeons with enhanced visualization of the surgical site, improving depth perception and spatial awareness. Such advancements would facilitate better coordination and more precise surgical interventions.

3. Development of a Robotic Manipulator Arm for Surgical Applications

The project centers on the development of a sophisticated robotic manipulator arm, comprising both the robotic arm itself and a control console designed to operate the arm. The design of the robotic arm meticulously emulating the structure and partial functionality of a human arm.

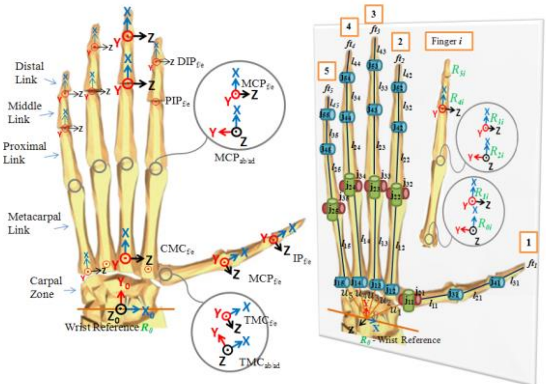

Figure 3. Kinematic configuration of the human hand. Thumb is defined by 3 links and 4 degrees of freedom whereas index, middle, ring and little are defined by 4 links and 5 DoFs [3].

The core components of the arm are proposed to be fabricated using advanced 3D printing technology, which significantly reduces the overall weight and cost of the arm [27]. The flexion of individual finger phalanges is achieved using a mechanism akin to traction prosthetics, which considerably simplifies the design and enhances the efficiency of the manipulator arm.

Figure 4. Prototype for the development of a robotic hand-manipulator based on shell models of traction prosthesis

This innovative approach ensures that the arm's movements are both precise and smooth, closely mimicking natural human movements. The control console is designed with an ergonomic focus to ensure user comfort during prolonged use. Like the arm, the console is also manufactured using 3D printing technology, which allows for customization and optimization of the console's shape and features. The console includes specially designated slots for five primary control elements—joysticks that are intuitively positioned to be easily accessible to the surgeon's fingers. This design enhances the surgeon's ability to control the arm with minimal effort and maximum precision. Additionally, the structure of the robotic arm, particularly each distal finger phalanx, incorporates designated areas for installing both dynamic and static load sensors. These sensors are crucial for providing real-time feedback and control to the surgeon. The corresponding actuators on the control console are of two types. The first set of actuators delivers tactile feedback based on signals from the dynamic load sensors, enabling the surgeon to feel the objects being manipulated. This feedback mechanism is essential for delicate tasks that require a high degree of precision and sensitivity. The second set of actuators restricts joystick movements based on signals from the static load sensors, allowing the surgeon to control the force and grip of the instruments effectively by sensing the pressure exerted on the joysticks. An integral component of this system is the SG90 servo motor, which offers several advantages, making it an ideal choice for various functions within the robotic manipulator arm: compact and lightweight design; high precision and reliability; cost-effective; ease of integration; widely available and well-supported.

By incorporating the SG90 servo motor, the robotic manipulator arm project can achieve a balance between high performance and cost-efficiency, making it a viable solution for both research and practical applications in fields requiring precise robotic manipulation:

- 3D Printing and Material Selection – the utilization of 3D printing for constructing the robotic arm and control console allows for customized designs that are lightweight and cost-effective. The materials chosen for 3D printing, such as high-strength polymers or composites, ensure durability and reduce the overall weight of the system, making it easier to handle during surgeries.
- Traction Mechanism for Finger Movement – implementing a traction mechanism for the finger phalanges mimics the natural movements of human fingers. This approach simplifies the design and enhances the functionality of the robotic arm, enabling more natural and precise manipulations during surgery.
- Ergonomic Control Console Design – the control console is designed with ergonomics in mind, ensuring that surgeons can operate it comfortably for extended periods. The layout of the joysticks and other control elements is optimized for ease of use, reducing fatigue and improving the surgeon's control over the robotic arm.
- Tactile Feedback and Sensory Integration – integration of dynamic and static load sensors in the robotic arm provides real-time tactile feedback to the surgeon. This sensory feedback is crucial for delicate surgical tasks, allowing the surgeon to feel the texture and resistance of tissues and instruments, thereby improving precision and control.
- Safety and Efficiency – proposed system not only improves the efficiency of surgical procedures but also enhances safety by providing precise control and reducing the risk of human error. The tactile feedback and adaptive control mechanisms enable surgeons to perform complex operations with greater confidence and accuracy.

Table 1 lists the specifications of the individual servos that can be used for the robotic arm, including model, torque, speed, operating voltage, overall dimensions, weight, and type.

Table 1

Characteristics of individual servos that can be used for a robotic arm

Model	Torque (kg.cm)	Speed (sec/60°)	Operating voltage (V)	Overal dimensions (mm)	Weight (g)	Type
SG90	1.8	0.12	4.8 - 6.0	22.8 x 12.6 x 22.3	9	Analog
MG90S	2.2	0.1	4.8 - 6.0	23 x 12.2 x 29.2	13.4	Analog
MG995	10	0.2	4.8 - 7.2	40.7 x 19.7 x 42.9	55	Analog
MG996R	11	0.19	4.8 - 7.2	40.7 x 19.8 x 42.9	55	Analog
DS3218	20	0.16	4.8 - 6.8	40 x 20 x 41	60	Digital
HS-311	3.7	0.19	4.8 - 6.0	40.6 x 19.8 x 36.6	43	Analog
HS-422	3.7	0.21	4.8 - 6.0	40.6 x 19.8 x 36.6	45	Analog
HS-645MG	9.6	0.24	4.8 - 6.0	40.7 x 19.8 x 37.5	55	Analog
DS3218MG	20	0.16	4.8 - 6.8	40 x 20 x 41	60	Digital
S3010	3.9	0.16	4.8 - 6.0	40.6 x 19.8 x 36.0	48	Analog

Moreover, artificial neural network elements are integrated into the feedback loop to enhance the coordination, precision, and speed of movements. Compared to existing designs of robotic surgical systems, the proposed robotic manipulator arm offers several significant advantages:

I. Anthropomorphic Design – robotic arm is designed to mimic the human arm, both in structure and functionality. This anthropomorphic design ensures that the robotic arm can replicate the natural movements of a surgeon's hand, without restricting their range of motion. This natural replication of movements enhances the surgeon's ability to perform delicate and complex tasks with greater accuracy and ease.
II. Intelligent Feedback Loops – inclusion of intelligent feedback loops, incorporating artificial neural networks, significantly enhances the coordination, precision, and speed of movements. These feedback systems allow the robotic arm to adapt to the surgeon's techniques and optimize its performance in real-time, providing a higher level of control and accuracy.
III. Enhanced Coordination and Precision – intelligent feedback systems and tactile feedback mechanisms work together to improve the coordination and precision of surgical movements. This ensures that the surgical procedures are not only accurate but also executed swiftly, reducing operation times and improving patient outcomes.

4. Conclusion

The presented prototype of the robotic manipulator arm represents a substantial improvement over existing robotic surgical systems. Its user-friendly design, integration of tactile feedback, anthropomorphic structure, intelligent feedback mechanisms, and cost-effective production make it a superior choice for modern surgical applications. These advancements promise to enhance the efficiency, safety, and effectiveness of surgical procedures, benefiting both surgeons and patients.

The development of a robotic manipulator arm with advanced control features and tactile feedback mechanisms signifies a significant advancement in surgical technology. By leveraging 3D printing, high-performance micro-motors, and artificial neural networks, this project aims to create a highly functional and cost-effective solution for robotic surgery. The integration of Internet of Things (IoT) technologies further enhances this system by enabling real-time monitoring, data collection, and remote control, which can improve coordination and precision during surgeries.

This innovative approach promises to enhance the precision, safety, and efficiency of surgical procedures, making it a valuable tool for modern healthcare. The use of IoT technologies also opens up new possibilities for remote surgeries and continuous performance optimization through data analytics, contributing to the ongoing advancement of robotic surgery.

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