DEVELOPMENT OF AN ALGORITHM AND SOFTWARE FOR PERFORMING ULTRASOUND STUDIES ON A SPECIFIC HUMAN ORGAN USING A ROBOT.

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Abstract. Ultrasound imaging is a widely used diagnostic tool in modern medicine due to its non-invasive nature, real-time imaging capability, and safety. However, the quality and consistency of ultrasound scans are highly dependent on the operator’s skill, which can introduce variability and affect diagnostic accuracy. This study presents the development of a robotic-assisted ultrasound system designed to autonomously perform scans on a specific human organ, minimizing operator dependency and enhancing reproducibility. The system integrates a six-degree-of-freedom robotic manipulator, motorized joints, sensors for real-time feedback, and an ultrasound imaging probe mounted on the robot’s end-effector. A control algorithm translates desired probe positions into joint movements while dynamically adjusting probe placement based on image analysis.

Keywords. Robotic-assisted ultrasound, ultrasound imaging, autonomous probe control, medical robotics, real-time image processing, diagnostic accuracy.

Annotatsiya. Ultratovushli tasvirlash zamonaviy tibbiyotda keng qo‘llaniladigan diagnostika vositasi bo‘lib, uning invaziv bo‘lmagan tabiati, real vaqtda tasvir olish qobiliyati va xavfsizligi bilan ajralib turadi. Biroq, ultratovush skanerlari sifati va izchilligi operatorning malakasiga bog‘liq bo‘lib, bu natijada o‘zgaruvchanlik va diagnostik aniqlikka ta’sir qilishi mumkin. Ushbu tadqiqot insonning ma’lum bir organida mustaqil skanerlashni amalga oshirish uchun mo‘ljallangan robot yordamidagi ultratovush tizimini ishlab chiqishni taqdim etadi. Tizim operatorga bo‘lgan bog‘liqlikni minimallashtiradi va takrorlanishni oshiradi. Tizimga olti darajali erkinlikka ega robot manipulyatori, motorli bo‘g‘inlar, real vaqtda ma’lumot beruvchi sensorlar va robotning uchida o‘rnatilgan ultratovush probe’i integratsiya qilingan. Boshqaruv algoritmi istalgan probe pozitsiyasini bo‘g‘in harakatlariga aylantiradi va tasvir tahliliga asoslanib probe joylashuvini dinamik tarzda sozlaydi.

Kalit so‘zlar. Robot yordamidagi ultratovush, ultratovushli tasvirlash, avtonom probe nazorati, tibbiyot robototexnikasi, real vaqtda tasvirni qayta ishlash, diagnostik aniqlik

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Аннотация. Ультразвуковая визуализация является широко используемым диагностическим инструментом в современной медицине благодаря своей неинвазивной природе, возможности получения изображений в реальном времени и безопасности. Однако качество и согласованность ультразвуковых сканирований сильно зависят от навыков оператора, что может приводить к вариативности и снижению точности диагностики. В данном исследовании представлена разработка роботизированной системы ультразвуковой диагностики, предназначенной для автономного сканирования конкретного органа человека, что минимизирует зависимость от оператора и повышает воспроизводимость результатов. Система интегрирует робота-манипулятора с шестью степенями свободы, моторизованные суставы, сенсоры для обратной связи в реальном времени и ультразвуковой датчик, установленный на конце роботизированного устройства. Алгоритм управления преобразует требуемые позиции датчика в движения суставов и динамически корректирует положение датчика на основе анализа изображений.

Ключевые слова. Роботизированный ультразвук, ультразвуковая визуализация, автономное управление датчиком, медицинская робототехника, обработка изображений в реальном времени, диагностическая точность

Introduction

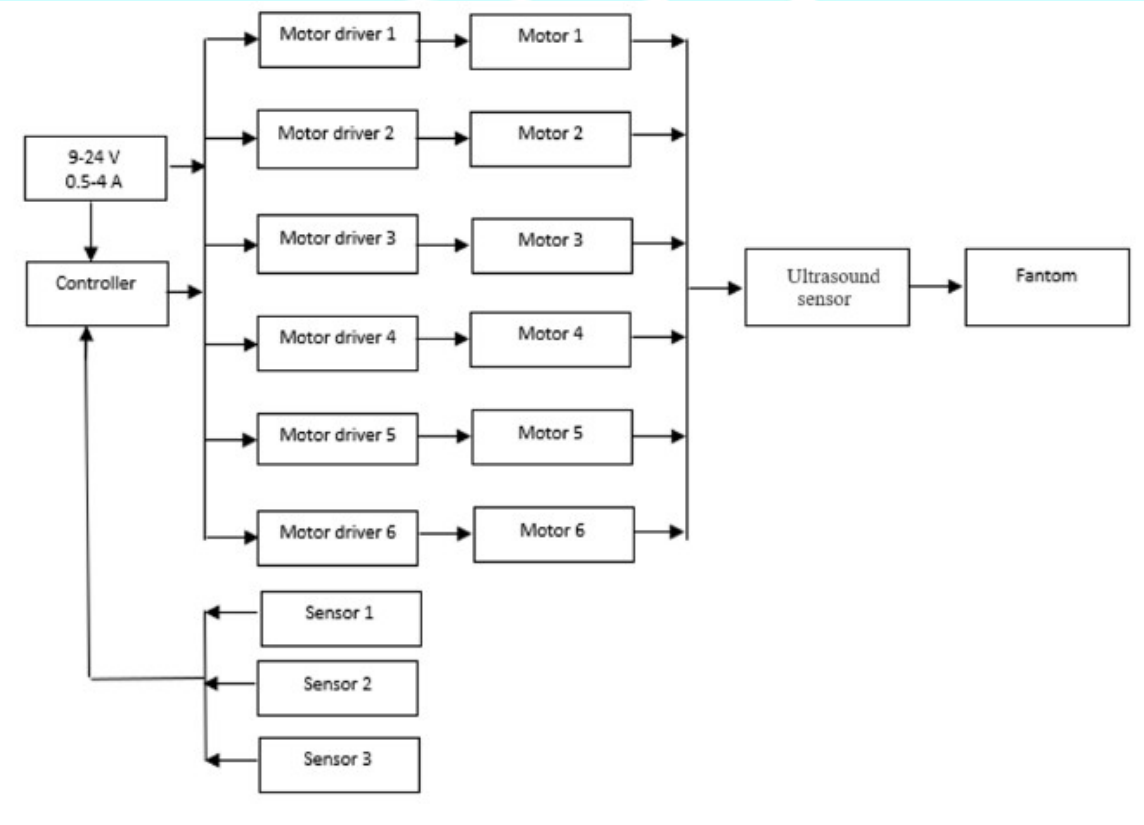
Ultrasound imaging remains one of the most effective and widely used diagnostic methods in contemporary medicine due to its non-invasive nature, real-time imaging capability, and absence of ionizing radiation. The accuracy and diagnostic value of ultrasound studies are critically dependent on the skill of the operator, who must skillfully manipulate the ultrasound probe by adjusting its position, angle, and applied pressure to acquire the clearest and most informative images possible. However, manual probe operation is inherently subject to variability, influenced by the operator's experience, fatigue, and patient-specific factors, which can lead to inconsistent image quality and challenges in replicating scans for follow-up examinations. To overcome these challenges, robotic-assisted ultrasound systems have been proposed and developed, aiming to automate probe positioning and manipulation to reduce operator dependency, enhance repeatability, and improve overall diagnostic accuracy. This paper focuses on the development of a comprehensive system integrating a robotic manipulator, control algorithms, and ultrasound image processing software designed to autonomously perform ultrasound scans on a specific human organ. The system is designed to deliver precise spatial control of the ultrasound probe through a six-degree-of-freedom robotic arm equipped with motorized joints driven by dedicated drivers,

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monitored via sensors providing feedback for closed-loop control. The control system receives power from a regulated power source and operates motors via motor drivers under commands from a central controller that also interfaces with sensory inputs for real-time feedback. The ultrasound sensor mounted on the robot's end-effector captures imaging data, which is processed to guide the robot's positioning for optimal imaging. The system is tested and validated using a phantom model that mimics human tissue properties, enabling calibration and performance evaluation without risk to patients. The primary objectives of this research are to develop an algorithm that translates desired probe positions into joint movements, implement a feedback loop based on real-time ultrasound image analysis to dynamically adjust probe placement, and create software capable of managing the hardware and processing imaging data efficiently. By achieving these objectives, the system promises to improve the standardization and reliability of ultrasound diagnostics, minimizing the variability introduced by manual operation and providing consistent, high-quality imaging necessary for accurate clinical assessment.

The hardware architecture of the system comprises a power supply capable of delivering a voltage range from 9 to 24 volts with a current output between 0.5 and 4 amperes to meet the energy demands of motors and control electronics. The central controller orchestrates the system's operations, issuing commands to motor drivers that control six individual motors corresponding to the robotic arm's joints, enabling complex multi-axis movement. Sensors positioned strategically on the robotic arm provide crucial data on position and force, feeding this back to the controller for precision in movement and safety. The motor drivers act as intermediaries, amplifying control signals from the controller into appropriate current and voltage levels required to drive the motors with the necessary torque and speed. The integration of these components forms a feedback-controlled system where the controller continuously monitors sensor data to adjust motor inputs, ensuring the robotic arm positions the ultrasound probe with high accuracy. The ultrasound sensor captures acoustic reflections from tissue, producing imaging data that is sent to the processing unit. The use of a phantom model during system testing facilitates calibration and performance measurement in a controlled environment, providing a reliable benchmark for clinical application. The entire hardware configuration is designed for seamless communication and synchronized operation, ensuring the robotic arm responds accurately to control commands and image-based feedback.

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Picture 1. Block diagram of robotic system

The hardware and software architecture of the robotic ultrasound system integrates several components working in concert to achieve autonomous scanning. At the core of the system lies a robotic manipulator with six degrees of freedom (DOF). Each joint of the robotic arm is powered by an individual motor controlled by dedicated motor drivers, which are managed centrally by a controller unit. Power Supply: The system is powered by a 9 to 24-volt power source capable of delivering between 0.5 and 4 amperes, ensuring sufficient power for motors and control electronics. Controller: A microcontroller or embedded processor that orchestrates motor commands, reads sensor inputs, and executes control algorithms. Motor Drivers (1-6): Interface circuits between the controller and motors that amplify control signals to drive the motors at required torque and speed. Motors (1-6): Actuators that physically move the robotic arm's joints, enabling complex spatial positioning. Sensors (Sensor 1-3): These may include position encoders, force sensors, or accelerometers that provide feedback to the controller on the arm's actual state and contact forces. Ultrasound Sensor: Mounted at the end-effector, this probe captures ultrasound images of the target organ. Phantom Model: A synthetic object mimicking human tissue properties, used for calibration, testing, and validation.

The second image depicts a robotic arm designed for precise manipulation, equipped with multiple articulated joints, enabling it to achieve complex spatial positioning necessary for performing ultrasound examinations

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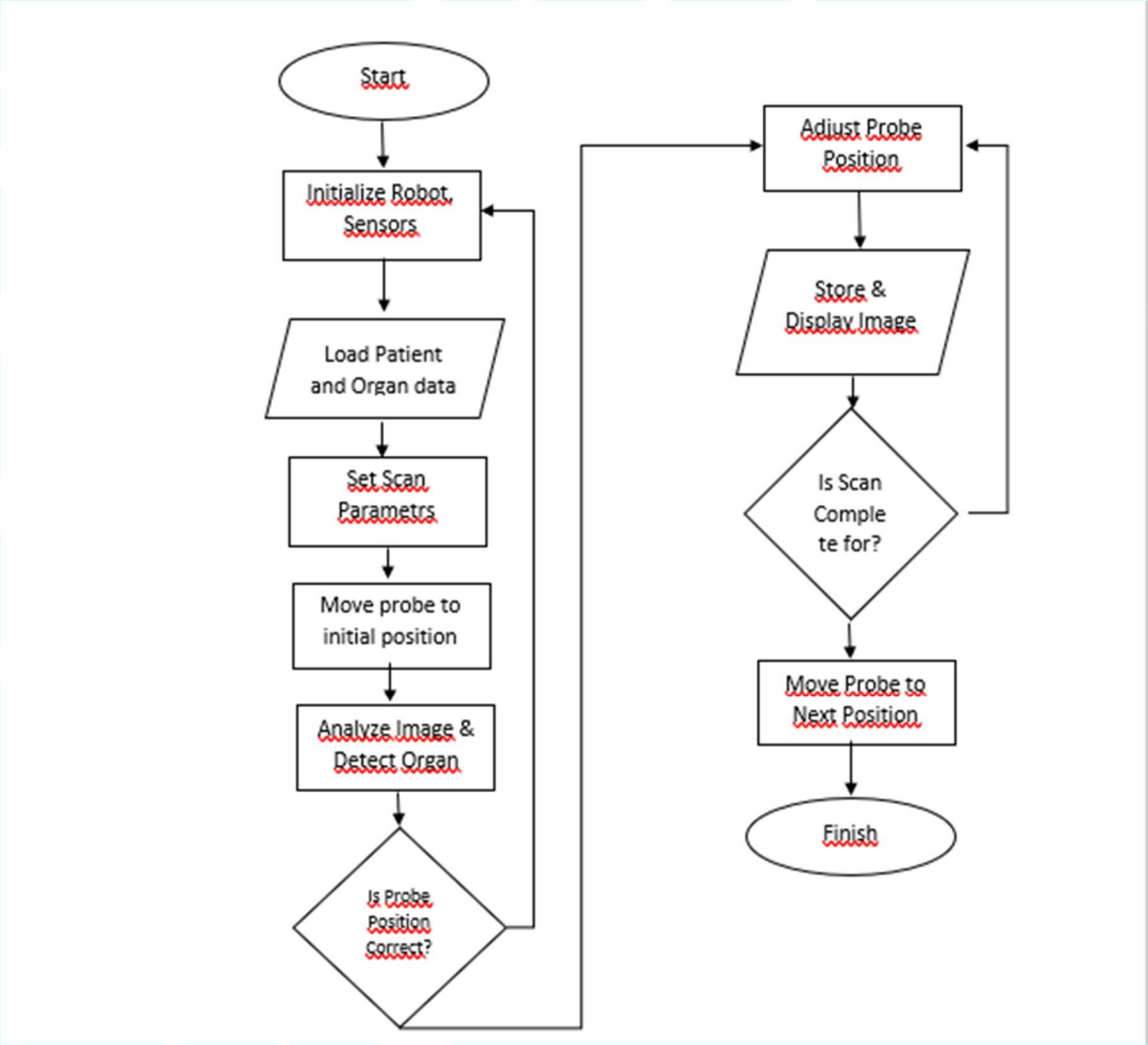
on a specific human organ. The image highlights the angular measurements between segments of the robotic arm, specifically showing angles of 45.15° and 48.35°, which are critical for positioning the ultrasound probe at optimal inclinations to ensure the best contact and imaging quality. These angles correspond to clinically recommended probe orientations that maximize ultrasound wave penetration and reflection, thereby enhancing image clarity. The robotic arm's flexibility, facilitated by these joint angles, allows it to adapt to the anatomical contours of the patient, ensuring consistent probe pressure and accurate scanning coverage.



Picture 2. Position of robot

The robotic arm provides six degrees of freedom, allowing complex positioning and orientation of the ultrasound probe. As demonstrated in Picture 2**,** the arm adjusts the probe's orientation with precise angular control, with typical angles shown as 45.15° and 48.35°. These angles optimize the contact between the probe and the organ surface for high-quality imaging.The control algorithm uses forward and inverse kinematics to compute the required motor positions and velocities. The controller sends commands to motor drivers, which in turn drive the motors to the desired angles.The control algorithm governing the robotic arm relies on both forward and inverse kinematics to determine the precise joint angles and motor commands required to achieve the desired probe position and orientation. Forward kinematics is used to compute the end-effector's current position and orientation based on the known angles of each motorized joint, providing real-time feedback for monitoring the arm's movement. Inverse kinematics, on the other hand, calculates the necessary joint angles and angular velocities that will position the probe at a specific target location with the correct orientation.

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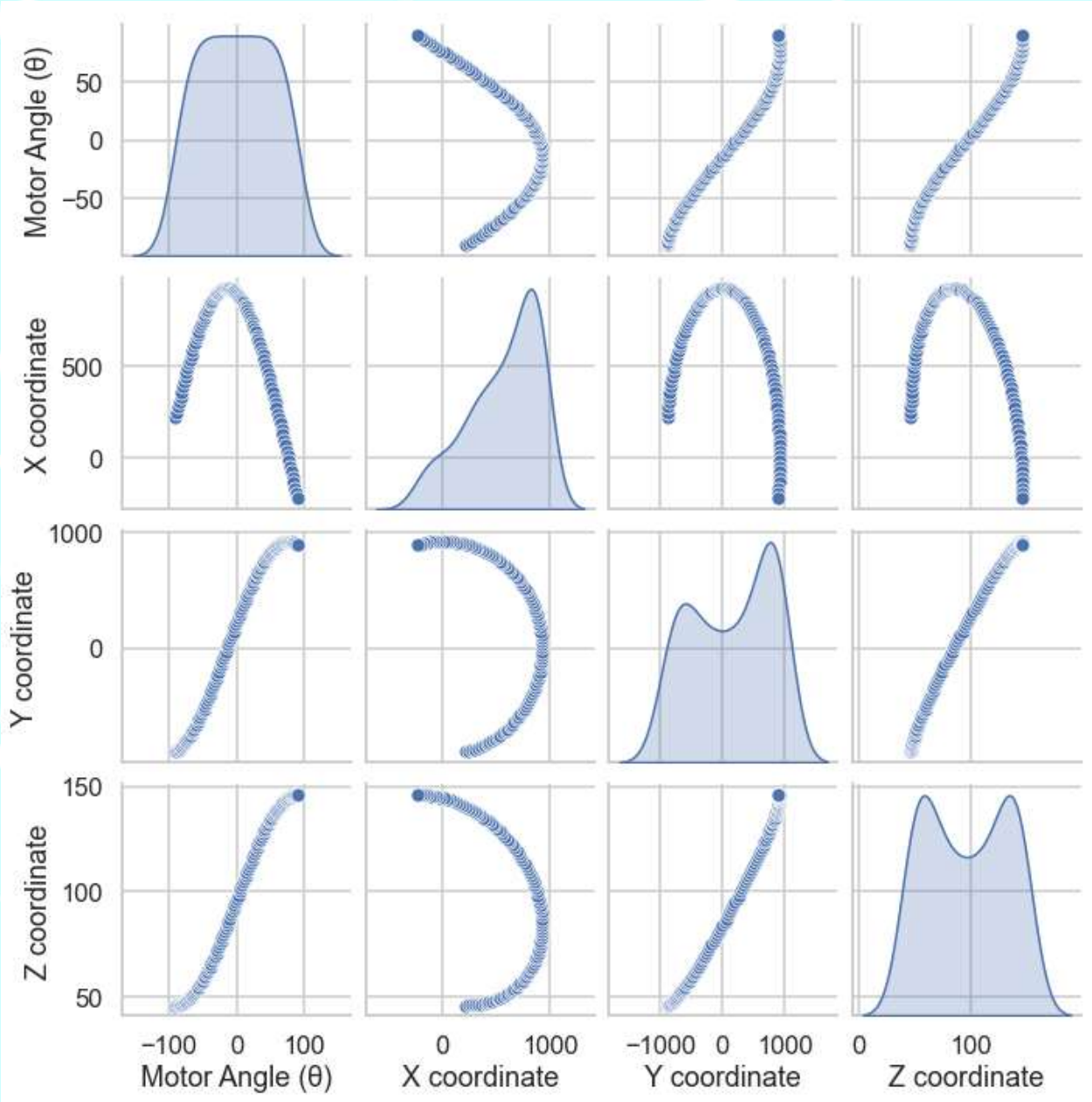
Picture 3. Algorithm (Step-by-Step Textual Flow)

1. Initialization: Load robotic arm parameters, sensor calibrations, and organ-specific anatomical data. Set scanning parameters such as velocity, angle limits, and safety thresholds.
2. Target Definition: Determine the target organ or tissue region using preloaded anatomical coordinates or preliminary imaging data.
3. Trajectory Calculation: Use inverse kinematics to calculate required joint angles for the probe to reach the target location. Plan smooth trajectories respecting acceleration and velocity constraints.
4. Probe Placement: Command the robotic arm to move the probe to the initial target position using motor drivers and joint feedback.
5. Image Acquisition: Capture real-time ultrasound images via the probe sensor.
6. Image Analysis: Process images using segmentation and boundary detection algorithms to identify the organ and evaluate image quality.
7. Feedback Correction: Compare detected organ position with desired target location. If misalignment occurs, calculate corrective joint movements and update motor commands.

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8. Loop Execution: Repeat steps 5–7 until the complete organ scan is performed, ensuring continuous optimization of probe placement.

9. Output Generation: Compile final ultrasound images, organ contours, and relevant diagnostic metrics for clinical use.



Picture 4. The relationship between the motor angle and the end-effector coordinates.

The Plotly graph is designed to comprehensively visualize and demonstrate the dynamic relationship between the motor angle of a robotic manipulator and the resulting spatial coordinates of the end-effector in three-dimensional space, capturing the precise X, Y, and Z positions corresponding to each specific motor joint rotation. Each point plotted in this interactive graph represents a unique configuration of the motor angle, and the associated position of the end-effector, allowing users to see how incremental changes in the joint rotation propagate through the manipulator to influence the final location of the

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robot's end-effector, providing a detailed understanding of the kinematic behavior of the system. The color of each point is mapped to the motor angle, employing a continuous gradient that intuitively conveys the variation of the angle across the trajectory, and making it immediately apparent how changes in the motor angle correlate with movements in three-dimensional space. The graph also connects consecutive points with a line, forming a trajectory that visually represents the continuous motion path of the end-effector as the motor rotates through its operational range, offering an intuitive perception of the manipulator's workspace coverage, reachability, and motion patterns. Users can interact with the graph using rotation, zoom, and pan functions, which allow them to examine the end-effector's trajectory from multiple viewpoints, inspect detailed positional data, and analyze both the overall behavior of the system and localized movements in specific regions of the workspace, enhancing understanding of how the robot operates in real-world conditions. Additionally, hovering over individual points provides precise numerical readouts of the X, Y, Z coordinates and the corresponding motor angle, which supports quantitative analysis, validation of kinematic models, and comparison against theoretical predictions or experimental measurements. This interactive visualization is particularly valuable for robotics research, education, and system design, as it bridges the gap between abstract joint angles and tangible spatial positions, facilitating both intuitive and analytical insights into the manipulator's kinematic performance. By providing an integrated view of motor input and end-effector output, the graph serves as a powerful tool for analyzing the efficiency, precision, and reliability of the robotic system, enabling engineers and researchers to optimize motion planning, trajectory generation, and control algorithms, and ensuring that the manipulator can achieve desired positions accurately while maintaining smooth and predictable motion, ultimately contributing to the development of more robust, precise, and intelligent robotic systems capable of performing complex tasks such as autonomous ultrasound scanning or other high-precision applications, while simultaneously offering a visually engaging and informative representation that enhances comprehension, communication, and decision-making in the design, analysis, and operation of robotic manipulators.

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