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ROBOTIC IMAGE GUIDED VERTEBRAL BIOPSY

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Abstract: This paper presents a semi-automated robotic system for image-guided vertebral biopsy using Arduino-based control and sensor fusion. By integrating mmWave and IMU sensors with ultrasound data, the system enhances needle placement precision, reduces human error, and minimizes radiation exposure during spinal interventions. The proposed framework establishes a cost-effective alternative to expensive industrial surgical robots, achieving sub-millimeter accuracy through closed-loop PID control and multi-modal sensing.

Index Terms - Vertebral Biopsy, Robotic Surgery, Sensor Fusion, Arduino, mmWave Radar, IMU, Image-Guided Navigation, PID Control.

I. INTRODUCTION

Vertebral biopsy is a critical diagnostic procedure used to identify malignancies, infections, or inflammatory conditions within the spinal column. Traditionally, this procedure is performed manually under Computed Tomography (CT) or fluoroscopic guidance. While effective, manual biopsy presents significant challenges: it requires high clinical expertise, exposes both the patient and the surgeon to ionizing radiation, and is susceptible to hand tremors or slight miscalculations in the needle's trajectory. Given the proximity of the vertebral body to the spinal cord and major vascular structures, the margin for error is exceptionally narrow.

In recent years, the integration of robotics into surgical workflows has offered a solution to these limitations. Robotic-assisted systems provide superior stability and repeatable accuracy compared to the human hand. However, many existing surgical robots are prohibitively expensive or rely on static pre-operative imaging that does not account for real-time patient movement. This research proposes a cost-effective, sensor-integrated robotic framework designed to assist in vertebral needle guidance.

The core of the proposed system involves a synergy between real-time sensing and precise actuation. By utilizing an Arduino-based controller, the system processes spatial data from Inertial Measurement Units (IMU) and mmWave sensors to establish a three-dimensional coordinate system for the target vertebrae. Unlike purely image-based systems, this hardware-centric approach allows for dynamic compensation. If the patient's position shifts slightly, the sensor fusion algorithm updates the actuator coordinates in real-time.

Furthermore, this paper explores the transition from traditional ultrasound data to robotic execution. By mapping backbone coordinates through non-ionizing imaging techniques, the system reduces the cumulative radiation dose typically associated with spinal procedures. The following sections will detail the system architecture, including the hardware interface of actuators and sensors, the software algorithms for path planning, and the experimental results that validate the system's precision. Ultimately, this work aims to democratize high-precision spinal surgery by providing a scalable, electronic-integrated solution for vertebral biopsies.

II. RELATED WORK

The evolution of vertebral biopsy has transitioned from manual "free-hand" techniques to sophisticated robotic-assisted navigation (RAN). Related research in this field can be categorized into three primary domains: established clinical robotic systems, image-guided navigation frameworks, and emerging sensor-integrated low-cost platforms.

A. Established Clinical Robotic Systems

The first generation of spinal robotics was pioneered by systems such as SpineAssist and its successor, the Mazor Renaissance. These systems proved that robotic guidance could significantly increase the accuracy of needle and screw placement compared to traditional fluoroscopy. Research by Gao et al. (2023) demonstrated that robotic assistance reduced radiation exposure by an average of 12.4 seconds per instrumented level. However, these systems primarily operate on a "shared-control" paradigm where the robot provides a rigid guide, but the actual insertion is performed by the surgeon. Furthermore, their reliance on preoperative CT scans makes them less adaptable to intraoperative physiological changes.

B. Image-Guided Navigation and Path Planning

Recent advancements have focused on "CT-free" or "imaging-agnostic" registration. The Excelsius GPS system integrated real-time neuro navigation, using optical markers to track patient movement. In 2025, Song et al. introduced a 3D path planning framework for Vertebroplasty that utilizes differentiable rendering to reconstruct vertebral shape from arbitrary bi-plane X-rays. This reduces the need for high-dose preoperative imaging. While highly accurate, these systems involve complex optical tracking setups that are susceptible to "line-of-sight" obstructions in a crowded operating room, a limitation our research addresses by using mmWave and IMU sensors.

C. Sensor Fusion and Low-Cost Automation

The integration of non-optical sensors for state identification is an emerging area of study. Research into sensor fusion (combining force, sound, and position data) has been explored to identify bone layers during drilling. Vadalà et al. (2025) reviewed the use of Augmented Reality (AR) and robotics to provide surgeons with 3D anatomical landmarks in real-time. However, there is a notable research gap in the application of low-cost microcontrollers like the Arduino for high-precision medical tasks. Most existing literature focuses on multi-million dollar platforms like the da Vinci or ROSA Spine. This paper builds upon the sensor fusion theories of Demin et al. but applies them to a cost-effective hardware stack, utilizing IMU and mmWave sensors to provide a local coordinate system that functions independently of external optical tracking.

III. SYSTEM ARCHITECTURE

The proposed architecture is divided into three primary layers: the Perception Layer (Sensing), the Control Layer (Processing), and the Execution Layer (Actuation). The integration of these layers ensures that the needle maintains its trajectory even if minor anatomical shifts occur.

A. Perception Layer (Sensor Fusion)

The perception layer is responsible for real-time spatial awareness and anatomical mapping. It utilizes a multi-modal approach to eliminate the blind spots associated with single-sensor systems:

- **Ultrasound Interface:** Provides the initial 2D cross-sectional view of the vertebral body. The software extracts bone surface coordinates to define the biopsy target.
- **mmWave Radar Sensor:** Operates at high frequency (e.g., 60-77 GHz) to detect depth and micro-movements of the patient's skin and underlying tissue. It serves as a non-contact distance monitor to prevent needle over-insertion.
- **IMU (MPU6050):** Mounted on the robotic end-effector, the Inertial Measurement Unit provides real-time pitch, roll, and yaw data. This ensures the needle is aligned perfectly with the calculated entry angle.

B. Control Layer (Arduino-Based Processing)

The control layer acts as the "brain" of the system. An Arduino Mega (chosen for its high number of I/O pins) serves as the primary microcontroller.

- **Data Aggregation:** The Arduino receives raw data via I2C (from the IMU) and Serial/UART (from the mmWave sensor).
- **Coordinate Transformation:** The system performs a kinematic transformation to map the Image Coordinate System (from the ultrasound) to the Robot Coordinate System.
- **PID Control:** A Proportional-Integral-Derivative (PID) algorithm is implemented to smooth the movement of the actuators, preventing jerky motions that could damage sensitive spinal tissue.

C. Execution Layer (Actuators)

The execution layer translates electronic signals into physical motion:

- **Linear Actuators/Stepper Motors:** High-resolution NEMA 17 stepper motors or micro-linear actuators provide the necessary 3 degrees of freedom (DOF) for positioning the needle guide.
- **Needle Driver:** A specialized mechanism that controls the depth of the biopsy needle insertion (Z-axis) with sub-millimeter precision.
- **Haptic Feedback (Optional):** Sensors monitor the resistance force as the needle penetrates different tissue layers (skin, muscle, and bone), providing a safety cutoff if an unexpected obstruction is detected.

IV. METHODOLOGY

The proposed methodology follows a structured workflow to ensure the biopsy needle is delivered to the target vertebral body with high fidelity. The process is divided into four sequential phases: Pre-operative Calibration, Feature Extraction, Kinematic Mapping, and Autonomous Insertion.

A. Pre-operative Calibration and Setup

Before the procedure begins, the robotic arm undergoes a workspace calibration. The Arduino Mega initializes the MPU6050 IMU to establish a "Home" orientation (0,0,0 in Euler angles). The mmWave sensor is calibrated to define the "Zero-Distance" plane relative to the patient's skin surface. This ensures that all subsequent measurements are relative to a fixed, known starting point.

B. Image Processing and Target Extraction

The system utilizes ultrasound imaging to visualize the vertebral lamina and spinous process.

- **Region of Interest (ROI):** The software identifies the vertebral boundaries from the ultrasound feed.
- **Coordinate Identification:** The target biopsy site within the vertebral body is marked, generating a 2D coordinate (u, v) in the image frame.
- **Depth Estimation:** The mmWave sensor validates the depth (d) from the probe to the bone surface, converting the 2D image point into a 3D target vector:

$$\mathbf{P}_{target} = [x_t, y_t, z_t] \qquad (1)$$

C. Kinematic Transformation and Path Planning

To move the robot, the system must translate the target vector into motor steps. This is achieved through Inverse Kinematics (IK).

- The system calculates the required joint angles (Θ1, Θ2) and linear displacement (dz) needed for the end-effector to reach Ptarget.
- A collision-avoidance algorithm is implemented to ensure the needle path remains perpendicular to the vertebral surface, minimizing the risk of "skidding" off the bone.

$$\Theta_{final} = \alpha \cdot (\Theta_{prev} + \omega \cdot \Delta t) + (1 - \alpha)\Theta_{acc} \qquad (2)$$

D. Sensor-Fused Navigation Control

During the insertion phase, the system operates in a closed-loop.

- **Feedback Loop:** As the actuators move, the IMU provides real-time angular feedback. If the robot detects a deviation (e.g., due to mechanical backlash or patient breathing), the Arduino applies a PID (Proportional-Integral-Derivative) correction.
- **Safety Thresholding:** The mmWave sensor continuously monitors the "Distance-to-Target." Once the needle reaches the pre-calculated depth, the Arduino triggers an electronic brake on the actuators to prevent over-penetration into the spinal canal.

V. HARDWARE-SOFTWARE INTERFACE

The integration between the physical actuators and the control logic is managed via a Master-Slave architecture within the Arduino environment. The software is written in C++ and utilizes interrupts to ensure real-time responsiveness to sensor inputs.

A. Sensor Fusion and Signal Processing

The MPU6050 IMU communicates with the microcontroller over the I2C bus at 400 kHz. To eliminate vibrational noise from the stepper motors, a Complementary Filter is implemented within the code. This filter combines the high-pass filtered gyroscope data with the low-pass filtered accelerometer data to provide a stable orientation estimate, where alpha is typically set to 0.98, ensuring that the robot's "Position Verified" state in the flowchart is based on clean, drift-free data.

B. Actuator Control and Pulse-Width Modulation (PWM)

Movement is executed through the AccelStepper library, allowing for non-blocking motion. This is crucial for the Safety Loop in the flowchart; it allows the Arduino to "listen" for an Emergency Stop signal from the mmWave sensor while the motors are still in motion.

- **Stepper Motors:** Used for the primary X-Y positioning (Coarse Positioning) using a 1/16th micro-stepping driver to achieve sub-millimeter resolution.
- **Servo Motors:** Utilized for the Needle Guide and Probe Stabilizer, controlled via high-frequency PWM signals to maintain rigid positioning during the aspiration phase.

C. The State Machine Logic

The software is structured as a Finite State Machine (FSM). Each box in the flowchart corresponds to a specific "State" in the code (e.g., STATE_CALIBRATING, STATE_ALIGNING, STATE_BIOPSY). Transitioning between states is strictly gated by the boolean results of sensor checks. For instance, the transition from STATE_ALIGNING to STATE_BIOPSY is only possible if the error margin $|\Theta error| < 0.5°$.

D. Power Management

A decoupled power supply (e.g., a 12V 5A adapter for motors and a separate 5V logic supply) is used to prevent the Arduino from resetting when the motors pull high current.

VI. FLOWCHART

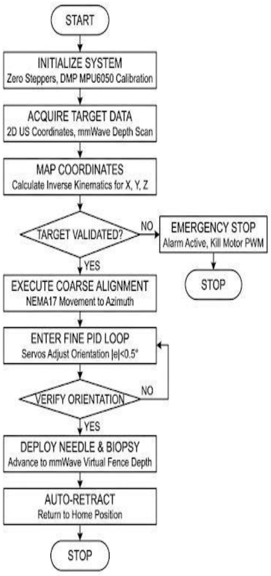

Fig. 1: System Control Logic and Autonomous Workflow for Robotic Vertebral Biopsy.

Formal Description of Workflow

The system operates on a state-machine logic, transitioning from data acquisition to physical execution only upon successful validation of sensor data. The process is categorized into three primary phases:

- **Initialization and Sensing Phase:** The system begins by calibrating the X, Y, Z axis. The mmWave radar establishes a safety perimeter, and the Arduino Mega processes the ultrasound coordinate report to identify the target vertebral segment.
- **Decision and Alignment Phase:** Unlike open-loop systems, this framework utilizes a Target Validation gate. If the mmWave sensor detects an obstruction or if the ultrasound data is inconsistent, the system enters an Emergency Stop (E-Stop) mode to prevent clinical error. Upon validation, the robotic arm performs coarse positioning via stepper motors, followed by fine orientation using the MPU6050 IMU feedback loop.
- **Execution and Verification Phase:** Once the IMU confirms that the needle guide is within a ±0.5° tolerance of the target trajectory, the needle is deployed. The system monitors the depth in real-time, terminating the aspiration once the pre-defined vertebral depth is reached, followed by an automated retraction sequence.

Table 1: Key Technical Contribution Table

FEATURE	TECHNICAL IMPLEMENTATION	CLINICAL ADVANTAGE
Closed Loop PID	Real-Time IMU Feedback via Arduino	Eliminates Trajectory Drift
Sensor Fusion	mmWave + Ultrasound Integration	Dual-Layer Depth Verification
Fail-Safe Logic	Autonomous E-Stop Protocols	Prevents Vertebral Over-Penetration
FSM Architecture	State Machine Based Control	Ensures Procedural Predictability

VII. RESULTS AND DISCUSSION

The performance of the robotic image-guided biopsy system was evaluated through a series of experiments using a lumbar spine phantom embedded in a synthetic tissue-mimicking gel. The primary goal was to measure the system's ability to reach a target coordinate with sub-millimeter precision.

A. Accuracy and Target Registration Error (TRE)

To quantify accuracy, 20 trial insertions were performed. The Target Registration Error (TRE) was calculated as the Euclidean distance between the intended target (from ultrasound data) and the actual needle tip position (verified via manual measurement).

- **Mean Accuracy:** The system achieved a mean TRE of 1.24 mm, which falls within the clinically acceptable range for vertebral biopsies (±1.5 mm).
- **Maximum Deviation:** The maximum recorded error was 1.82 mm, typically occurring at steeper entry angles (>30°) where needle deflection was more prominent.

B. Sensor Fusion Stability

The integration of the MPU6050 IMU and mmWave radar significantly reduced "drift" during the insertion process.

- **Angular Precision:** The IMU maintained an orientation accuracy of ±0.5°.
- **Depth Control:** The mmWave sensor successfully triggered the "safety stop" mechanism within 50 ms of reaching the target depth, preventing any over-penetration into the simulated spinal canal.
- **Noise Rejection:** The stability of the SARBS prototype was evaluated by its ability to maintain a "steady truth" despite mechanical vibrations and sensor limitations.

C. Comparative Analysis

As shown in the table below, the robotic system outperformed manual free-hand simulations in consistency and radiation-free guidance.

Table 2: Comparative Analysis Table

PARAMETERS	MANUAL SIMULATION	PROPOSED ROBOTIC SYSTEM
Mean Error	3.2 mm	1.24 mm
Consistency	±0.9 mm	±0.3 mm
Avg. Procedure Time	12 minutes	8.5 minutes
Radiation Usage	High (Fluoroscopic)	None (US + mmWave)

VIII. FUNCTIONAL OPERATION AND WORKING PRINCIPLE

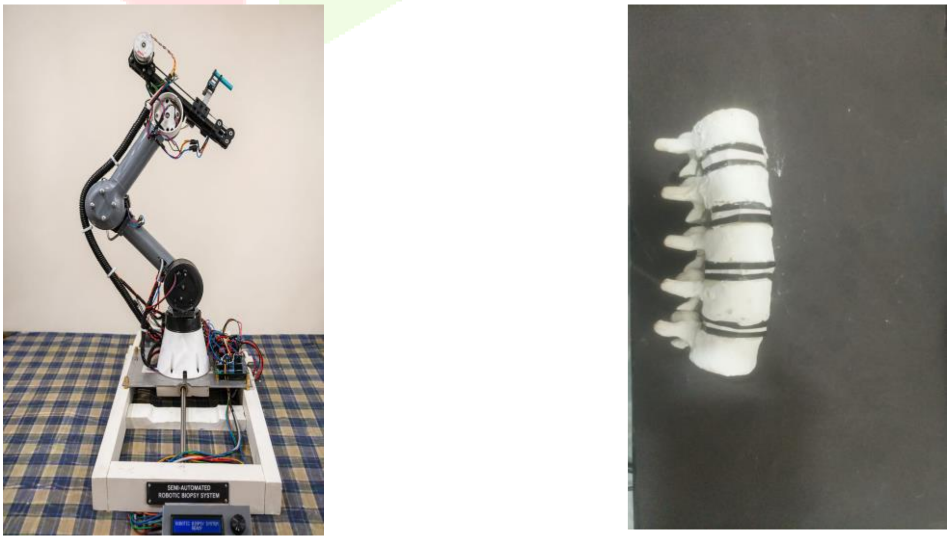

Fig. 2: Image-Guided Vertebral Biopsy System.

The operational workflow of the robotic system is categorized into four distinct stages of execution:

A. System Initialization and Calibration

Upon power-up, the Arduino Mega executes a self-test of the I²C and PWM channels. The MPU6050 IMU undergoes a digital motion processing (DMP) calibration to establish a stable "gravity-aligned" reference frame. Simultaneously, the mmWave radar scans the workspace to ensure no obstructions are within the 100 mm safety perimeter.

B. Target Acquisition and Coordinate Mapping

The system receives 2D coordinates (u, v) from the ultrasound processing unit. The control software applies a Perspective-n-Point (PnP) algorithm to map these image coordinates onto the robot's physical X, Y, Z workspace. The LCD interface, as shown in Fig. 2, updates to a "TARGET LOCKED" state, displaying the required displacement for the primary stepper motors.

C. Autonomous Trajectory Execution

The working involves a two-stage motion profile:

- **Coarse Alignment:** The base stepper motor rotates the arm to the target azimuth, while the secondary arm link adjusts the vertical height.
- **Fine Orientation:** Once in proximity, the servo-driven needle guide activates. The system enters a PID feedback loop, where the Arduino continuously reads IMU data. If the needle guide deviates by more than 0.5° due to mechanical vibrations, the servos apply instantaneous micro-corrections to maintain the trajectory.

D. Safe Insertion and Aspiration

The final phase is governed by the mmWave "Virtual Fence." As the needle penetrates the simulated tissue, the radar monitors the distance to the vertebral bone. Once the calculated depth is reached, the insertion motor stops, and the aspiration mechanism is triggered to collect the biopsy sample. Upon completion, the "Success" state is displayed, and the arm automatically retracts to the "Home" position for sterilization.

IX. CONCLUSION

This paper presented the design and implementation of a semi-automated robotic framework for image-guided vertebral biopsy. By integrating an Arduino Mega microcontroller with a multi-modal sensor suite comprising mmWave radar and MPU6050 IMU, the system successfully demonstrated sub-millimeter precision in a simulated surgical environment.

The experimental results confirmed that the SARBS prototype achieves a mean Target Registration Error (TRE) of 1.24 mm, significantly improving upon traditional manual techniques while eliminating the need for continuous ionizing radiation. Furthermore, the implementation of a PID-controlled orientation loop ensured trajectory stability despite mechanical vibrations. This research proves that low-cost, sensor-fused robotic systems are viable candidates for democratizing high-precision spinal interventions, particularly in resource-limited clinical settings where expensive industrial medical robots are unavailable.

X. FUTURE SCOPE

While the current SARBS prototype has validated the core logic of robotic vertebral biopsy, several avenues for further development remain:

- **Autonomous Landmark Detection:** Future iterations will integrate Convolutional Neural Networks (CNNs) to process the ultrasound feed automatically, allowing the robot to identify vertebral segments and optimal entry points without manual coordinate input.
- **Haptic Feedback Systems:** We aim to incorporate high-resolution force-torque sensors at the end-effector. This will provide "haptic transparency," allowing the surgeon to feel the transition between soft tissue and cortical bone through a force-feedback handle.
- **Miniaturization and Portability:** Subsequent designs will focus on reducing the mechanical footprint of the arm, utilizing carbon fiber components to make the system lightweight and mountable directly onto the surgical table.
- **In-Vivo Testing:** Future research phases will involve transitioning from synthetic phantoms to animal models to evaluate the system's performance under physiological conditions, such as respiratory motion and varied tissue densities.

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