Conceptual Design Review Report
Fall 2024

Augmented Reality assisted Robotic Total Knee Arthroplasty

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Sponsor: Smith+Nephew

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Project Description

Affecting millions globally, osteoarthritis causes joint damage and pain, primarily in older adults. Rising obesity and aging populations highlight the need for precise surgical solutions. This project aims to develop an AR-assisted robotic system for Total Knee Arthroplasty (TKA) to address the growing prevalence of osteoarthritis. The project integrates robotics and AR to enhance surgical precision, minimize risks, and improve patient outcomes. Core modules include hardware development, perception systems for real-time bone segmentation, surgical planning algorithms, and an AR interface for enhanced surgeon guidance. This innovative approach aims to revolutionize TKA procedures by improving accuracy and addressing the complex challenges posed by osteoarthritis.

Use Case

Dr. Napoleon (he/him), an experienced orthopedic surgeon, is preparing to perform a total knee replacement surgery for a patient with severe arthritis. Before the operation, using the 3D model of the bone anatomy obtained from medical images, he generates a pre-operative surgical plan that details the desired location and pose of the surgical pins on the bone.

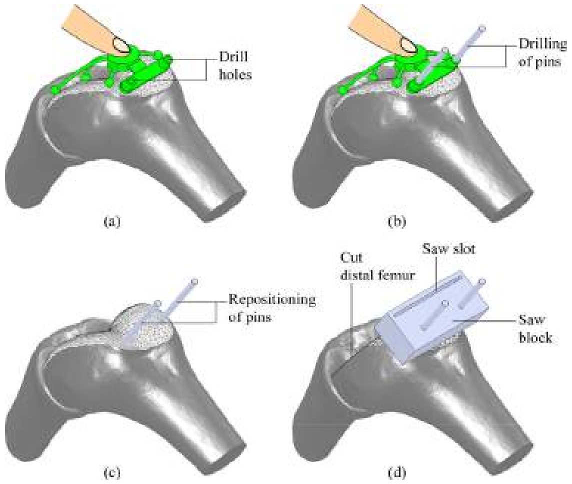


Figure 1: An artistic impression of how surgical pins and guides are used in TKA

The procedure begins with the patient positioned on their back, with the affected knee fully flexed and facing upward. Dr. Napoleon, taking visual cues from the Augmented Reality (AR) headset, clears the surgical site, carefully removing skin and fat to expose the knee joint. He then positions the robot arm to be directly above the knee joint. With the joint partially exposed, the robot arm camera creates a 3D point cloud of the surgical workspace, which is used to register the pre-operative bone model and surgical plan with the patient's exposed bone.

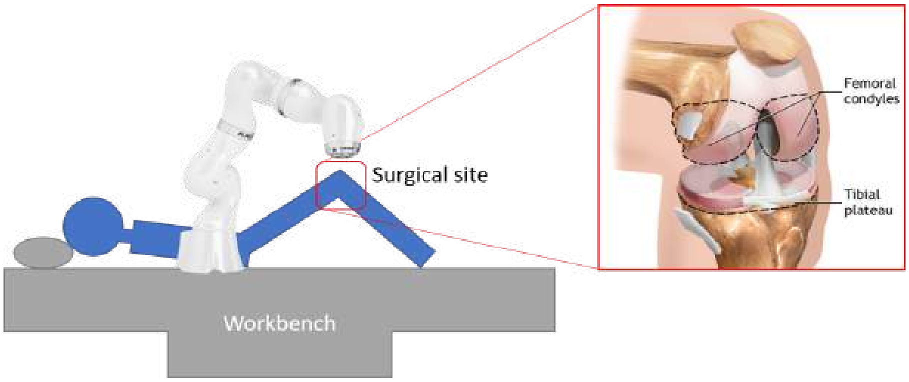


Figure 2: Graphical representation of surgical positioning

In the event of osteophytes or unexpected soft tissue that was not accounted for in the surgical plan, Dr. Napoleon uses the AR headset's intuitive surgical plan editing user interface (UI) to make immediate adjustments to the surgical plan. Once the surgical plan is finalized, the AR headset visualizes the robot arm's planned movements within the surgical environment. Dr. Napoleon ensures there are no obstacles in its path, confirming a clear operational environment.

With final approval from the surgeon, the robot arm autonomously drills the surgical pins into the bone at the drill sites. If the patient flinches before the drilling starts, the robot arm camera and the AR headset camera work in conjunction to compensate for the motion and re-register the bone model in the view of the robot arm camera. After precisely drilling a pin, Dr. Napoleon loads the end effector with another surgical pin, and the robot drills it at the following site. This process repeats for all planned drill sites. The AR headset provides continuous feedback throughout the procedure, including live visuals of the robot's actions. If needed, Dr. Napoleon can instantly halt the process using a physical emergency stop (E-stop) button on the workbench or the virtual button in the AR.

Once the robot has drilled all five pins, it stops, allowing the doctor to remove the arm from the surgical environment and make cuts in the bone to proceed with the operation.

The following diagram outlines the workflow for a total knee replacement surgery, highlighting the roles of the surgeon(highlighted in white) and the BONE.P.A.R.T.E. system (highlighted in green).

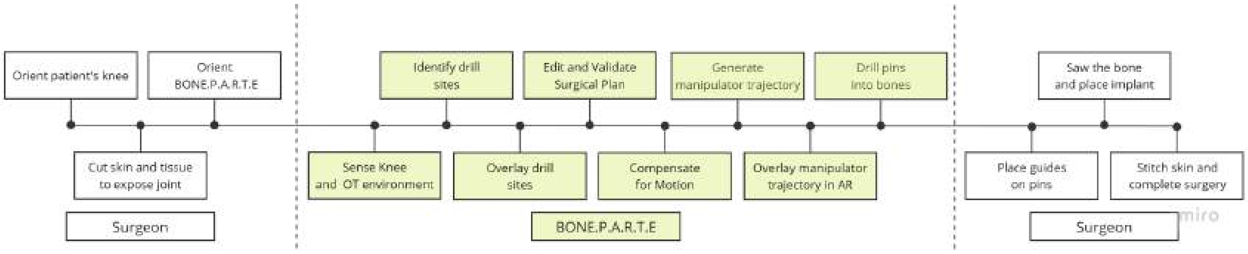


Figure 3: Total Knee arthroplasty timeline highlighting surgeon and system roles

System-Level Requirements

Through our thorough needs analysis which consisted of meetings with the customer (the sponsor), reaching out to the users (the doctors) and factoring in our learning objectives, we arrived at the below lists of functional and non-functional requirements.

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 **M.P.3.2:** Perform registration with a target registration error of less than 4.0+- 0.5mm	State of the art surgical systems have <2mm registration accuracy 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 derives from the tracking performance of Apple vision Pro
M.F.5: Visualize Drill sites as AR overlay on patients bone	**M.P.5:** Display the drill sites with a positional error of less than 1 mm	Derived based on Paradocs's 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 **M.P.6.2:** Allow changes in the orientation with a precision of 0.5 degrees in 3DoF **M.P.6.3:** Allow changes with a motion-to-photon latency of less	Plan changes are always minor, based on patient anatomy, therefore require high precision A culmination of all latencies from moving the hand to edits in the plan, Based on AR specs.

	than 300ms	
M.F.7: Display Manipulator Trajectory in the AR	**M.P.7:** Display the manipulator trajectory with a overlay error of less than 2cm	Relaxed, because the goal is obstacle avoidance not surgical accuracy
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 < 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 100 ms(physical) and 250 ms(AR) in the event of an emergency	Competitor systems have similar quantification

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.

Functional Architecture

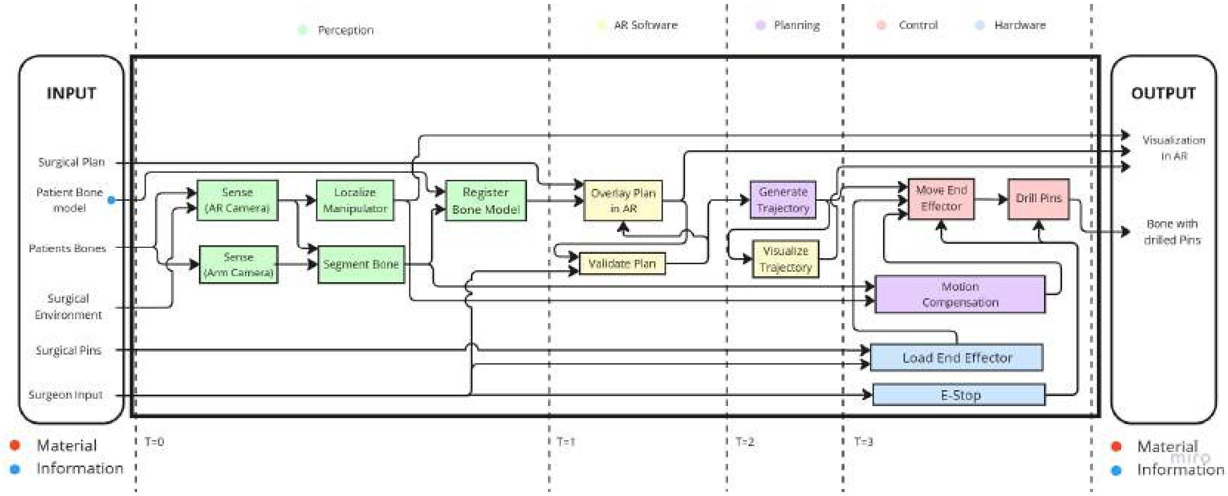


Figure 4: Functional Architecture

The system has been divided based on the when a function will be performed between T=0 (representing the start of system) and T=4 (representing post-drilling time stance)

- **T=0 to T=1**
  The system begins with inputs such as the surgical plan, patient bone model, and surgical environmental data. It uses the cameras available to sense the environment as a point cloud, localize the manipulator with the help of fiducial markers, segment the bone from the sensed information and finally register the pre-operative bono model onto the sensed cloud
- **T=1 to T=2**
  In the second phase, the augmented reality headset enables the surgeon to overlay the surgical plan directly onto the patient’s actual bone, providing a more intuitive and lifelike visualization. Additionally, the AR system allows for iterative edits to the plan, enabling the surgeon to refine and re-visualize it until fully satisfied.
- **T=2 to T=3**
  In the third phase, the finalized surgical plan is sent to the off-board computer, which generates a trajectory for the robotic manipulator to drill pins at the specified points. The trajectory is visualized through the AR headset, allowing the surgeon or assistant to remove potential obstacles, ensuring safety in the constrained surgical environment.
- **T=3 to T=4**
  Finally, the trajectory is executed, guiding the end effector to drill pins into the bone. The surgeon or assistant loads the end effector with surgical pins as needed during the manipulator's homing process. Before drilling, the motion compensation function aligns the manipulator with the patient’s knee joint, allowing limited movement while maintaining precision.

System and Subsystem Level Trade Study

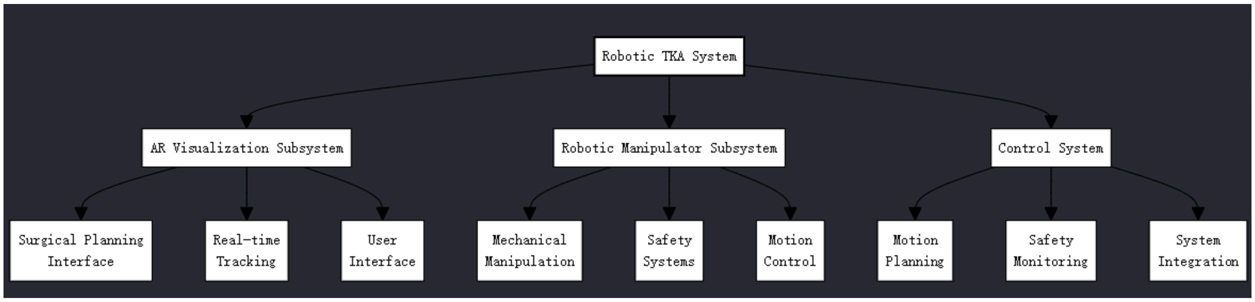


Figure 5: Subsystems Overview

System Level Trade Study

The system-level trade study evaluates four configurations for robotic assistance in total knee arthroplasty (TKA): Manual, Fully-Teleoperated, Robot-Assisted, and Robot-Assisted with AR (Augmented Reality). The goal is to identify the optimal system that balances precision, safety, usability, and adaptability for enhanced surgical outcomes.

Evaluation Criteria

The systems were scored based on the following weighted criteria:

- Accuracy (13%): Essential for precise pin placement and implant alignment.
- Safety (13%): Minimizing risks to patients and surgeons.
- Task Operation Time (11%): Speed of surgical execution.
- Quality of Visual Feedback (10%): Clarity of real-time feedback.
- Setup Time (10%): Preparation required before surgery.
- Ease of Use (8%): Simplicity of the system interface.
- Comfort of Operation (8%): Ergonomics for the surgeon.
- Dynamic Adaptability (7%): Adjusting to patient movement in real time.
- Cost (7%): Financial feasibility.
- Other factors include Ease of Sterilization (5%), Learning Curve (5%), and FDA Approval Time (3%).

Conclusion

The Robot-Assisted with AR configuration is the optimal solution, excelling in precision, adaptability, and visualization. It addresses deficiencies in other methods, making it the most suitable for TKA surgeries. Future work will focus on refining ergonomic aspects and seamless integration into surgical workflows.

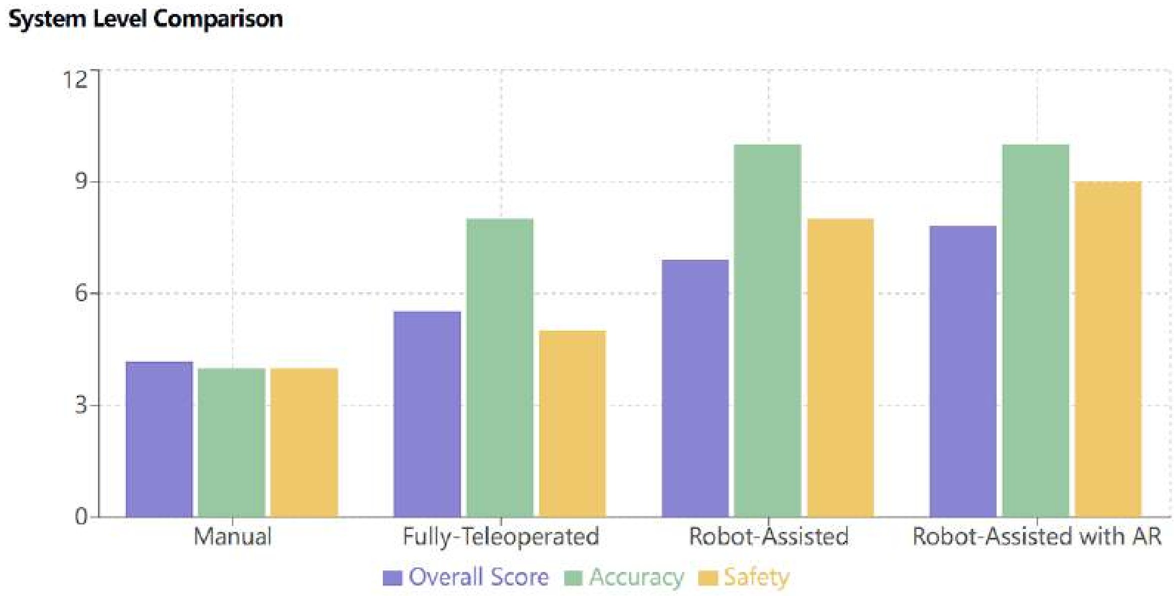


Figure 6: System Level Comparison

Augmented Reality Headset Trade Study

The AR system is critical for precise visualization, surgical planning, and real-time feedback in total knee arthroplasty (TKA).

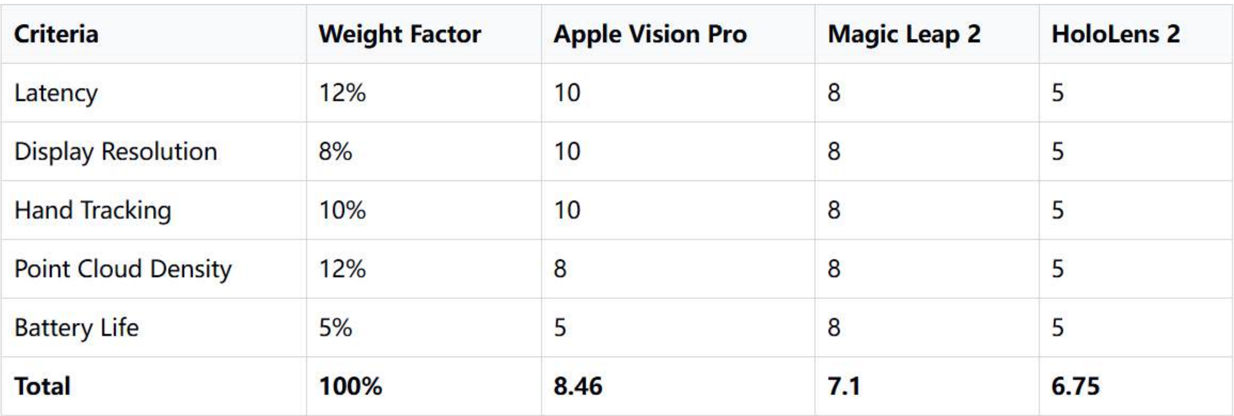
Comparison Method

We employed the Weighted Objectives Method to evaluate the alternatives. The weighting factors and scores were derived from system requirements, emphasizing attributes like latency (critical for real-time feedback), display resolution (for surgical precision), and hand tracking (for intuitive surgeon input).

Key Evaluation Criteria and Scoring

- Latency (12%): Apple Vision Pro scores 10 due to its advanced hardware optimized for low-latency operations. Magic Leap 2 follows with 8, while HoloLens 2 lags with 5, reflecting limitations in its processing capability.
- Display Resolution (8%): Apple Vision Pro leads with a sharp and high-resolution display, earning a score of 10. Magic Leap 2 scores 8, while HoloLens 2 scores 5 due to its comparatively lower resolution.
- Hand Tracking (10%): Apple Vision Pro excels in intuitive surgeon input, scoring 10, while Magic Leap 2 scores 8, and HoloLens 2 scores 5 due to inconsistent tracking performance.

Illustration of Design Concepts



Criteria	Weight Factor	Apple Vision Pro	Magic Leap 2	HoloLens 2
Latency	12%	10	8	5
Display Resolution	8%	10	8	5
Hand Tracking	10%	10	8	5
Point Cloud Density	12%	8	8	5
Battery Life	5%	5	8	5
Total	**100%**	**8.46**	**7.1**	**6.75**

Conclusion

The Apple Vision Pro is the most suitable AR platform, meeting critical system requirements like low latency, high-resolution display, and effective hand tracking. Its ability to integrate seamlessly into the surgical environment ensures precision and usability. The Magic Leap 2 is a secondary option, while the HoloLens 2, despite its ergonomic design, lacks the necessary performance metrics for this application.

Manipulator Arm Trade Study

The robotic manipulator is a key component in the Robotic Total Knee Replacement with AR project, responsible for precise pin placement and surgical guide alignment. This trade study evaluates three options—KUKA LBR Med 7 R800, UR5E, and ABB GoFa 5—based on performance against critical system requirements.

Evaluation Criteria

The manipulators were scored using a Weighted Objectives Method with key criteria:

- Pose Repeatability (12%): Precision for surgical accuracy.
- Safety Features (12%): Patient and surgeon safety.
- Maximum Reach (8%): Workspace coverage.
- Work Volume (10%): Usable operational space.
- Integration and Support (16%): Ease of system integration and manufacturer support.
- Other factors: Speed, weight, IP rating, and cost.

Results

KUKA LBR Med 7 R800:

- Strengths: High precision (0.1 mm), robust safety, and medical-grade certification.
- Weaknesses: Moderate reach (800 mm).

Final Score: 7.39—Ideal for TKA due to precision and safety.

UR5E:

- Strengths: High reach (850 mm) and cost-effectiveness.
- Weaknesses: Lower precision and fewer medical-specific safety features.

Final Score: 6.26—Versatile but lacks surgical precision.

ABB GoFa 5:

- Strengths: Longest reach (950 mm) and high speed (2.2 m/s).
- Weaknesses: Limited medical compliance and integration challenges.

Final Score: 6.51—Better suited for industrial tasks.

Conclusion

The KUKA LBR Med 7 R800 is the best option, balancing precision, safety, and medical compatibility. Future work will focus on integrating this manipulator into the system and validating its performance.

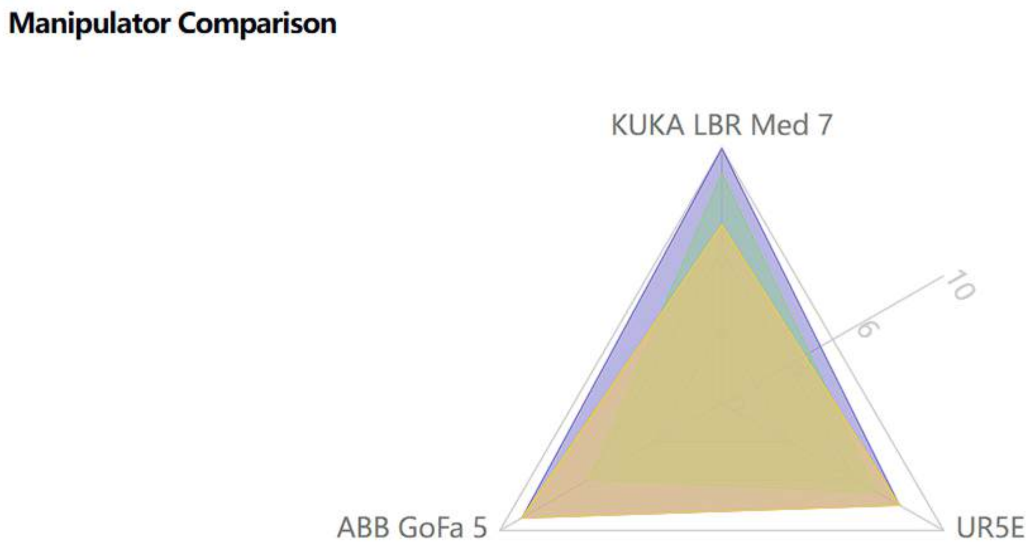


Figure 7: Manipulator Comparison

Cyber-physical Architecture

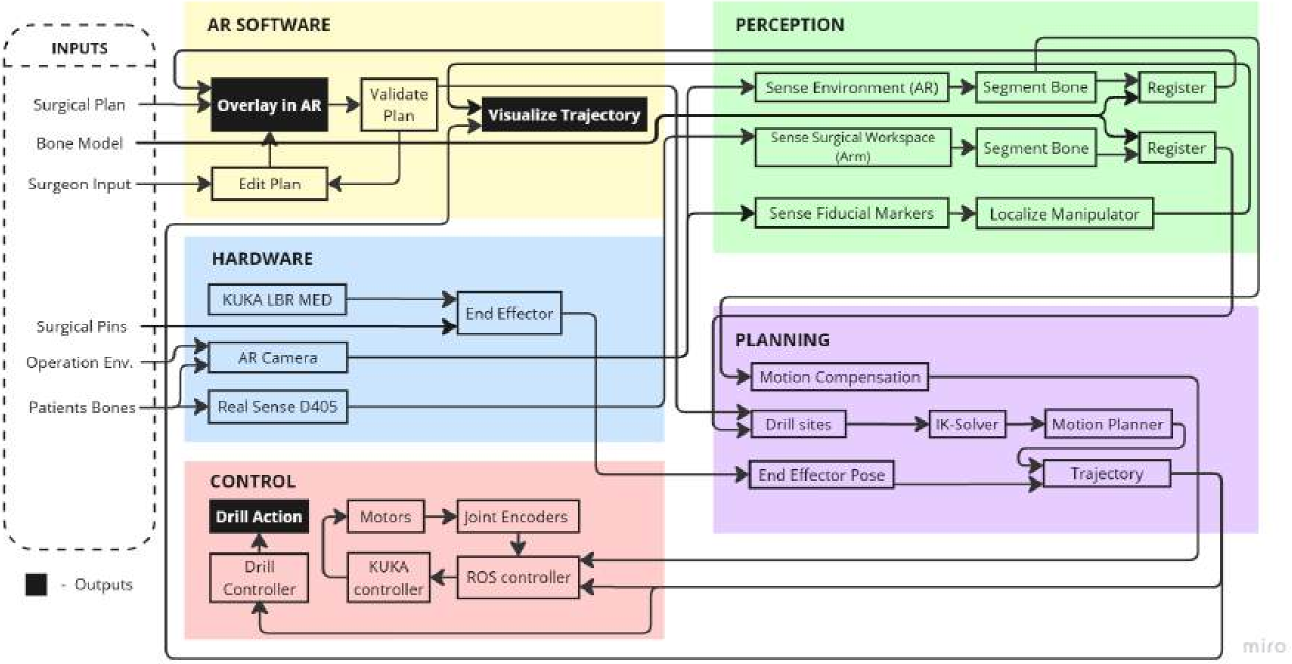


Figure 8: Cyber-physical ARchitecture

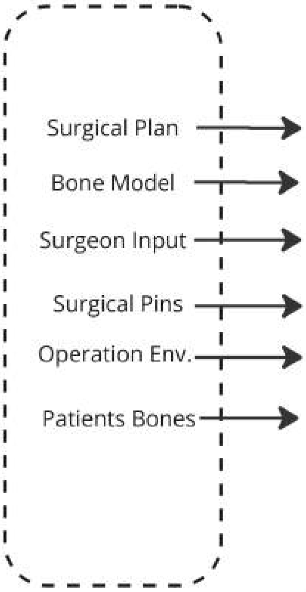
The complete Cyber-Physical architecture of our system is shown above. It was constructed by expanding on each functional block and various steps that are needed to perform that function. The system is organized into five main modules and an input block, below is a brief overview of each block.

- Input
- AR Software
- Perception
- Hardware
- Planning
- Control

Subsystem Descriptions

In this section, we will elaborate on the subsystems highlighted in our cyber-physical architecture and compare them to the subsystems used by team Paradocs to highlight where the technical differences between both methods lie.

- INPUT :



1. **Surgical Plan**: A preoperative plan developed by the surgeons, outlining the procedure.
2. **Bone Model**: A 3D model (STL file) generated from medical imaging techniques.
3. **Surgeon Input**: Interaction between the surgeon and the system, facilitated through hardware and the AR headset for software control.
4. **Surgical Pins**: Pins referenced in the project overview, essential for the procedure.
5. **Operation Environment**: A bird’s-eye view of the surgical bed, encompassing the patient and surrounding equipment.
6. **Patient’s Bones**: The physical bones of the patient, which are perceived by the cameras and manipulated by the robotic system for drilling.

AR SOFTWARE

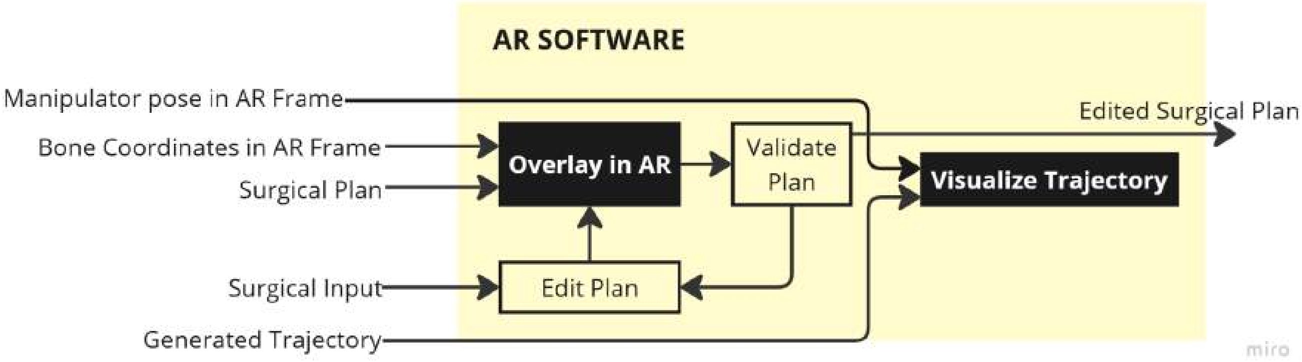


Figure 9: AR Software Subsystem

The primary use case of the Augmented Reality (AR) headset is to make the surgery more comfortable and efficient for surgeons by providing a visual user interface that displays information critical to the surgery such as an overlay of the input 3D bone model on the patient's exposed bone. This feature will allow doctors to verify visually if the pre-operative surgical plan still holds good after exposing the knee bone and seeing it for the first time. Additionally, the AR software subsystem will allow for the surgeon to visualize the manipulator arm trajectory in 3D space so as to ensure that the operating workspace is devoid of any person or object that might pose a safety risk to the robot, or equipment, or patient, or surgeon.

The AR subsystem receives “bone coordinates in the AR frame” from the perception module and the surgical plan as input. These inputs are processed to overlay the surgical plan, represented as highlighted markers (e.g., red dots) on the patient’s bone. To allow plan adjustments, the AR interface includes a user-friendly editing UI for the surgeon, which is then sent as an output of the subsystem to the planning stack. Furthermore, the AR subsystem visualizes the manipulator's motion trajectory in real time. This visualization is achieved by combining the manipulator’s current position from the perception module with the planned trajectory from the planning block. Together, these features enable surgeons to adjust, validate, and monitor the surgical procedure effectively.

PERCEPTION

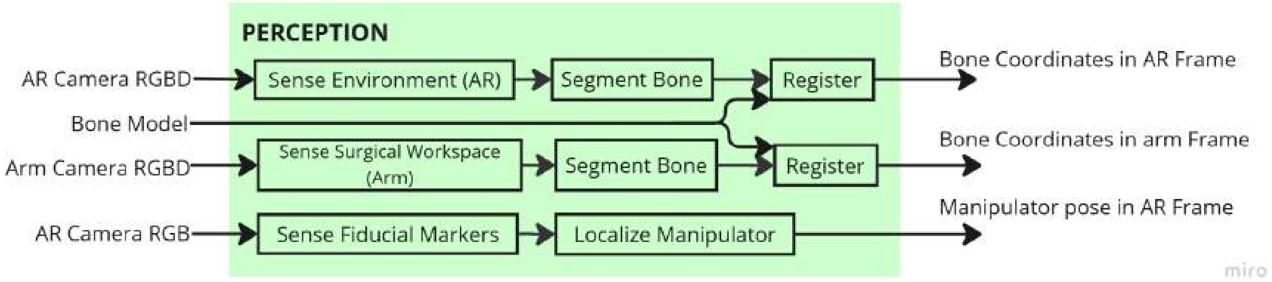


Figure 11: Perception Subsystem

A sponsor requirement is to eliminate the "line-of-sight" issue that is posed by having an externally mounted camera that is meant to sense the workspace, being blocked by an environment variable like the surgeon themselves. To tackle this, the ideal placement of the camera would be on the robot end-effector. However, this location poses constraints on the form factor and weight of the camera and ideally the smaller and lighter the camera - the better for our task - as a camera with a smaller baseline would provide better depth resolution closer to the camera than a camera with a larger baseline - and overall system reliability.

The ideal choice for this camera is the Intel Realsense D405 with dimensions of 42mm x 42mm x 23mm and a weight of 60 grams cite. Team Paradocs has successfully developed this camera using the realsense-ros package that wraps around the librealsense2 library. This camera view gives us the surgical workspace point cloud that is then processed to segment out the bone its 3D mesh model and register it to the pre-operative surgical bone model.

Moreover, the AR serves as not just a visualization interface between the robot arm system and the human (surgeon) but also provides spatial information from its onboard sensing. Similar to the operation done on the surgical workspace point cloud, we will develop an algorithm bespoke to the, and tune its parameters to extract as much information as possible from the sensing system (either RGBD or LiDAR) on the AR headset of choice. Additionally, the AR sensing system will use the fiducial markers present on the manipulator base to localize the location of the manipulator with respect to the headset in 3D space. Using manipulator forward kinematics, the location of the end-effector can easily be determined in the AR coordinate frame.

Thus, we can see that given the multi-sensory nature and scale of our 3D workspace sensing task, we will utilize as much of the Paradoc's perception stack as possible and also build over it, particularly utilizing the capabilities of AR, not just as a visualization tool but as a sensor stack in itself.

HARDWARE

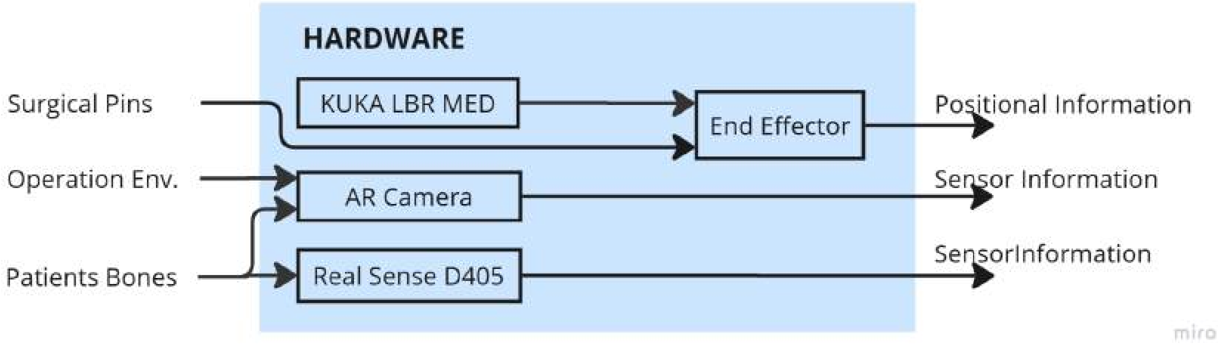


Figure 11: Hardware Subsystem

The hardware subsystem comprises four key components: the robotic arm, a custom-designed end effector, the camera mounted on the end effector, and the AR sensors. Together, these elements form the physical infrastructure of the system, facilitating both perception and interaction within the surgical environment. The primary inputs to the hardware include surgical pins, which are manipulated by the end effector, and the operating environment, which is captured by the cameras. These inputs allow the hardware to execute critical functions such as drilling surgical pins into the bone and gathering environmental data for real-time perception.

The system leverages RGB-D data acquired from both the AR cameras and the RealSense D405, which is transmitted to the perception stack for processing. The robotic manipulator, equipped with its proprietary KUKA controller, provides positional feedback that feeds into the planning stack to ensure precise motion control. To meet the specific requirement of drilling five pins in accordance with the surgical plan, a custom end effector will be developed. This end effector presents two main challenges: first, it must allow the surgeon to reload the surgical pin so it can be drilled into place; second, it must include a mechanism to detach the surgical pin once the drilling action is completed. Addressing these challenges will require significant mechanical design expertise. Consequently, only the drill and robotic arm functionalities from Paradocs' existing work will be leveraged

PLANNING

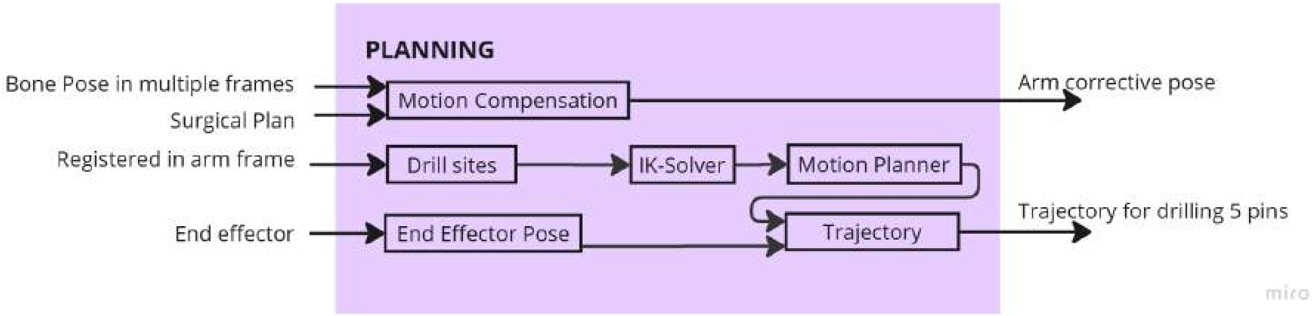


Figure 12: Planning Subsystem

The planning stack is responsible for translating the surgical plan into actionable robotic motions. Its primary goal is to generate a collision-free trajectory for the robotic manipulator to drill surgical pins at precise locations on the patient's bone. It also handles real-time adjustments to account for unintended patient movement through the Motion Compensation module. A key difference from Paradocs' implementation lies in the complexity of our task, as we are drilling at five separate sites and inserting the pins directly into the bone. As the procedure progresses, the pins remain embedded, altering the manipulator's workspace and necessitating updates in the MoveIt planner. These changes will be simulated within the planning stack to ensure accurate trajectory planning before execution.
The planning stack processes multiple inputs, including the bone pose in various frames, registered drill sites in the arm frame, and the real-time pose of the end effector. It starts with the Motion Compensation module, which generates corrective arm poses to maintain alignment by using both top-view data from the AR sensors and a complete environment view. Next, the Perception block's top-view data is used to map the surgical plan to spatial coordinates, which are fed into the Inverse Kinematics (IK) Solver to compute feasible joint configurations. The Motion Planner then generates a trajectory for the arm to follow, accounting for constraints introduced by previously drilled pins.

This stack outputs two critical components: corrective arm poses for motion compensation and trajectories for the drilling sequence. Due to the unique challenges of dynamic compensation and sequential drilling, we anticipate minimal reuse of Paradocs' tech stack, relying primarily on their basic MoveIt integration with the KUKA arm for compatibility.

CONTROL

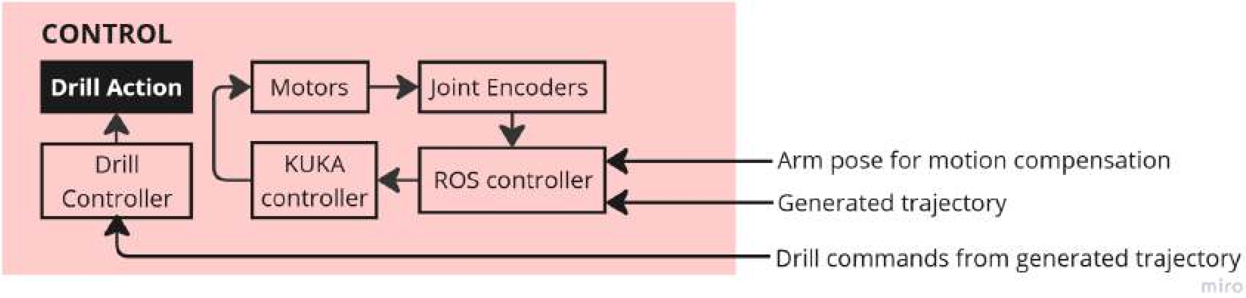


Figure 13: Control Subsystem

With the added functionality of the AR Emergency Stop and a pause between each drill operation, our control stack should share every functionality offered by the Paradoc's control stack, thus we estimate to use 100% of the Paradoc's control stack in our project.

Project Management

Project Schedule

Derived from the Work-breakdown structure, our internal and external milestones for Spring 2024 are listed below in table __.

For milestone 1, we aim to get familiar with the existing tech stack completely which we have inherited from the MRSD 2025 team Paradocs. For milestones 2 and 3, we will build the full end effector subsystem and test its operation by drilling a bone model without any involvement of the manipulator arm. After the extensive and testing of all the 3 available headsets we will choose the final AR headset to work with for milestone 4. For milestone 5, our plan is to demonstrate the overlaying of the drill sites onto the patient's bone i.e., the Sawbones bone model in our case, and perform a successful single drill on the bone model to complete milestone 6. For milestones we will attain the functional requirements we selected for SVD and SVD Encore.

For milestone 8-10, we will once again be building modules under specific subsystems, and integrate all the subsystems in milestone 11. For milestone 12, we will test the full system. For milestone 13 and 14, we will attain all the functional and performance requirements we selected for FVD.

For progress review 1, we aim to have the workbench ready and KUKA arm and drill attached.

For progress review 2, we aim to have developed individual modules and have made a first attempt at integrating the system.

The detailed schedule Gantt chart for Spring 2024 is given in Figure 8.2. The schedule for Fall 2024 can

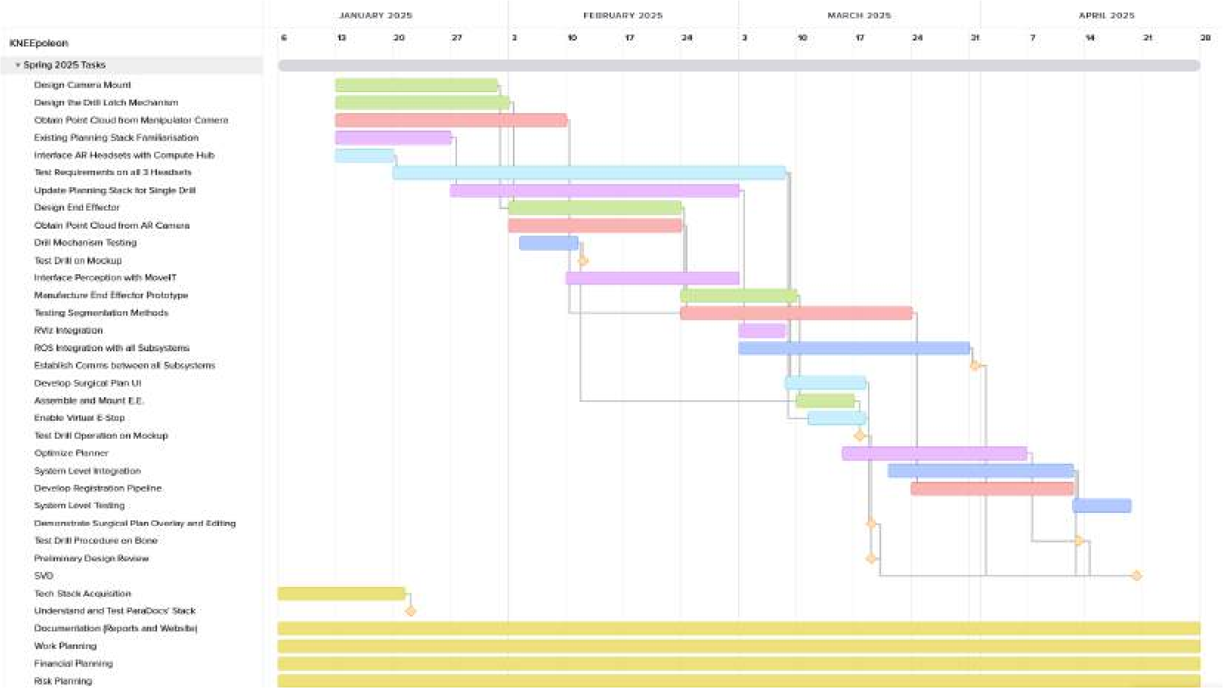


Figure 14: Spring 2025 Gantt Chart

Work Breakdown Structure

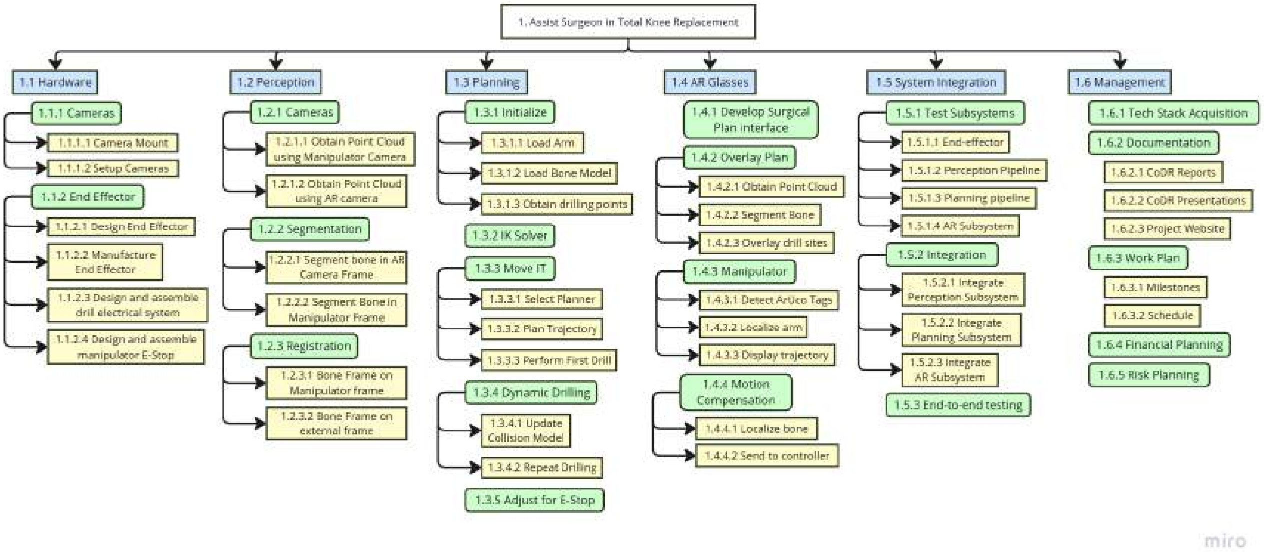


Figure 15: Work-breakdown Structure

The Work Breakdown Structure (WBS) provides a systematic framework to organize, manage, and execute the development of an augmented reality-assisted robotic system for Total Knee Arthroplasty (TKA). By breaking down the project into discrete and manageable components, the WBS ensures clarity in defining roles, responsibilities, deliverables, and interdependencies. This approach is critical to ensuring that each team member focuses on their assigned tasks while contributing to the overall project goals. The following provides an overview of the key areas within the WBS and how they contribute to the successful realization of the project.

Hardware development serves as the foundational layer of the KNEEpoleon project, underpinning the robotic operations with reliable physical components. This phase begins with the camera systems, which are pivotal for capturing the surgical site in three-dimensional detail. The team first focuses on designing and installing robust camera mounts to ensure stability during surgery. Subsequently, the cameras are calibrated and configured to deliver precise imaging and depth data, which will be used throughout the surgical planning and execution processes. Another significant element of hardware development is the end effector, the critical component responsible for interacting with the patient’s bone during the procedure. The end effector is meticulously designed to meet stringent medical standards and to perform its tasks with accuracy. Once the design phase is complete, the team manufactures and assembles the end effector, integrating it with a specially developed electrical system for drilling operations. Additionally, a safety-critical emergency stop (E-stop) mechanism is designed and incorporated into the manipulator. This ensures that the system can be halted instantly in the event of an unexpected issue, safeguarding both the patient and the surgical staff.

The perception module is equally vital in enabling the system to interpret and adapt to the surgical environment in real time. This module begins by leveraging cameras mounted on both the manipulator and the augmented reality (AR) system to capture point cloud data, creating a highly detailed three-dimensional representation of the surgical workspace. This data is used as the basis for segmenting the bone, where advanced algorithms process the images to extract precise bone structures. These segmentation tasks are conducted within two different frames of reference: the AR camera frame and the manipulator frame, ensuring redundancy and accuracy in identifying critical landmarks on the bone. Following this, the system performs registration processes to align the segmented bone data with the surgical coordinate system. This step establishes a common reference frame that integrates the preoperative surgical plan with the real-time physical environment, ensuring that all subsequent operations are executed with pinpoint accuracy.

Planning is another cornerstone of the KNEEpoleon project, focusing on the generation of surgical plans and the robotic paths necessary for accurate execution. This begins with the initialization phase, where the system loads the patient’s preoperative bone model and robotic arm configurations. Using this information, the system identifies optimal drilling points on the bone, which are critical for correctly placing surgical pins. The planning module also incorporates an inverse kinematics (IK) solver to calculate the precise movements required for the robotic arm to reach these drilling points while adhering to physical constraints. Dynamic drilling is a particularly innovative aspect of this module, where the system continuously updates a collision model to account for changes in the surgical environment, such as patient movement or unexpected obstacles. This adaptive capability ensures that the robot's movements remain safe and accurate throughout the procedure, reducing the risk of errors. Furthermore, the planning module allows for real-time adjustments, giving surgeons the flexibility to modify the plan if unexpected anatomical variations are encountered.

The augmented reality (AR) module adds an interactive and intuitive dimension to the system, enhancing the surgeon's ability to visualize and interact with the surgical plan. The development of the surgical planning interface is a key step in this module, providing a user-friendly platform for surgeons to view and modify preoperative plans using AR glasses. Once the plan is finalized, the system overlays critical information, such as bone structures and drilling sites, onto the surgeon's AR display, enabling them to see these elements directly in the surgical field. This integration of virtual and physical spaces ensures that the surgeon always has access to real-time, contextualized data. Another vital feature of the AR module is motion compensation. The system continuously tracks the bone's position relative to the manipulator and adjusts the displayed information to account for any shifts. This ensures that the augmented visuals remain accurately aligned with the physical environment, even if the patient moves during the procedure.

System integration phase ensures all subsystems work seamlessly together. Each subsystem—hardware, perception, planning, and AR—is tested independently for functionality and reliability. Once validated, they are integrated step-by-step, starting with perception, followed by planning and AR. Comprehensive end-to-end testing in realistic scenarios identifies and resolves any issues to ensure smooth operation.

Project Management phase coordinates tasks and deliverables, including acquiring necessary tools, creating detailed documentation, and establishing a clear work plan with milestones. Risk management addresses potential challenges, while financial planning ensures efficient resource use and budget adherence.

In conclusion, the Work Breakdown Structure of the KNEEpoleon project provides a clear and organized framework for managing the complex tasks involved in developing an augmented reality-assisted robotic system for TKA. Each module—hardware, perception, planning, augmented reality, system integration, and project management—plays a critical role in ensuring the system's success. By systematically addressing each aspect of the project, the WBS not only facilitates effective task management but also aligns the team's efforts toward achieving the overarching goal of enhancing surgical precision and patient outcomes. This structured approach lays the foundation for a groundbreaking solution that promises to revolutionize the field of robotic-assisted surgery.

WBS Dictionary

The WBS dictionary is an essential component of the Work Breakdown Structure (WBS) that provides detailed information about each task or work package, offering clarity and precision to project stakeholders. It serves as an accompanying document to the WBS hierarchy, offering descriptions, deliverables, estimated time frames, resource requirements, and dependencies for every identified task.

For the KNEEpoleon project, the WBS dictionary ensures that each work package, ranging from hardware development to system integration, is well-defined and aligned with project goals. Below is a detailed overview of how the WBS dictionary is structured and its role in the project's success.

WBS ID: 1.1.2.2

Work Package Name: Manufacture End Effector

Task Description: Fabricate and assemble the end effector based on the finalized design specifications. This includes machining components, assembling parts, and conducting initial inspections for quality and functionality.

Deliverables: A fully manufactured and assembled end effector.

Estimated Time: 3 weeks.

Resource Requirements: Access to a machining workshop and 3D printers. Raw materials. Assembly tools and quality testing equipment.

Dependencies: Requires completion of 1.1.2.1 (Design End Effector).

Take the above WBS dictionary as an example, each work package in the WBS dictionary begins with a unique identifier corresponding to its position in the WBS hierarchy. For example, a hardware-related task such as "1.1.2.2 – Manufacture End Effector" includes critical details about what the task entails. This work package involves fabricating and assembling the robotic end effector based on the finalized design specifications. The deliverable for this task is a fully functional and tested end effector ready for integration into the larger robotic system. The estimated timeframe for this task is three weeks, requiring access to machining workshops, raw materials, and quality testing equipment. This task also has specific dependencies, such as the prior completion of "1.1.2.1 – Design End Effector," ensuring a logical sequence of execution.

Here are more examples:

WBS ID: 1.2.1.1

Work Package Name: Obtain Point Cloud using Manipulator Camera

Task Description: Use the camera mounted on the manipulator to capture depth images and process them into a 3D point cloud. This involves configuring the camera, calibrating it, and ensuring accurate data acquisition.

Deliverables: A calibrated and functional manipulator-mounted camera. A high-quality 3D point cloud dataset of the target object/environment.

Estimated Time: 2 weeks.

Resource Requirements: Manipulator-mounted camera hardware. Access to the robotic manipulator for testing and setup.

Dependencies: Requires completion of 1.1.1.2 (Setup Cameras).

WBS ID: 1.3.2

Work Package Name: IK Solver

Task Description: Develop an Inverse Kinematics (IK) solver to calculate the joint angles required for the manipulator to reach a desired end-effector position and orientation. This includes algorithm design, implementation, and validation using simulation and real-world scenarios. Deliverables: A functional IK solver algorithm integrated with the manipulator control system. Validation results and test cases.

Estimated Time: 2 weeks.

Resource Requirements: Programming environment setup. Manipulator simulation environment.

Dependencies: Requires completion of 1.3.1 (Initialize).

WBS ID: 1.5.3

Work Package Name: End-to-end Testing

Task Description: Perform comprehensive testing of the integrated system to ensure all subsystems (hardware, perception, planning, AR, etc.) function cohesively as a single unit.

Deliverables: A detailed report on system performance, including success rates and failure points. Test logs and videos documenting the end-to-end functionality.

Estimated Time: 3 weeks.

Resource Requirements: Access to the fully assembled and integrated system.

Dependencies: Requires completion of 1.5.2 (Integration).

WBS ID: 1.4.2.3

Work Package Name: Overlay Drill Sites Task

Description: Develop a feature to visually overlay the identified drill sites onto the real bone using AR glasses. This involves aligning the AR display with the real-world coordinates and ensuring accurate registration between virtual markers and physical locations.

Deliverables: AR visual markers accurately displaying drill site locations. Testing and validation reports of the overlay accuracy.

Estimated Time: 3 weeks.

Resource Requirements: AR glasses hardware and SDK. Access to the point cloud and segmented bone data.

Dependencies: Requires completion of 1.4.2.1 (Obtain Point Cloud) and 1.4.2.2 (Segment Bone).

In summary, the WBS dictionary provides a comprehensive description of all tasks within the KNEEpoleon project, ensuring that every work package is clearly defined with specific deliverables, timelines, resources, and dependencies. By documenting these details, the dictionary acts as a reference guide, aligning team efforts and maintaining accountability throughout the project lifecycle. It is an indispensable tool for managing complexity, enabling the project to stay on track and achieve its overarching objectives efficiently.

Risk Management:

When planning out how to manage a project, it's important to account for and manage the risks that might rise due to technical difficulties, communication mishaps, or even malady. Thus, in the following table, we highlight the five most pertinent risks to our project and briefly describe how these risks affect the project as a whole in terms of its schedule and the scope of what the end deliverable will be.

For our project, below, we outline the five most prevalent risks associated with the project and discuss them in further detail in person.

Likelihood and Estimation

Risk ID	Risk Description	Likelihood	Consequence	Mitigation

01	Augmented Reality Headset breaks while testing.	3	4	We test with other headsets given by the sponsor first
02	AR Technical Lead falls ill	3	4	Everyone does some programming on the headset
03	The manipulator end-effector breaks while testing.	3	5	Manufacture end-effectors using Computer-Numeric-Control (CNC) methods
04	Camera Calibration is incorrect	2	4	We try april tags.
05	Chosen AR glasses dont have the speciality needed or guaranteed by others.	4	4	We increase the length of our trade study and test really well.
06	We don’t get the workspace and equipment used by the seniors.	4	2	We email Prof. Dolan to move into the space left by the seniors.

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