NEEpolean

Spring Test Plan

MRSD Project I

Sponsor: Smith + Nephew

Team D

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1 Introduction

This document provides a comprehensive overview of the testing protocols and methodologies for the Augmented Reality (AR) and Robot-Assisted Total Knee Replacement Surgery project. The testing strategy is designed to systematically evaluate individual hardware and software components, progressing through increasingly complex integrations to ensure robustness and precision.

Central to this project is the exploration of three AR headsets—HoloLens 2, Magic Leap 2, and Apple Vision Pro—to determine their effectiveness in providing an interface between the surgeon and the robotics system. Testing will focus on assessing their spatial tracking accuracy, latency, and overall suitability for integration in this human-robot loop. Concurrently, the robotic platform will be subject to rigorous evaluation to ensure high standards of precision and repeatability needed to meet the safety standards for surgical robots.

The outlined testing schedule details the specific functionalities targeted in each phase, demonstrating their alignment with the overarching system requirements. The culmination of these efforts will be showcased in our Spring Validation Demonstration. This structured approach enables thorough validation at each stage, ultimately leading to a fully functional system capable of autonomously drilling pins into a patient's bone while delivering precise, real-time feedback to the surgeon.

2 Logistics

2.1 Personnel

We will not need any additional personnel beyond the 5 team members when testing or demonstrating the system.

2.2 Location and Equipment

All of the testing and the final demonstration will take place at NSH B512, the Modern Robotic Systems Development Lab. In terms of equipment, the project sponsor Smith + Nephew have provided us with the following:

1. **Augmented Reality Headsets**: Microsoft HoloLens2, Magic Leap 2 and Apple Vision Pro
2. **Robot Manipulator**: KUKA LBR Med 7 that is mounted on a Vention Table.
3. **Bone Model**: Bone models from SawBones which will allow us to test our setup.
4. **Bone STL**: An STL file of the patient's knee on which the surgical plan is defined.
5. **Camera**: Currently, we are using the Intel Realsense D405 as it fits the desired physical characteristics for the camera system we want to mount on the end effector.
6. **Compute**: This includes an RTX 4070 powered workstation from the MRSD inventory and an Apple mac-mini ordered using the project budget.

3 Schedule

Identifier	Capabilities	Test(s)	Requirement(s)
Progress Review 1 (14th Feb)	• Can extract sensor data from one or more of the AR headsets • HoloLens 2 can stream a real time point cloud of the surgical workspace to the workstation over WiFi • Can manually drill the surgical pin into the bone and detach it from the drill machine	T1, T2, T3	M.F.1
Progress Review 2 (28th Feb)	• Teleoperate/Backdrive the KUKA arm to manually drill and let go of the surgical pin in the bone model • Can send messages from AR to the workstation at minimal latency	T4	M.F.10
Progress Review 3 (21st Mar)	• KUKA arm can now drill autonomously and lets go of the surgical pin in the bone model • All subsystems interfaced with ROS2 • Able to register surgical plan to live point cloud data	T5, T6	M.F.3
Progress Review 4 (4th Apr)	• Drill sites can be overlaid and updated on the patient's bone in real time • Demonstrate E-stop for both drill and manipulator	T7, T8, T9	M.F.5, M.F.11
SVD (17th Apr)	• Obtain drilling pose and depth from surgical plan through registration • Overlay the drill sites in augmented reality. • Move end-effector to drill pose and drill autonomously, leaving the pin into the bone model	T10	M.F.9, M.F.13
SVD Encore (24th Apr)	Improve the system according to the feedback from SVD	—	—

4 Tests

The section contains the tables for each test, specifying objectives, elements involved, locations, equipment, personnel, procedures to be followed, and verification criteria for the successful validation of our system to be able to meet the desired performance requirements.

Test No. 1: Reliably access sensor data from the Microsoft HoloLens2	
Objective	Deem the suitability of the headset
Elements	Subsystem Interface
Location	NSH B512
Equipment	Workstation, Microsoft HoloLens2
Personnel	Sreeharsha, Daksh
Procedure	
1.	Setup a custom Wifi network for data transmission between the headset and the Workstation.
2.	Deploy a Unity based app on the HoloLens2 to read sensor data and wirelessly transmit RGB and pointcloud data.
3.	Measure latency of the transmission between the offboard compute and the HoloLens2.
4.	Repeat the task in various settings within the testing environment and at various distances to the Wifi Router.
5.	Visualize the latency and distance graphs for the individual and combined data types.
Verification Criteria	
1.	Capture the bone's point cloud with a density of 0.5 point/mm^3
2.	Track the fiducial markers at the manipulator base at 1 frame per second (fps).
3.	The data is received off-board with minimal packet loss and is qualitatively of good quality.
4.	The latency is constant or doesn't change much as the AR moves closer and further away from the patient.
5.	Validate that the sensor data received is time synchronous.

Test No. 2: Reliably access sensor data from the Magic Leap 2	
Objective	Deem the suitability of the headset
Elements	AR Subsystem
Location	NSH B512
Equipment	Workstation, Magic Leap 2 AR Headset
Personnel	Parth
Procedure	
1.	Setup a custom Wifi network for data transmission between the headset and the Workstation.
2.	Develop an app on Unity and deploy on the Magic Leap 2 to read sensor data and wirelessly transmit RGB and depth data to the workstation.
Verification Criteria	
1.	Capture the bone's point cloud with a density of 0.5 point/mm^3
2.	Track the fiducial markers at the manipulator base at 1 frame per second (fps).

Test No. 3: Manually drill the surgical pin and detach it from the end effector	
Objective	Test the surgical pin latching mechanism
Elements	Hardware Subsystem
Location	NSH B512
Equipment	Surgical Pin, Drill End Effector, Bone Model
Personnel	Daksh
Procedure	
1.	Enable hand-guiding on the KUKA manipulator from the pendant.
2.	Manually insert the surgical pin into the drill.
3.	Manually retract the drill to test if the surgical pin latching mechanism.
4.	After the drill operation, return the manipulator to the home position.
Verification Criteria	
1.	The surgical pin is able to successfully detach from the drill with minimal force in the opposite direction.
2.	The retraction force applied should be less than the weight of the wooden leg rig.

Test No. 4: Lighting Condition Impact Test	
Objective	Determine how different lighting conditions affect AR tracking accuracy, including variations in brightness, shadow interference, and sudden lighting changes.
Elements	AR Subsystem
Location	NSH B512
Equipment	AR Headsets, Perception Module
Personnel	Zihan
Procedure	
1.	Conduct tracking tests in three different lighting environments: bright lighting, dim lighting, and shadowed areas.
2.	Introduce sudden changes in lighting (e.g., turning a spotlight on/off) and observe the impact on tracking stability.
3.	Repeat tests at varying distances and angles to analyze how lighting variations affect system performance.
Verification Criteria	
1.	The AR headset should maintain continuous tracking without significant frame drops or positional drift.
2.	Sudden changes in lighting should not cause loss of tracking for more than 1 second before stabilization.

Test No. 5: Benchmarking perception algorithms on HoloLens2 data	
Objective	Understand the hardware constraints imposed on the perception system
Elements	Perception Subsystem
Location	NSH B512
Equipment	Workstation, Microsoft HoloLens2, Bone STL, SawBone Model
Personnel	Sreeharsha
Procedure	
1.	Debug and build the Paradocs' Docker Container on a portable system like a laptop.
2.	Filter noise from the offline RGB and pointcloud data belonging to the same timestamp.
3.	Convert Bone Model STL to a pointcloud using Open3D.
4.	Repeat the experiment several times with the same RGB, Pointcloud pair, then with a pair taken from various distances and poses from the patient bone.
Verification Criteria	
1.	Successfully able to extract the patient bone from the noisy pointcloud model.
2.	Visualize the extracted pointcloud ontop of the RGB image.
3.	Ensure that the algorithm is running correctly by checking that it returns a non-identity matrix.

Test No. 6: Autonomously Drill a surgical pin with with the new end effector	
Objective	Demonstrate accurate drilling as a basis for repetitive drilling (extended goal)
Elements	Hardware and Planning Subsystem
Location	NSH B512
Equipment	Workstation, KUKA LBR MED 7 Manipulator, End Effector, Surgical Pin, Bone Model
Personnel	Parth, Daksh
Procedure	
1.	Setup the new drill end effector on the manipulator.
2.	Manually insert the surgical pin into the drill end effector.
3.	Send the "drill" command from the control computer to the manipulator and execute the drill operation on the desired drill site.
4.	After the drill operation, return the manipulator to the home position.
Verification Criteria	
1.	The system should be able to drill into the drill site with an accuracy of $\pm$2mm measured from the center of the site.
2.	Navigation to the drill site, drilling the surgical pin and then going back to the home position, all actions should be executed with a single command from the AR headset.

Test No. 7: Overlaying Surgical Points and Cutting Plane on Patient Bone	
Objective	Utilize the perception and AR subsystem of HoloLens 2 to register a bone model onto the actual bone and overlay surgical points and a cutting plane.
Elements	Perception Subsystem, Augmented Reality Subsystem
Location	NSH B512
Equipment	Workstation, Microsoft HoloLens2, Bone Model, Dummy Bone, Surgical Plan
Personnel	Sreeharsha, Parth, Daksh
Procedure	
1.	Convert Bone Model STL to a pointcloud using Open3D.
2.	Register obtained pointcloud data on the bone model pointcloud.
3.	Extract the surgical plan from the bone model, identifying drill points and the cutting plane.
4.	Overlay the extracted surgical points and cutting plane onto the patient's bone.
5.	Repeat the experiment for different viewing angles and distances from the patient bone.
Verification Criteria	
1.	Successfully register the bone model onto the actual patient bone with minimal error.
2.	Accurately extract surgical points and the cutting plane from the bone model and surgical plan.
3.	Visualize the drill sites overlaid on the patient's bone through the HoloLens 2 display with a positional error of $\leq 1mm$.
4.	Ensure the system maintains stable tracking across different perspectives and distances.

Test No. 8: Safety Test for E-Stops	
Objective	Verify both manipulator and drill E-stops are functional
Elements	Mechanical Subsystems
Location	NSH B512
Equipment	KUKA LBR MED 7 Controller, Drill mounted on End Effector, E-Stop attached on Workstation
Personnel	Sreeharsha, Parth, Daksh
Procedure	
1.	Robot is given an arbitrary pose goal that will lead to collision.
2.	Press E-Stop given on KUKA controller to avoid collision.
3.	Drill is turned on and a incorrect surgical point input is given as goal.
4.	Press E-Stop given on workbench to avoid drill breakage.
Verification Criteria	
1.	Confirm the E-stop effectively halts the robot's movement with minimal latency.
2.	Confirm the E-stop effectively halts the drill with minimal latency.

Test No. 9: Network Failure and Recovery Test	
Objective	Ensure that the system can recover if any critical network connection is lost, including AR headset connectivity, main controller communication with the robotic arm, and subsystem failures.
Elements	All Subsystems
Location	NSH B512
Equipment	Workstation, KUKA LBR Med 7 Manipulator, AR Headsets, Network Router, Perception Module
Personnel	Zihan
Procedure	
1.	Disconnect the AR headset from Wi-Fi, reconnect after 10 seconds, and check if the overlay resumes correctly.
2.	Disconnect the main controller from the robotic arm mid-operation and verify if the robot halts safely.
3.	Terminate the perception module during tracking and observe if it restarts automatically while maintaining accuracy.
4.	Cut power to the drill mid-operation, restore it, and ensure the drill does not resume unexpectedly without user confirmation.
Verification Criteria	
1.	The AR headset should reconnect and resume overlays within 30 seconds without misalignment.
2.	The drill should halt safely upon power loss and only resume after explicit user confirmation.

Test No. 10: Spring Validation Demonstration	
Objective	Verify repeatability and robustness of the integrated subsystems.
Elements	AR, Perception, Planning, Control and Hardware subsystems
Location	NSH B512
Equipment	Microsoft HoloLens2, Manipulator, Bone Model, Bone STL, Camera, Workstation
Personnel	All Team Members
Procedure	
1	Ensure the workspace is safe for robot operation.
2	Send *Home* command to manipulator, to test communication and set initial position.
3	Run the registration pipeline to obtain the exact drill site coordinates with respect to the bone setup
4	Overlay the desired drilling locations given by the surgical plan in the AR Headset.
5	Generate the Manipulator Trajectory and await surgeon validation.
6	In case the robot is going off track, or is in a dangerous position, press the Emergency Stop (E-Stop) button.
7	Insert a pin into the latching mechanism
8	Send the *Drill* command.
9	Once the robot finishes drilling, command it to reset its position to home.
Verification Criteria	
1.	The verification criteria for the Spring Validation Demonstration are a subset of the verification criteria of T1 4, T6 4, T7 4, T8 4 and T9 4. These criteria encompass all subsystems of the project.

5 Appendix

5.1 Functional and Performance Requirements

A list of all our Functional and Performance Requirements for the Spring Semester.

Functional Requirement	**Performance Requirement**	**Justification**
M.F.1: Sense and Segment Bone through manipulator and AR camera	M.P.1: Capture the bone's point cloud with a density of 0.5 point/mm^3	Derived based on Paradocs' performance in FVD/encore
M.F.2: Localize Manipulator in AR camera frame	M.P.2: Track fiducial markers on the manipulator at 1fps	Values are derived from the tracking performance of Apple vision Pro
M.F.3: Register bone model to obtained point clouds	M.P.3.1: Perform manipulator registration with a registration error of less than 2.0±0.5mm	State of the art surgical systems have ≤ 2mm registration accuracy
	M.P.3.2: Perform registration with a target registration error of less than 4.0±0.5mm	State of the art augmented reality surgical systems have ≤ 2mm registration accuracy
M.F.4: Compensate for motion of the bone in Surgical Environment	M.P.4: Compensate for motion at 1fps	Values are derived from the tracking performance of Apple vision Pro
M.F.5: Visualize Drill sites as AR overlay on patient's bone	M.P.5: Display the drill sites with a positional error of less than 1mm	Derived based on Paradocs' performance in FVD/encore
M.F.6: Enable Intraop Surgical Plan editing	M.P.6.1: Allow changes in the spatial position with a precision of 0.1mm in 3 DoF	Plan changes are always minor, based on patient anatomy, therefore require high precision
	M.P.6.2: Allow changes in the orientation with a precision of 0.5 degrees in 3 DoF	
	M.P.6.3: Allow changes with a motion-to-photon latency of less than 300ms	A culmination of all latencies from moving the hand to edits in the plan, Based on AR specs.
M.F.7: Display Manipulator Trajectory in the AR	M.P.7: Display the manipulator trajectory with an overlay error of less than 2cm	Relaxed, because the goal is obstacle avoidance not surgical accuracy

Functional Requirement	**Performance Requirement**	**Justification**
M.F.8: Provide Surgeon UI for control inputs	M.P.8: Updates at 4fps to update the surgeon with ”real-time” patient info	Based on general understanding of surgeon requirements
M.F.9: Drill Surgical pins at the 5 bone drill sites	M.P.9: Drill with error $\leq$ 2mm	Derived based on Paradocs' performance in FVD/encore
M.F.10: Allow manual loading/unloading of surgical pins in the end effector	M.P.10: The doctor should be able to swap out the pin in 10 seconds	Reduce time of operation
M.F.11: Provide both a physical and virtual Emergency Stop	M.P.11: Halt all motions within 100ms (physical) and 250ms (AR) in the event of an emergency	Competitor systems have similar quantification

5.2 Non-Functional Requirements

- N.R.1: The system will provide a simple, easy-to-understand interface.
- N.R.2: The system will minimize cognitive load by displaying only essential and critical information during surgery.
- N.R.3: The system will have a low latency AR sub-system to allow for real-time visualization.
- N.R.4: The system will allow the doctor to place the robot arm at a designated initial position.
- N.R.5: The system will be designed to enable quick setup in the operating room.
- N.R.6: The system will require minimal training for surgeons to operate effectively.
- N.R.7: The system will be ergonomic, ensuring comfortable use during surgery.
- N.R.8: The system will ensure all its components are easy to sterilize.
- N.R.9: The system will ensure the AR components have sufficient battery life for uninterrupted use during surgery.
- N.R.10: The system will follow all relevant ISO standards for medical robotic systems.