PAPER REVIEW

State Recognition of Pedicle Drilling With Force Sensing in a Robotic Spinal Surgical System

Prasad Vagdargi, for Computer Integrated Surgery 2, Background presentation.

Summary:

This paper focuses on the specific part of spinal orthopedic surgery for drilling and screw insertion, aiming to recognize the states of transition and contact with bone during the drilling procedure for better control and safety.

Background:

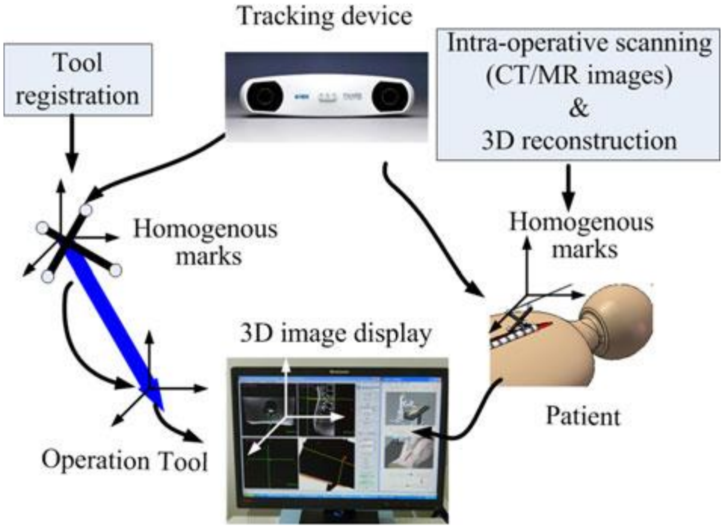
The use of robots in orthopedic surgery is increasing due to their benefits of precision and stability during surgery. A common problem during spinal surgeries is the placement and insertion of pedicle screws accurately within the vertebra, for procedures such as spinal fusion. For this procedure, bone screws are inserted into the vertebra, and drilled across the parts of the vertebra such as the vertebral lamina, pedicle and the cancellous tissue. The width of the pedicle is about 5–6 mm on the lumbar bones and even lesser on the cervical bones for drilling. This, along with the diameters of the bone screws being 4–4.5 and 2.5–3 mm respectively, create a challenging environment for the surgeon with the operational error as ±1 mm.

Previous attempts at introducing robots into this surgery include a kind of robotic system used for guiding of the manual operations where the robot can adjust the position and orientation to the target point, and the pedicle drilling process is still manually performed by the surgeon through the placement and alignment of a guiding rod.

The measurement of force signals done previously for this procedure include mounting a miniature distal force sensor on the operation tool, using a force sensor on conventional trocar with seals to measure the manipulation forces and to help the surgeon to monitor the operation status.

Current Workflow:

The normal procedure of manual spinal surgery with the navigation system based on CT/MR images is as shown below. The whole procedure is divided into two stages: preparation and operation. In the preparation stage, the homogeneous marks are fixed onto the vertebrae of the patient and scanned by a C-arm. The 3-D vertebrae's images are reconstructed by the navigation system so that the relevant positions can be registered.

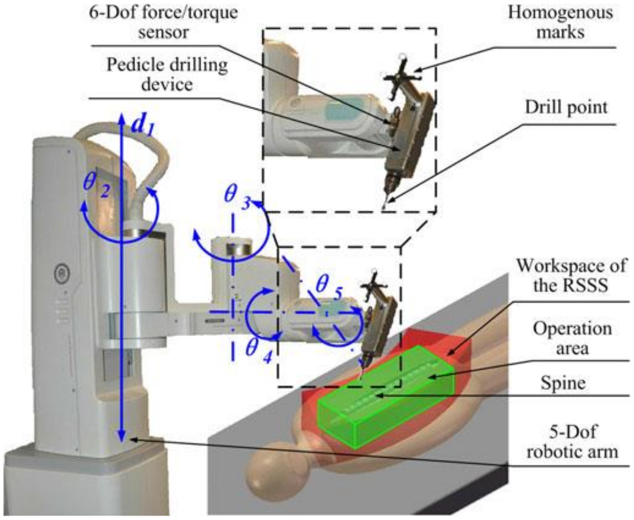


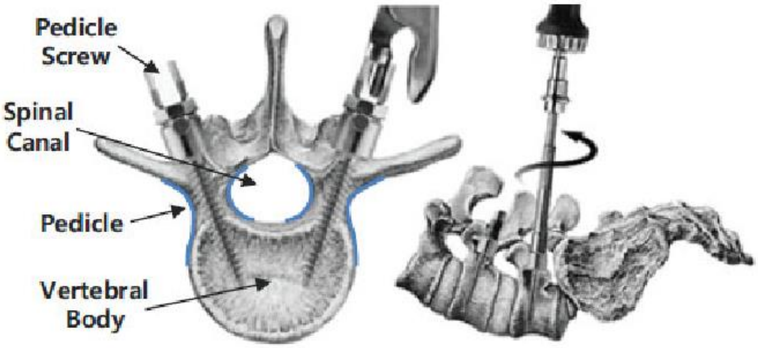
Intraoperatively, the surgeon operates using re-registered tools. Using the motion tracking markers, the location and pose of the patient along with operation tools are tracked and displayed in the operating room in real time. Using this information, the surgeon determines the location and angle of insertion for the screws and then operates the tools, such as bone drill to complete the operation.

Proposed Robotic Device and its control:

The paper describes a 5-DOF Prismatic/Revolute hybrid robotic arm and a 2-DOF pedicle drilling device for this procedure, where the drilling device includes a 6-DOF force/torque sensor. The actuated robotic arm is used for the adjustment of position/orientation of the drilling device with the navigation system, and the pedicle device is used for screw path drilling. The 6-DOF force/torque sensor was used to measure the general force acting on the pedicle drilling device during th e s crew-path-drilling process.

The Robotic arm proposed 5-DOF robotic arm proposed has two modes of operations: cooperative control mode and active mode. In the cooperative control mode, the surgeon can manually reposition the arm by freely moving the end effector, used for the coarse positioning. In contrast, the active control mode is





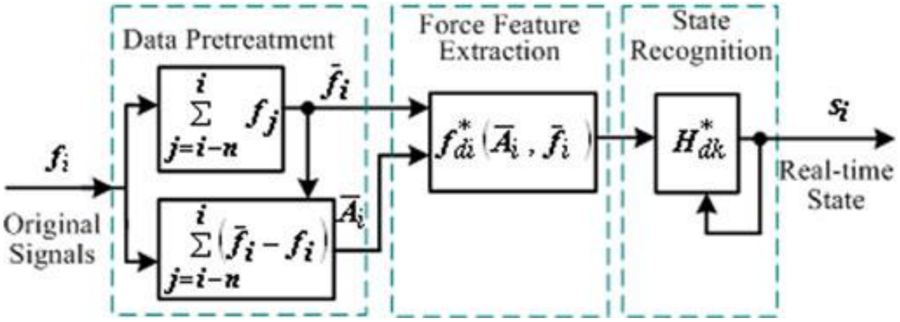
used for fine positioning the arm in the workspace. In this mode, the positions are calculated using the surgical path plan and followed using direct kinematic control of the robotic arm.

Feature Extraction:

The setup was then tested on bovine vertebra for drilling procedures, using two kinds of drills: Spherical and Twist drill. The force measurements were collected for both the procedures and recorded, along with the timestamp starting the drilling procedure from the surface of the bone.

The overall drilling into vertebra was classified into 5 stages:

1. Initial state: In this state, the drill establishes contact with the bony exterior surface. The drill slips and slides before drilling through the tissue. The force signals are elastic in nature and approximately linear with respect to depth of drilling.
2. State 1 (outer cortical state): After the initial membrane on the bone ruptures and the drill establishes contact, the drill tip begins to cut the outer cortical tissue. As it drills into the bone tissue, there is a sudden drop in the force and the average values decrease. The force signals are smoother in this region.
3. State 2 (cancellous state): In this stage, the drill goes through the cancellous tissue and cuts at a constant feedrate. The force measurements in this stage have a relatively big variation in both, amplitude and frequency. This is due to trabecular structure of cancellous bone, where the contact between the drill and the cancellous bone is discontinuous. The average value remains at a constant low level.
4. State 3 (transitional state): In this state, the drill approaches the transitional zone from the cancellous tissue into the cortical tissue. Force acting on the tool begins to increase, and the operating risk increases drastically with it. This state essentially warns the user that the drilling must be stopped immediately.
5. State 4 (inner cortical state): In this state, the drilling point penetrates the whole vertebra and forces drops rapidly. This stage must always be avoided in surgery. The average force decreases during this state.

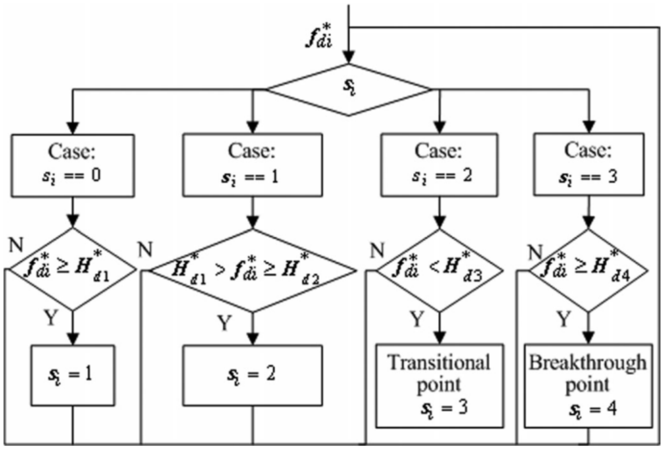


Using these states of drilling procedure, the authors devised a state feature function which combines the input of short window moving average force, and the magnitude difference of force from average force.

$$f_i^*(\bar{f}_i, \bar{A}_i) = \bar{f}_i . \bar{A}_i$$

Thresholding this feature function gave the output state as required using the moving real time forces. Other corrections and filtering to the signals was done as needed. The procedure is as shown above.

The thresholds were obtained experimentally as shown:

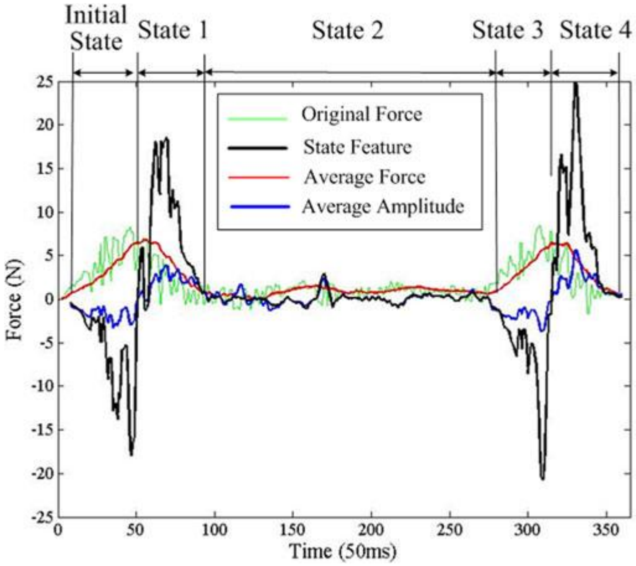


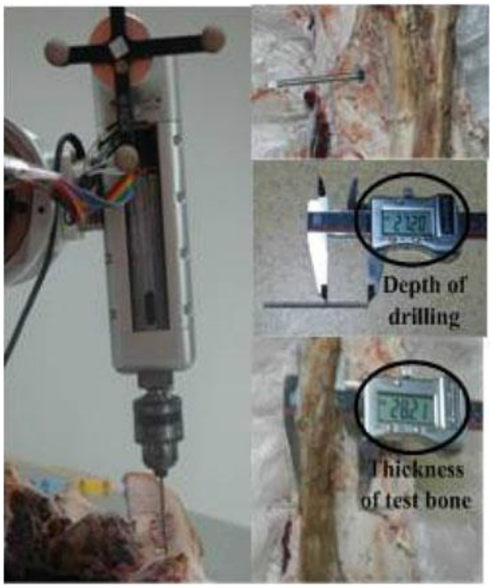
This procedure was completed with two different drill tips.

Results:

The experiments conducted were able to predict the state transition with fair accuracy. The transition points were marked for visualization for the initial stages, but more importantly between stage 3 and stage 4, which is the most critical part for better surgical outcome.

Another verification experiment conducted was to allow the robot to drill to the transition state between state 3 and state 4 and stop the motion as soon as it hits the safety limit. Measuring the bone thickness after this experiment showed the robot had indeed left a clearance of around 2mm, the average bone thickness before stopping.





Depth measurement before and after drilling through the bone

Conclusion:

This paper touches upon many aspects of design, sensing and experimentation. It introduces an improved structural configuration of a robot suitable for operating rooms and its control modes for simpler usability. It also describes a force sensing based method which segments the state of drilling and ensures a safety limit in real time using a force model. Finally, experiments are carried out to verify this result using various methods and two drill tips.

References:

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