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Augmented Reality assisted Robotic Total Knee Arthroplasty

Preliminary Design Review Presentation (PDR)

13th March, 2025

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Meet the Team

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01

Project Overview

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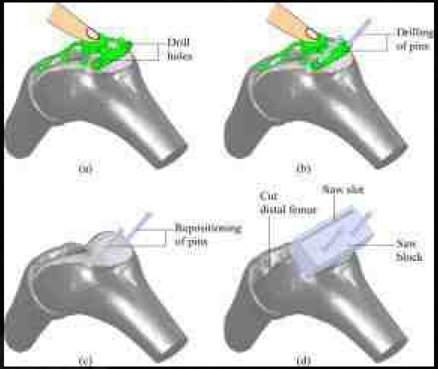
What is Arthritis?

- Can be caused by wear and tear, joint inflammation or sports injuries
- Most commonly manifests itself as Osteoarthritis
- Causes pain, stiffness and osteophytes
- Mandates a Total Knee Arthroplasty (TKA)

Steps in TKA

- Preoperative surgical plan from medical scan
- Patient anesthesia and incision
- Surgical pin screwing
- Guide placement
- Bone cutting
- Artificial joint placement
- Stitch the skin and after care



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Our Solution: **BONE.P.A.R.T.E**

BONE.P.A.R.T.E ->BONE Precision Augmented Reality Tracking Equipment

“A **semi-autonomous** robotic system that provides **detailed visualizations** in the **AR environment** and eliminates the need of surgeons to use intuition to **accurately screw** the pins into the patient’s bone”

This project will drive company growth by updating Smith and Nephew’s current robotic solution with cutting-edge technology that enhances patient and doctor experience

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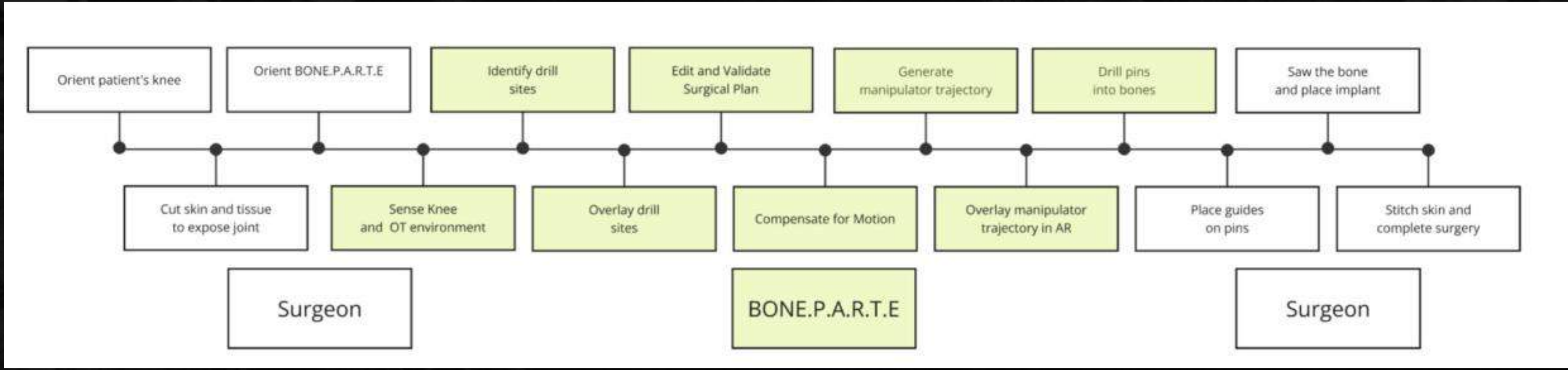

Orient patient's knee
Orient BONE.P.A.R.T.E
Identify drill sites
Edit and Validate Surgical Plan
Generate manipulator trajectory
Drill pins into bones
Saw the bone and place implant
Cut skin and tissue to expose joint
Sense Knee and OT environment
Overlay drill sites
Compensate for Motion
Overlay manipulator trajectory in AR
Place guides on pins
Stitch skin and complete surgery
Surgeon
BONE.P.A.R.T.E
Surgeon

02

Use Case

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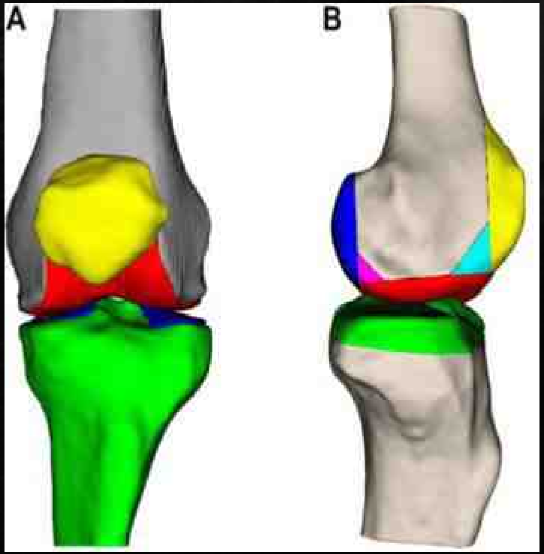
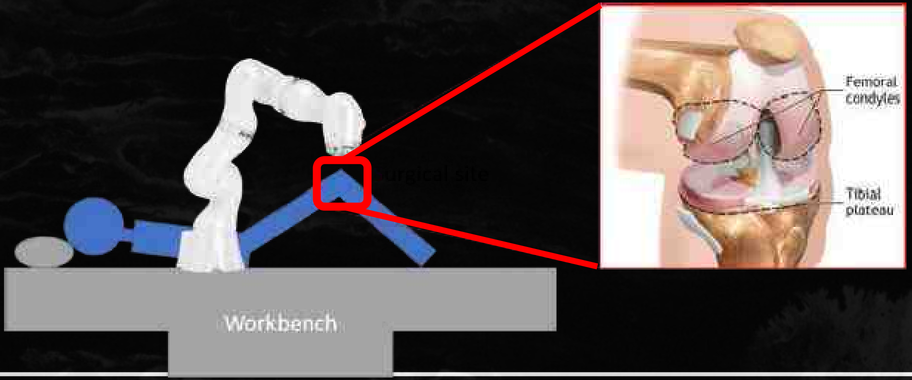
Dr. Napoleon (he/him), an orthopedic surgeon, is preparing to perform a total knee replacement surgery for a patient with severe arthritis. Before the operation, using the 3D model of the bone (obtained from medical imaging), he generates a **pre-operative surgical plan** that details the desired location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



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 surgical plan** with the patient's exposed bone.



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 screws** the surgical pins into the bone at the pin sites.

Source: Paradocsl

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Functional Requirements

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Functional Requirements	Performance Requirements	Justification
Sense and Segment Bone through manipulator and AR camera	Capture the bone's point cloud with a density of 0.5 point/mm^3	Derived based on Paradocs's performance in FVD/encore
Localize Manipulator in AR camera frame	Track fiducial markers on the manipulator at 1fps	Values are derived from the tracking performance of Apple vision Pro
Register bone model to obtained point clouds	• Perform manipulator registration with a registration error of less than 2.0+- 0.5mm • Perform registration with a target registration error of less than 4.0+- 0.5mm	State of the art surgical systems have <2mm registration accuracy
Compensate for motion of the bone in Surgical Environment	Compensate for motion at 1fps	Values are derives from the tracking performance of Apple vision Pro
Visualize Drill sites as AR overlay on patients bone	Display the drill sites with a positional error of less than 1 mm	Derived based on Paradocs's performance in FVD/encore

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Enable Intraop Surgical Plan editing	• Allow changes in the spatial position with a precision of 0.1mm in 3 DoF • Allow changes in the orientation with a precision of 0.5 degrees in 3DoF • Allow changes with a motion-to-photon latency of less than 300ms	• Plan changes are always minor, based on patient anatomy, therefore require high precision • 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.
Display Manipulator Trajectory in the AR	Display the manipulator trajectory with a overlay error of less than 2cm	Relaxed, because the goal is obstacle avoidance not surgical accuracy
Provide Surgeon UI for control inputs	Updates at 4fps to update the surgeon with "real time" patient info	Based on general understanding of surgeon requirements
Drill Sugical pins at the 5 bone drill sites	Drill with error < 2mm	Derived based on Paradocs's performance in FVD/encore
Allow manual loadin/unloadin of surgical pins in the end effector	The doctor should be able to swap out the pin in 10 seconds	Reduce time of operation
Provide both a physical and virtual Emergency Stop	Halt all motions within 100 ms(physical) and 250 ms(AR) in the event of an emergency	Competitor systems have similar quantification

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Functional Architecture

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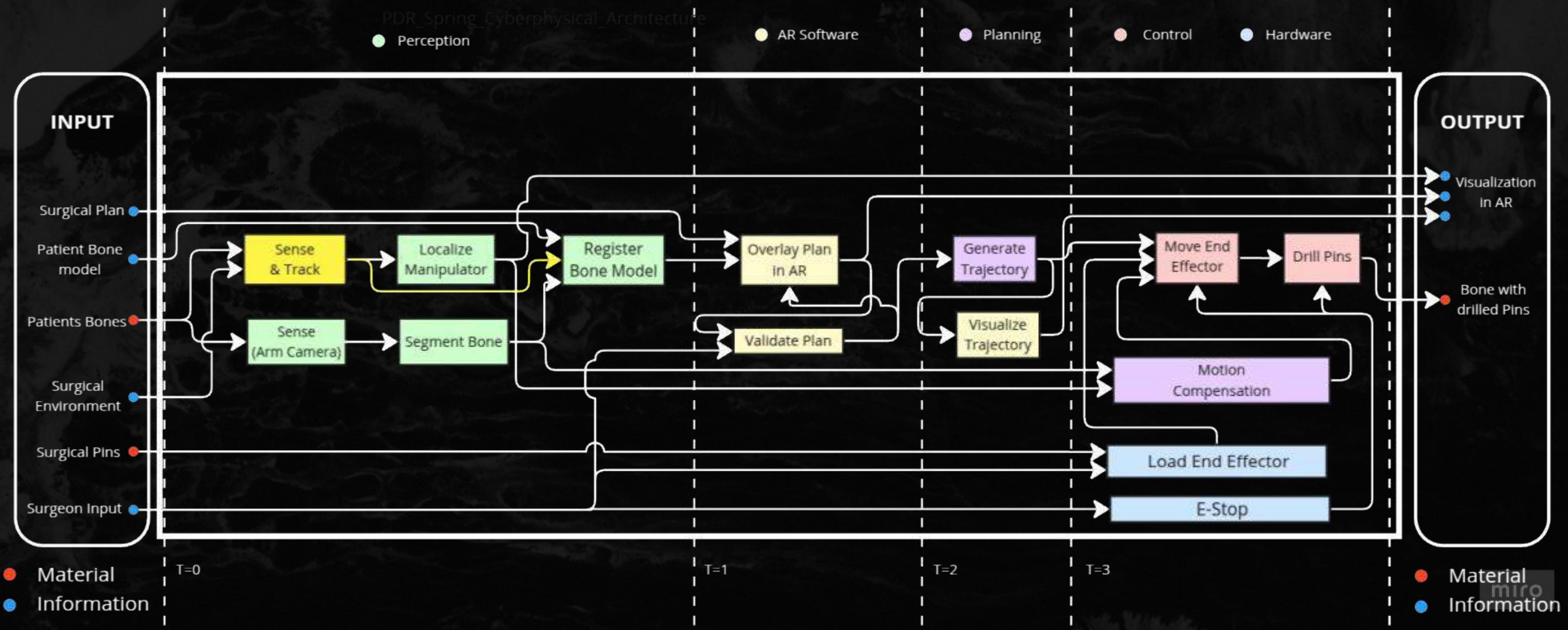

PDR_Spring_Cyberphysical_Architecture
Perception
AR Software
Planning
Control
Hardware
INPUT
OUTPUT
Surgical Plan
Patient Bone model
Patients Bones
Surgical Environment
Surgical Pins
Surgeon Input
Sense & Track
Localize Manipulator
Register Bone Model
Sense (Arm Camera)
Segment Bone
Overlay Plan in AR
Validate Plan
Generate Trajectory
Visualize Trajectory
Move End Effector
Drill Pins
Motion Compensation
Load End Effector
E-Stop
Visualization in AR
Bone with drilled Pins
T=0
T=1
T=2
T=3
Material
Information
Material
Information

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05

Cyber-Physical Architecture

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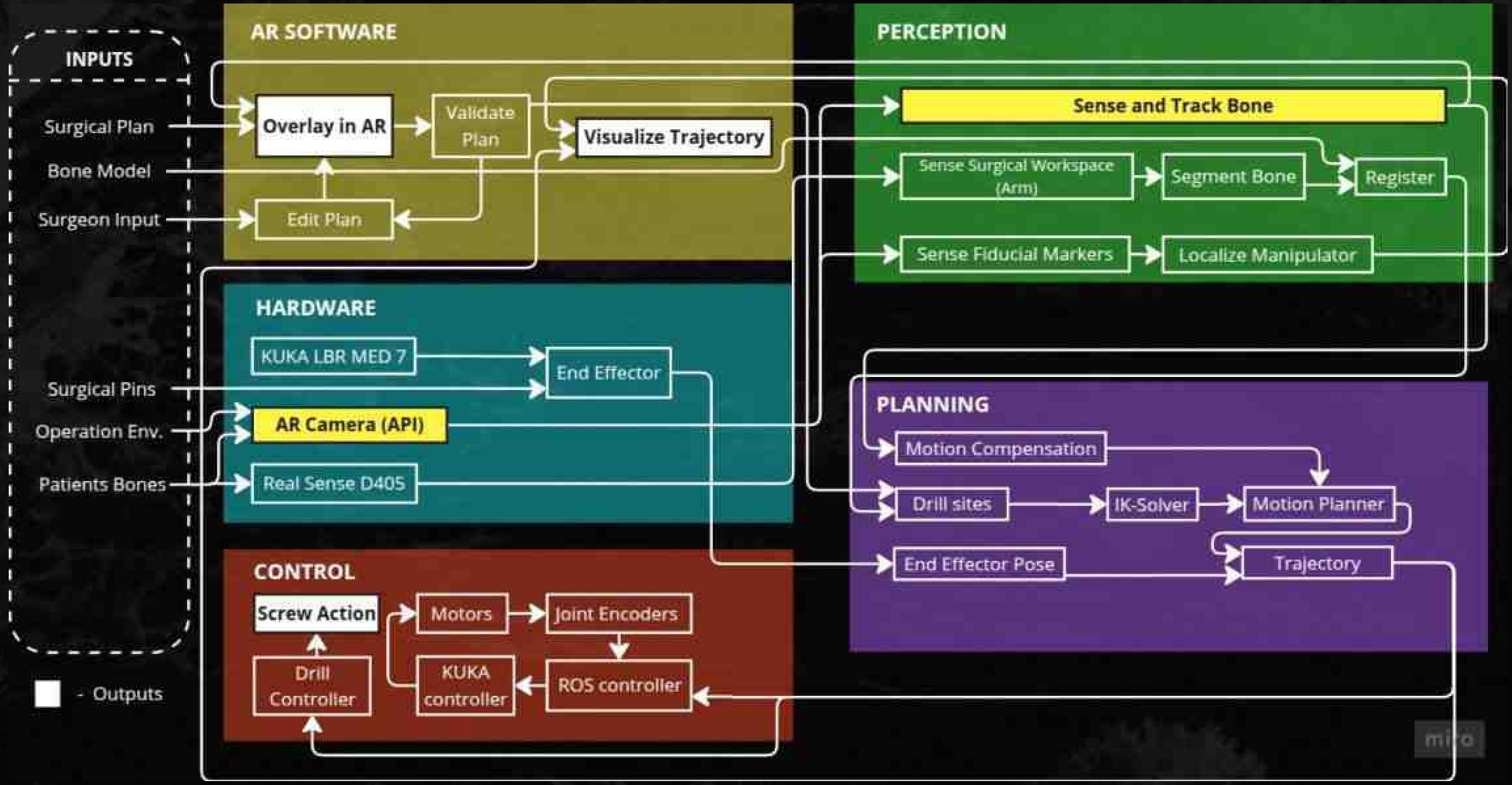
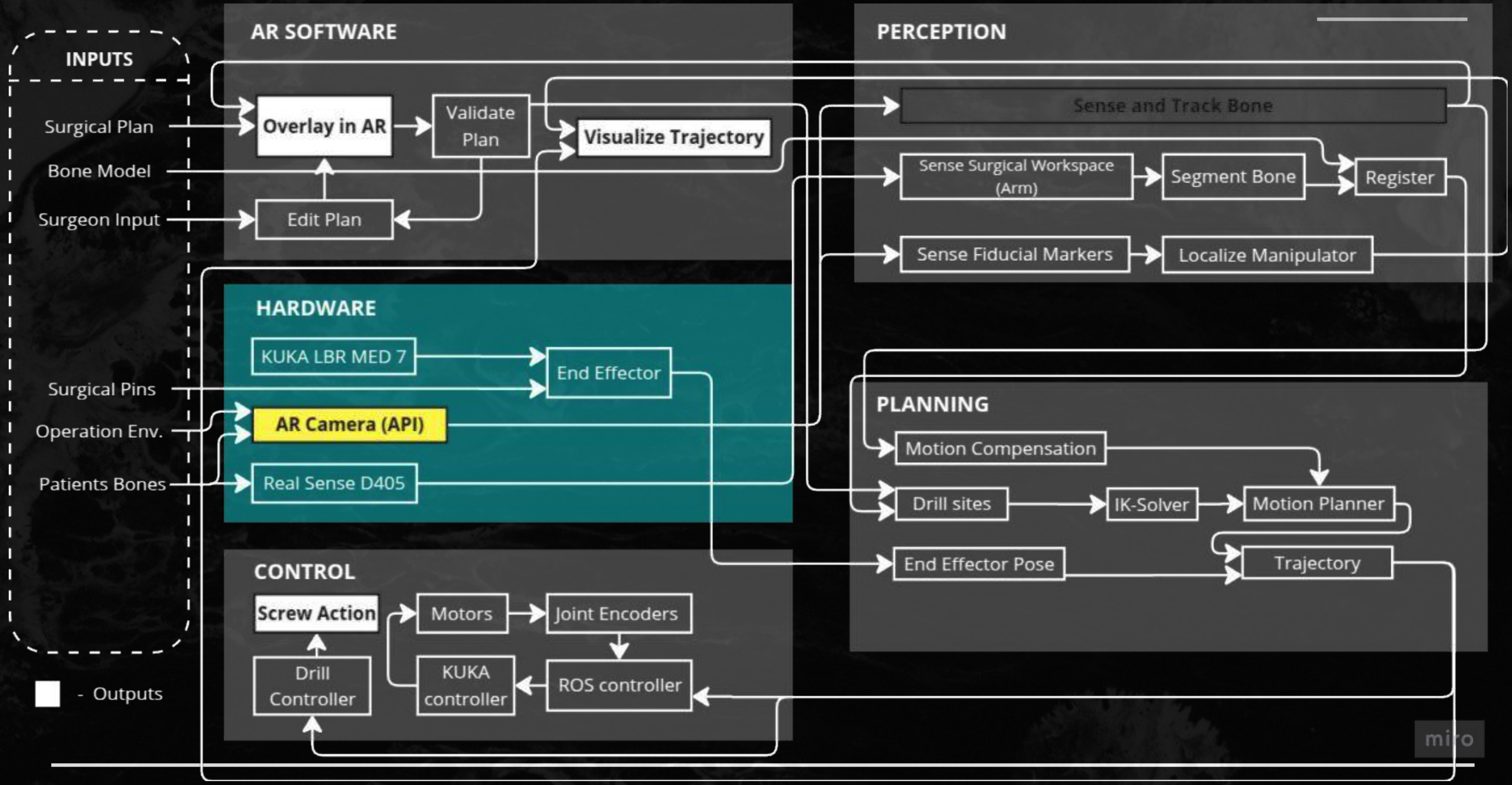

INPUTS
Surgical Plan
Bone Model
Surgeon Input
Surgical Pins
Operation Env.
Patients Bones
AR SOFTWARE
Overlay in AR
Validate Plan
Visualize Trajectory
Edit Plan
PERCEPTION
Sense and Track Bone
Sense Surgical Workspace (Arm)
Segment Bone
Register
Sense Fiducial Markers
Localize Manipulator
HARDWARE
KUKA LBR MED 7
End Effector
AR Camera (API)
Real Sense D405
PLANNING
Motion Compensation
Drill sites
IK-Solver
Motion Planner
End Effector Pose
Trajectory
CONTROL
Screw Action
Motors
Joint Encoders
Drill Controller
KUKA controller
ROS controller
- Outputs
miro



KNEEpoleon
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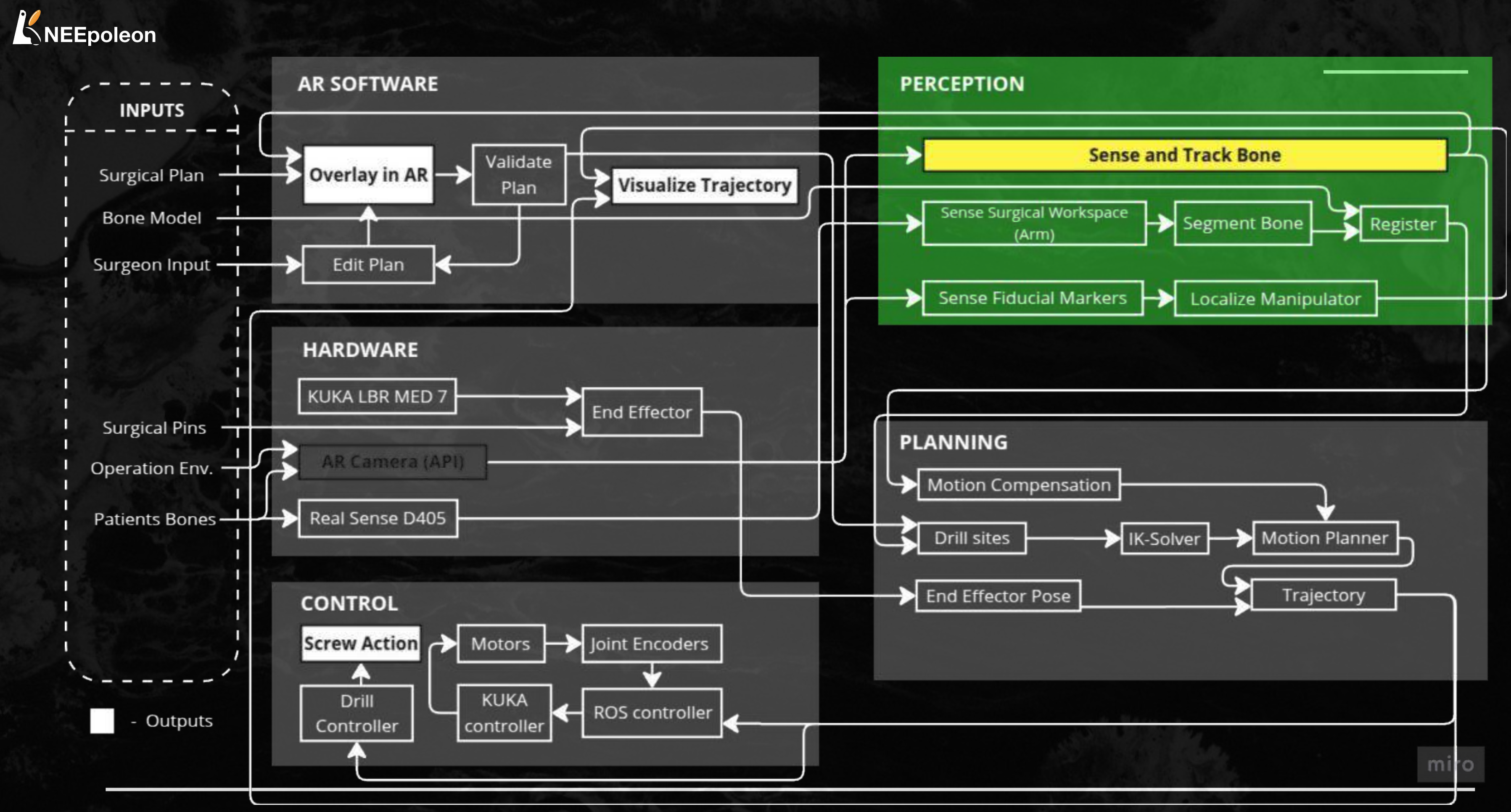

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miro

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* What is the main advance over Team ParaDocs?

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Criteria	Weights	Robot-Assisted + autonomous	Robot-Assisted with AR
Systems		Paradocs	BONEparte
Description		The Surgeon manually exposes the knee joint, the robot autonomously drills holes and then the surgeon inserts pins and places guides.	The surgeon has all visualizations in the AR environment and doesn't have to rely on intuition regarding the accuracy of drill sites and depth
Evaluation Criteria			
Accuracy	13	8	10
Safety	13	10	8
Task Operation Time	11	8	8
Quality of system visual feedback	10	2	10
Setup Time	10	8	8
Ease of Use (manual? tools?)	8	10	8
Comfort of operation	8	8	5
Dynamic Adaptability	7	5	10
Cost	7	8	5
Ease of Sterilization	5	5	8
Learning Curve for operation	5	8	5
Time needed for FDA approval	3	5	2
Final Score	**100**	**7.37**	**7.82**

VS.

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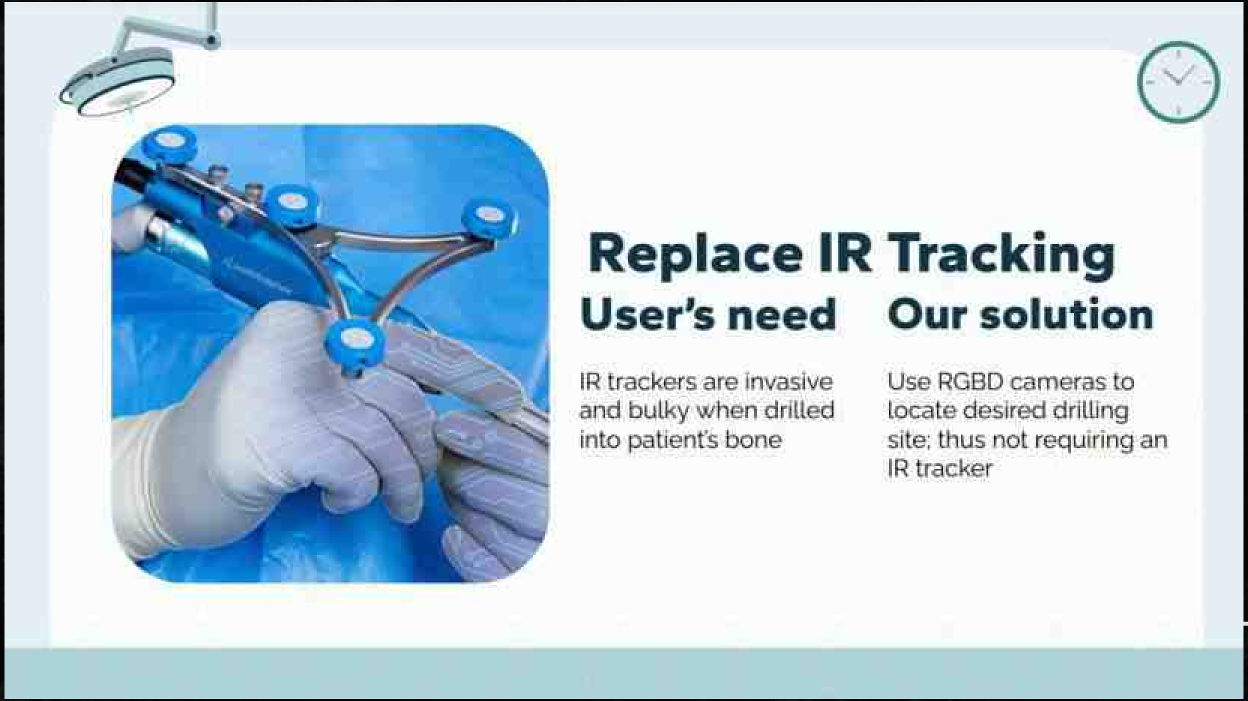
VS



Credits: ParaDocs

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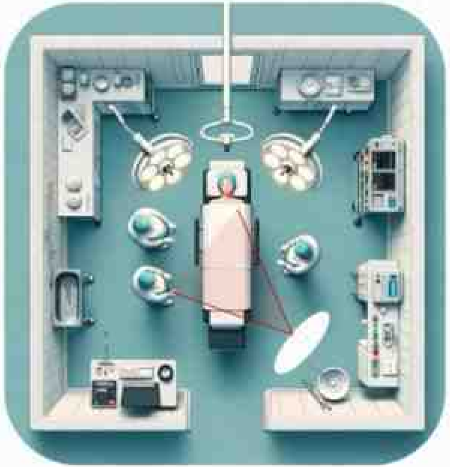
VS

Unobstructive system



User's need

IR Camera needs constant Line of Sight; surgeons need to be mindful and work around it.

Our solution

Design and mount RGBD cameras on the manipulator to avoid interference

Credits: ParaDocs

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VS

IMPROVED

Our Solution

Fully Automating screw procedure, no need to screw after drilling

Credits: ParaDocs

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VS

IMPROVED

Our Solution

Adds AR perspective, compensating for “out of frame” motion.

Credits: ParaDocs

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VS

3 dimensional Visualization through AR

Users Needs

Prevent the need to depend on external monitor/screen for surgical planning

Our Solution

Integrate AR, with visualization features like Overlay, Trajectory display, and interactive UI

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Current System Status + Subsystem Descriptions

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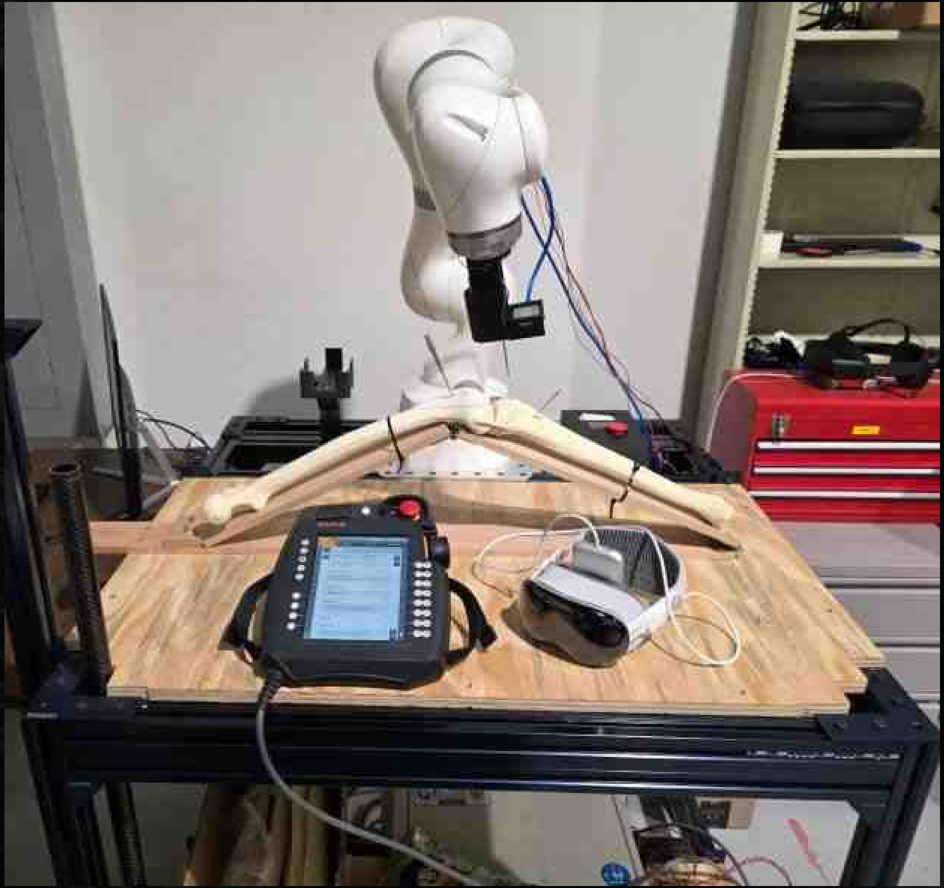
6.1

Overall System Representation



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6.2

Hardware

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SVD Focus

The system shall…

- Screw surgical pins at the planned sites
- Allow manual loading and unloading of the surgical pins
- Provide a physical E-Stop to stop all moving systems

Where we should be according to our schedule

- End Effector Designed
- Tested the pin latching mechanism
- Do a dry run by screwing a single pin

Source: Google Images

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ParaDocs’ Drill Flex Shaft broke frequently

Final End Effector

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Modified Drill Gearbox

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6.3

Planning

SVD Focus

The system shall…

- Perform single drill operation on bone autonomously
- Update the map after screwing one pin

Where we should be according to our schedule

- Existing stack familiarisation
- Update stack for single pin
- Interface perception with MoveIt

Source: Google Images

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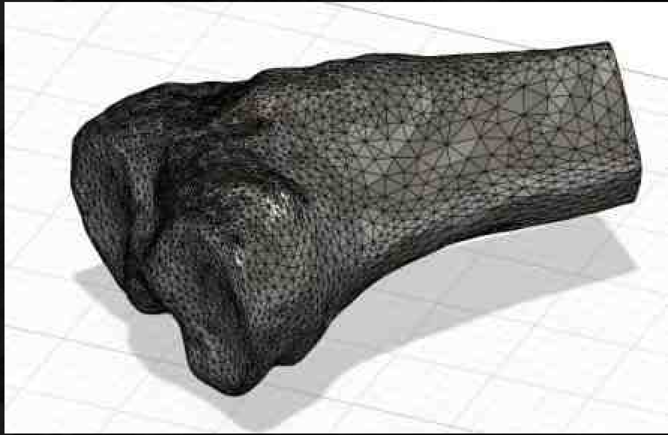

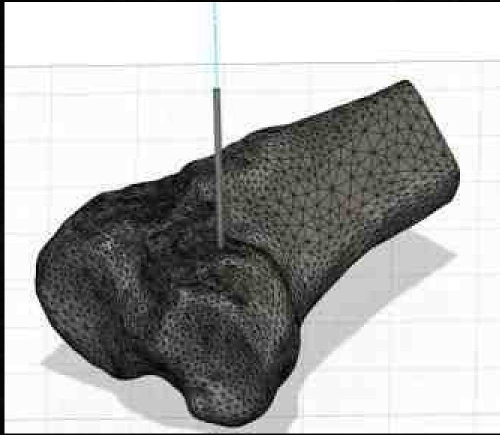

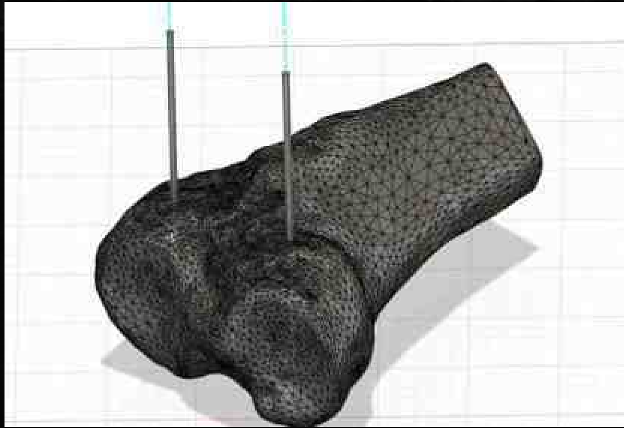

Initialize

Pin 1 Screwed

Pin 2 Screwed

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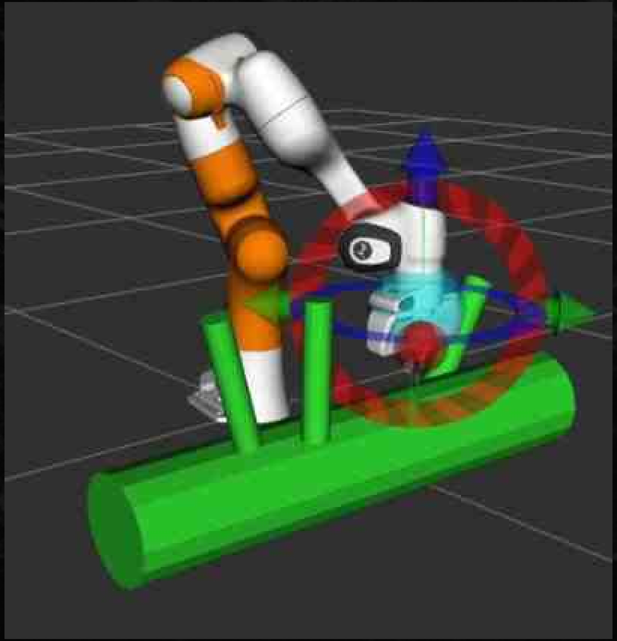
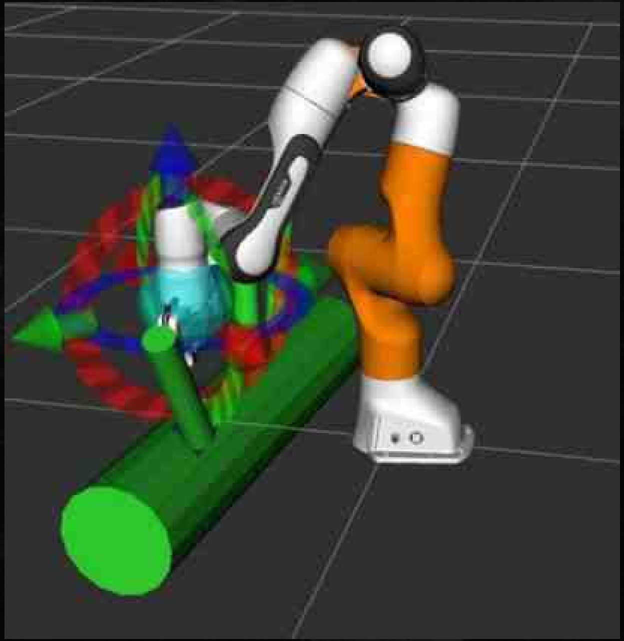
A Brief Test of Moveit





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6.4

Augmented Reality

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SVD Focus

The system shall…

- Send and receive data offboard using ROS
- Track the movement of the patients bone with low latency
- Be able to mark the pin sites on the patients bone

Where we should be according to our schedule

- Extensively test sensing capabilities of 3 AR headsets
- Demonstrate the ability to track the bone with low latency
- Finalize the AR headset to be used

Source: Google Images

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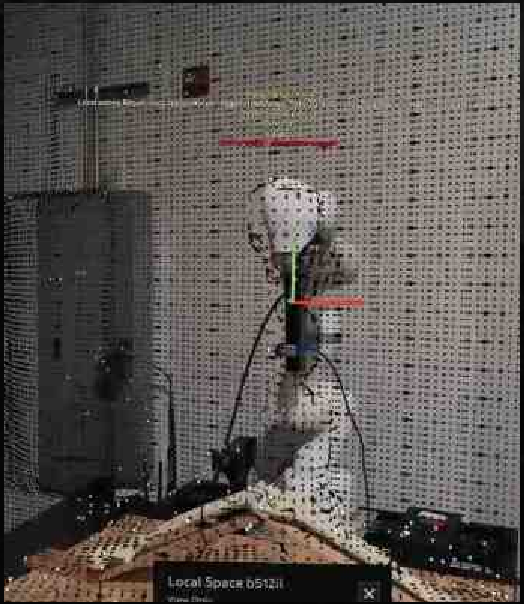
Magic Leap 2

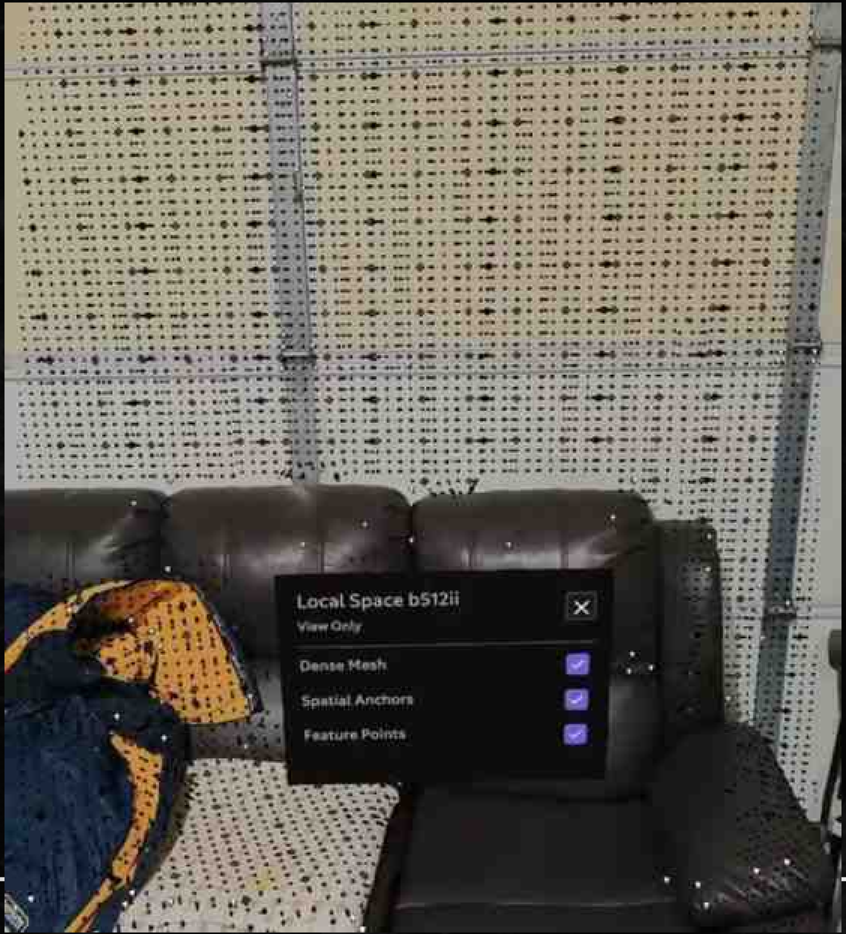
What worked well

- High-Quality sensor outputs
- Quick anchor point detections and self-localization
- Battery Life
- Helpful Community Forum

Conclusion: Eliminated

- High effort required to develop a C++/Unity App to get real time sensor data offboard
- Lack of Open-Source code or supporting libraries




Local Space b512ii
View Only
Dense Mesh
Spatial Anchors
Feature Points

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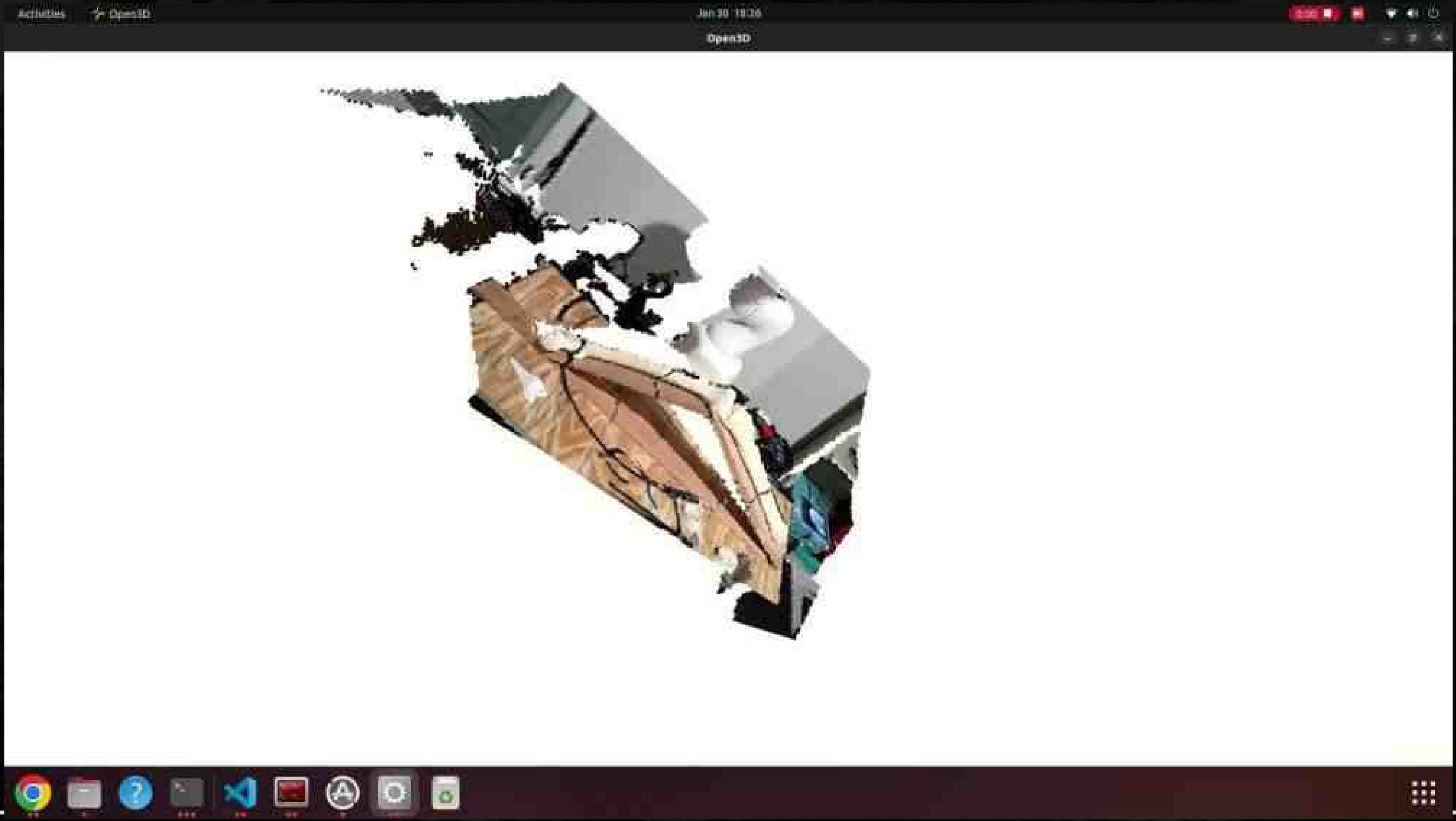
HoloLens 2

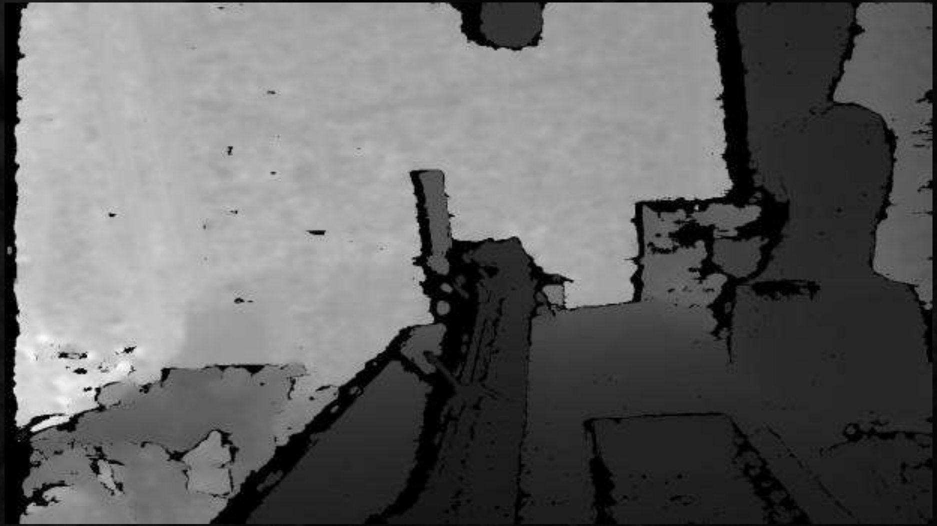
What worked well

- The most ergonomic headset
- Ease of Python-Unity API development
- Ability to run segmentation algorithms on real-time RGBD feed (> 30 FPS)

Conclusion: Eliminated

- Low-Density Point Cloud after processing
- Lack of onboard compute power
- Requires GUI development


Open3D




refrigerator
person
wall-other-merged
oven

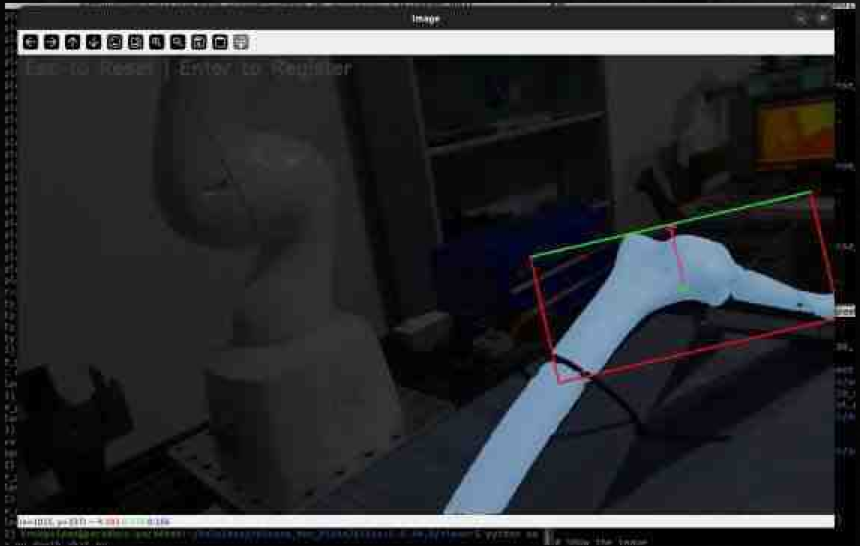


Image
Esc to Reset | Enter to Register

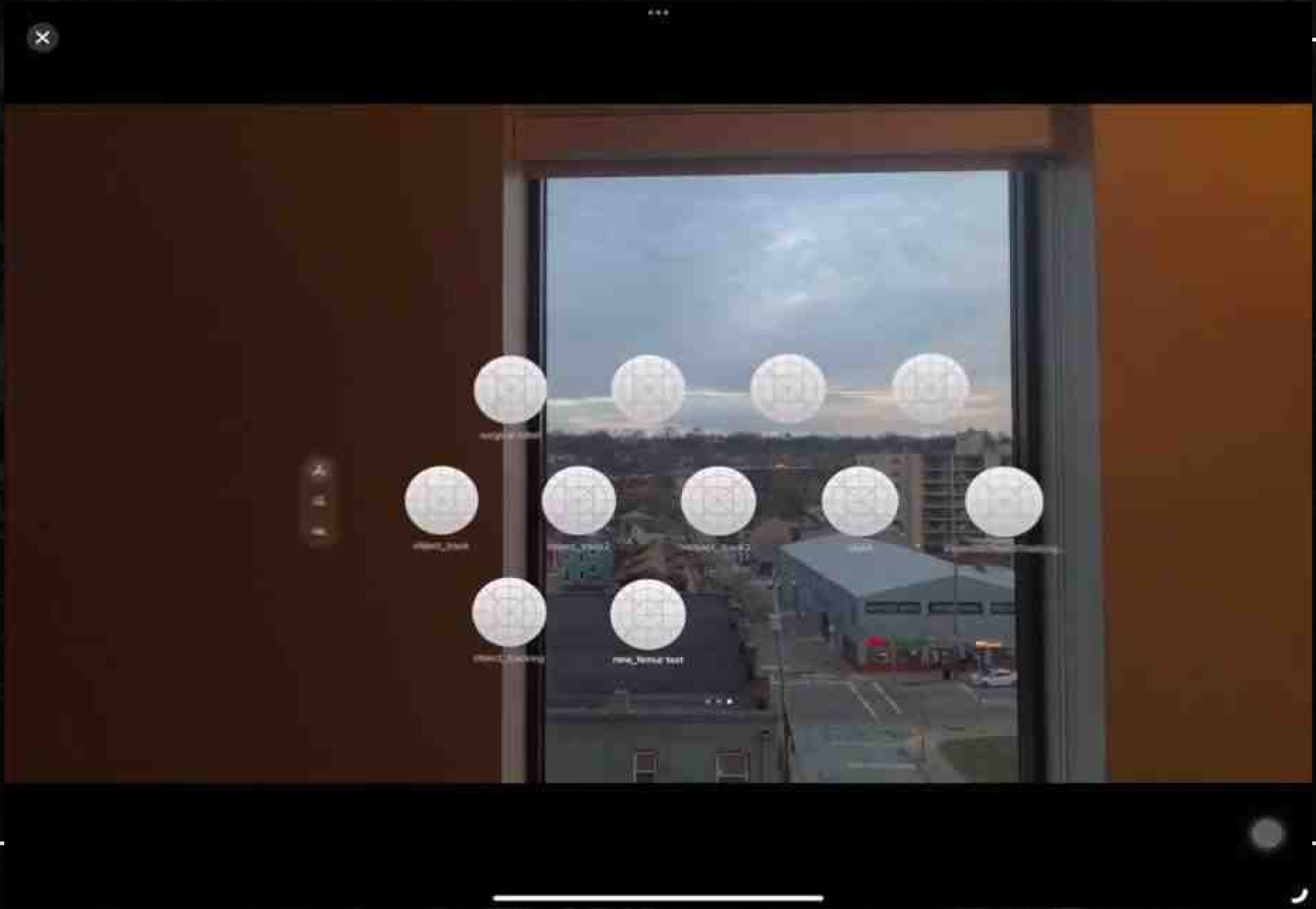
Apple Vision Pro

What worked well

- Low-Latency Object Tracking
- Support for running ML models onboard
- We know it can integrate with ROS

Conclusion: Approved

- Mature Development Platform
- Powerful Built-in Sensors
- Stable On-board Processing


object_track
new_femur test

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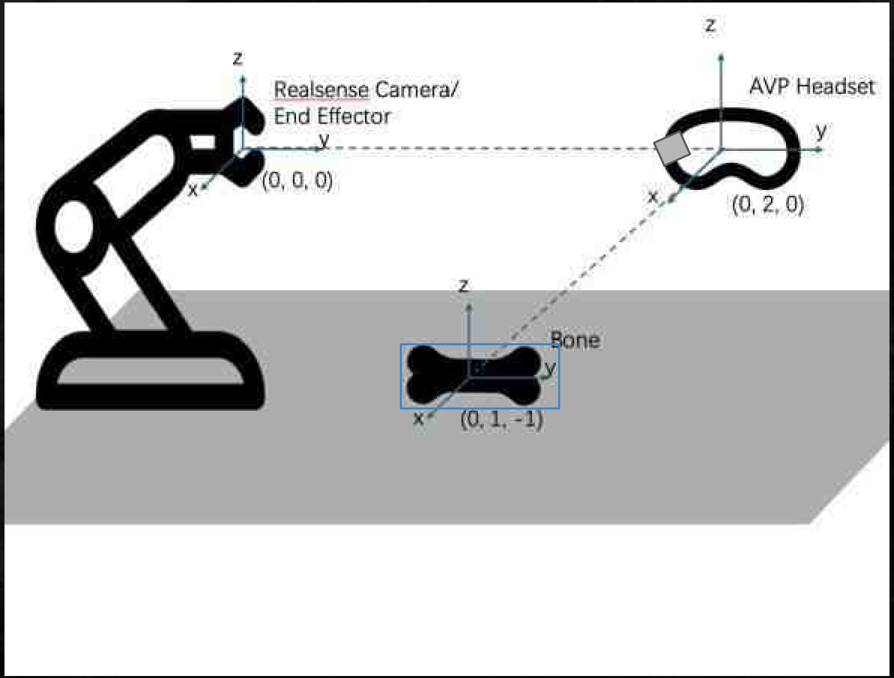
AVP Workflow: When the bone is Unseeable



Step 1: Use Realsense Camera Scan April tag that sticked on AVP, then Realsense Camera know AVP's position, assume (0, 2, 0).

Step 2: Then for AVP, Realsense Camera is on (0, -2, 0).

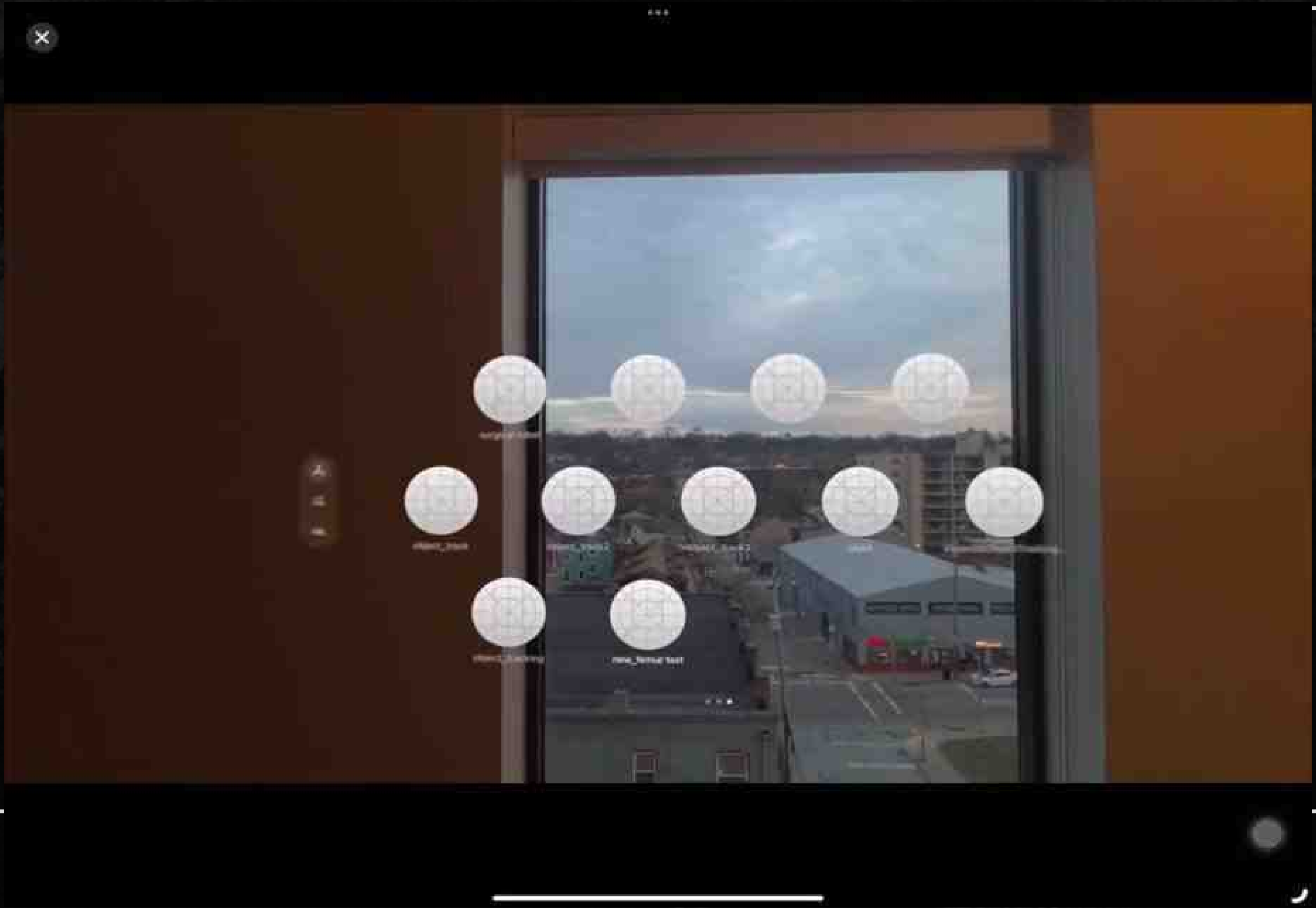
Step 3: Since Realsense Camera also know bone's position, assume (0, -1, 0).
So in the AVP frame, the bone's position can be calculated as (0, -2, 0) + (0, 1, -1) = (0, -1, -1)

Step 4: Highlight the bone, witch is on (0, -1, -1).

AR Frame: Robust & Real-time

AVP: Object Tracking Workflow

AVP: Real-time Object Tracking



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07

Project Management

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7.1

Work Breakdown Structure

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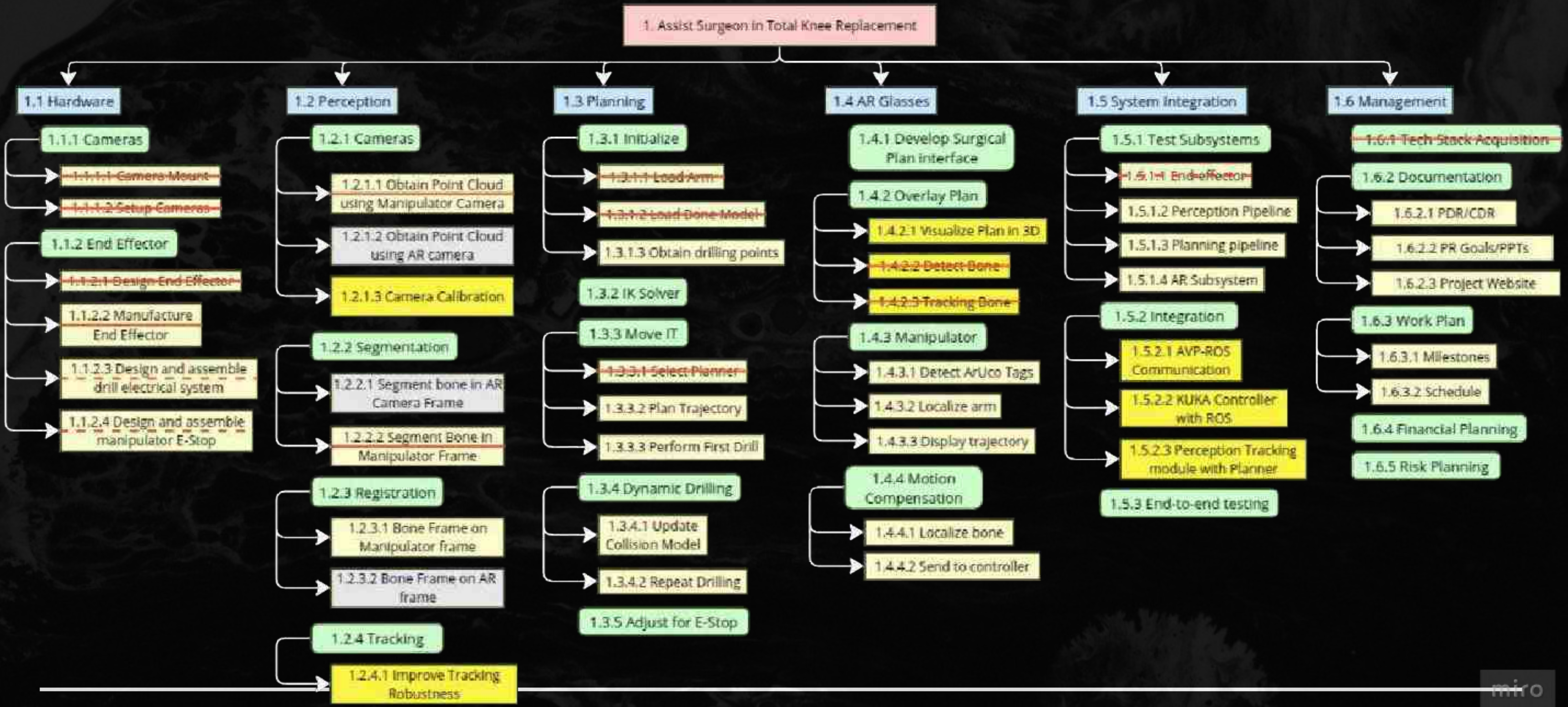
Work Breakdown Structure



7.2

Milestones + Schedule

9 Schedule and Milestones

Derived from the Work-breakdown structure, our internal and external milestones for Spring 2024 are listed below in the table 3.1.

Table 9 – Continued from previous page

No.	Task	Type	Date	Tasks
~~1~~	~~Understand and Test~~ ParaDocs' Stack	~~Internal~~	~~1/21/2025~~	~~Get familiar with the in-~~ herited tech stack
~~2~~	~~Choose the final Headset~~	~~Internal~~	~~2/28/2025~~	~~Decide on one out of the~~ 3 headsets after an extensive trade study
~~3~~	~~End Effector Prototype~~ Developed	~~Internal~~	~~3/15/2025~~	~~3D printed end effector~~ prototype is developed
4	Perform Single Drill Procedure	Internal	3/17/2025	Drill a pin on a bone to test the end effector mechanism
5	Overlay Surgical Plan	Internal	3/21/2025	Overlay the surgical drill sites onto the bone model
6	Perform Single Autonomous Drill on Bone	Internal	4/1/2025	Perform a single drill on the bone model
7	All Subsystems Integrated and Tested	Internal	4/13/2025	System and Subsystem Level Integration and Testing
8	SVD	External	4/18/2025	Demonstrate the attained Functional Requirements for SVD
9	SVD Encore	External	4/25/2025	Demonstrate the attained Functional Requirements for SVD Encore

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7.3

Test Plans

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Progress Review 3

Milestones

- Camera Calibration
- Integration between KUKA controller and ROS
- Visualise plan in 3D for femur

Tests

- Verify that the reprojection error of the calibration pattern is low
- Ensure the manipulator starts moving to a commanded joint position within 500ms
- Validate that the AR surgical plan aligns with the femur within a 2 mm tolerance.

Source: Google Images

Progress Review 4

Milestones

- AVP-ROS Communication
- Visualise and track surgical plan on femur and tibia
- Integration of the planning and hardware subsystem

Tests

- Send Start and E-STOP command from AVP to system
- Manipulate femur and tibia models in the AR GUI
- Perform autonomous drilling of a single pin

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Spring Validation Demonstration + Encore

Location: Newell-Simon Hall B512
Equipment: AR Headset, KUKA LBR MED 7 with a custom end-effector, Sawbones bone models of Femur and Tibia, Intel RealSense D405 camera with mount, surgical pins.

Objectives: Following are the goals that we aim to achieve in SVD-

- SVD1. Sense and segment the bones through manipulator ~~and AR camera~~ (MF1)
- SVD1.1 Sense and Track bone using Vision Pro
- SVD2. Register Pre-Op Bone Model onto the bone setup (MF3)
- SVD3. Show a pin latching mechanism for the end effector (MF10)
- SVD4. Overlay surgical sites on the bone setup (MF5)
- SVD5. Screw one pin with custom end effector (Partial MF9)
- SVD6. Demonstrate a functional physical E-Stop (Partial MF11)

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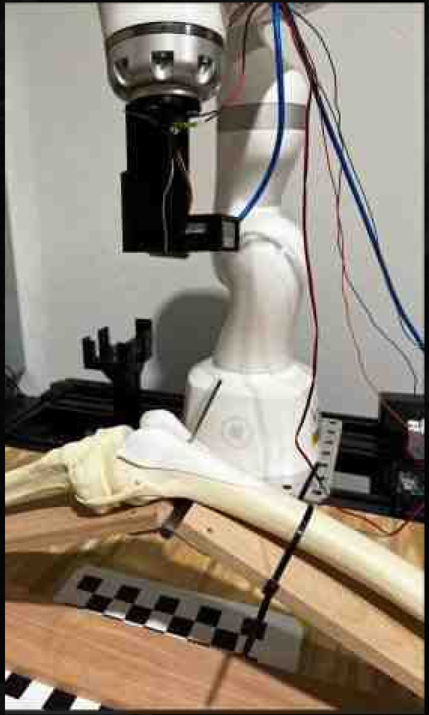
SVD Evaluation Criteria

- The robot should autonomously and accurately screw a surgical pin in the bone model, at the overlaid surgical site.
- It should successfully stop all operations within 250 millisecond if the E-Stop button is pressed.
- For SVD, we aim to achieve a drilling accuracy of 8mm.
- Tracking latency of less than 1000ms.



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Test Plan - Fall 2025

Location: Newell-Simon Hall B512
Equipment: AR Headset, KUKA LBR MED 7 with a custom end-effector, Sawbones bone models of Femur and Tibia, Intel RealSense D405 camera with mount, surgical pins.
Setup: The KUKA Manipulator will be mounted on a vention table and synthetic bone models of tibia and femur will be aligned in a 90-degree flexion pose with a custom jig on the same table. The mount for Intel D405 will be integrated within the new custom end effector. The surgical pins will be kept on a tray beside the vention table. One of the team members or the project evaluators will be wearing the AR Headset and using the intuitive UI during the demonstration.
Objectives: We aim to demo the complete end-to-end system meeting all specified system level requirements to achieve the following goals-

#	Feature Validation Demonstration (FVD)
FVD1	Sense and segment the bones through manipulator and AR camera (MF1)
FVD2	Register Pre-Op Bone Model onto the bone setup (MF3)
FVD3	Show a pin latching mechanism for the end effector (MF10)
FVD4	Overlay Drill sites on the bone setup (MF5)
FVD5	Drill one pin with custom end effector (partial MF9)
FVD6	Demonstrate a functional physical E-Stop (partial MF11)
FVD7	Track and compensate for motion throughout the procedure (MF4)
FVD8	Localize Manipulator with AR Headset (MF2)
FVD9	Display Manipulator Trajectory in AR Headset (MF7)
FVD10	Drill all 5 pins onto the bone semi-autonomously (MF9/MF10)
FVD11	Demonstrate intra-op Surgical Plan Editing (MF6/MF8)
FVD12	Demonstrate both physical and Virtual E-Stop (MF11)

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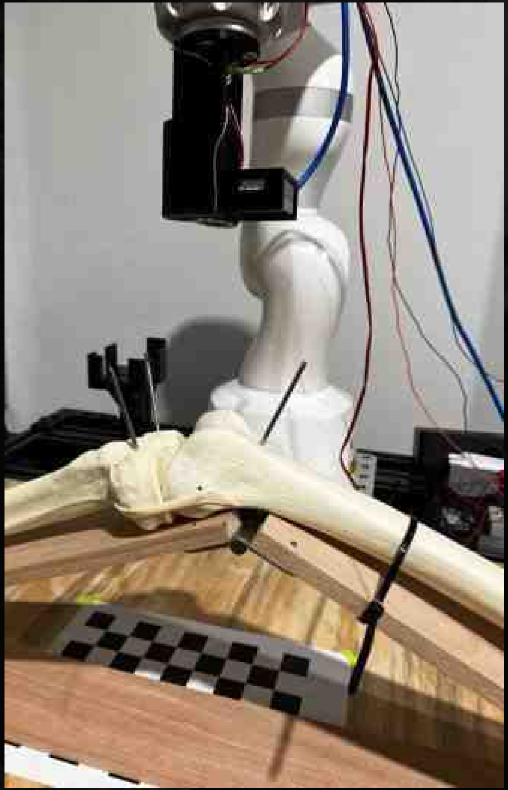
FVD Evaluation Criteria

- The robot should autonomously and accurately screw 5 surgical pins (3 in femur+2 in tibia) in the bone model, at the overlaid surgical sites.

- The system should successfully stop all operations in:
  - Less than 250ms when the Physical E-Stop is pressed.
  - Less than 1000ms when the AR E-Stop is pressed.

- For FVD, we aim to achieve a drilling accuracy of 2mm.

- Tracking latency of less than 500ms



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08

Budget

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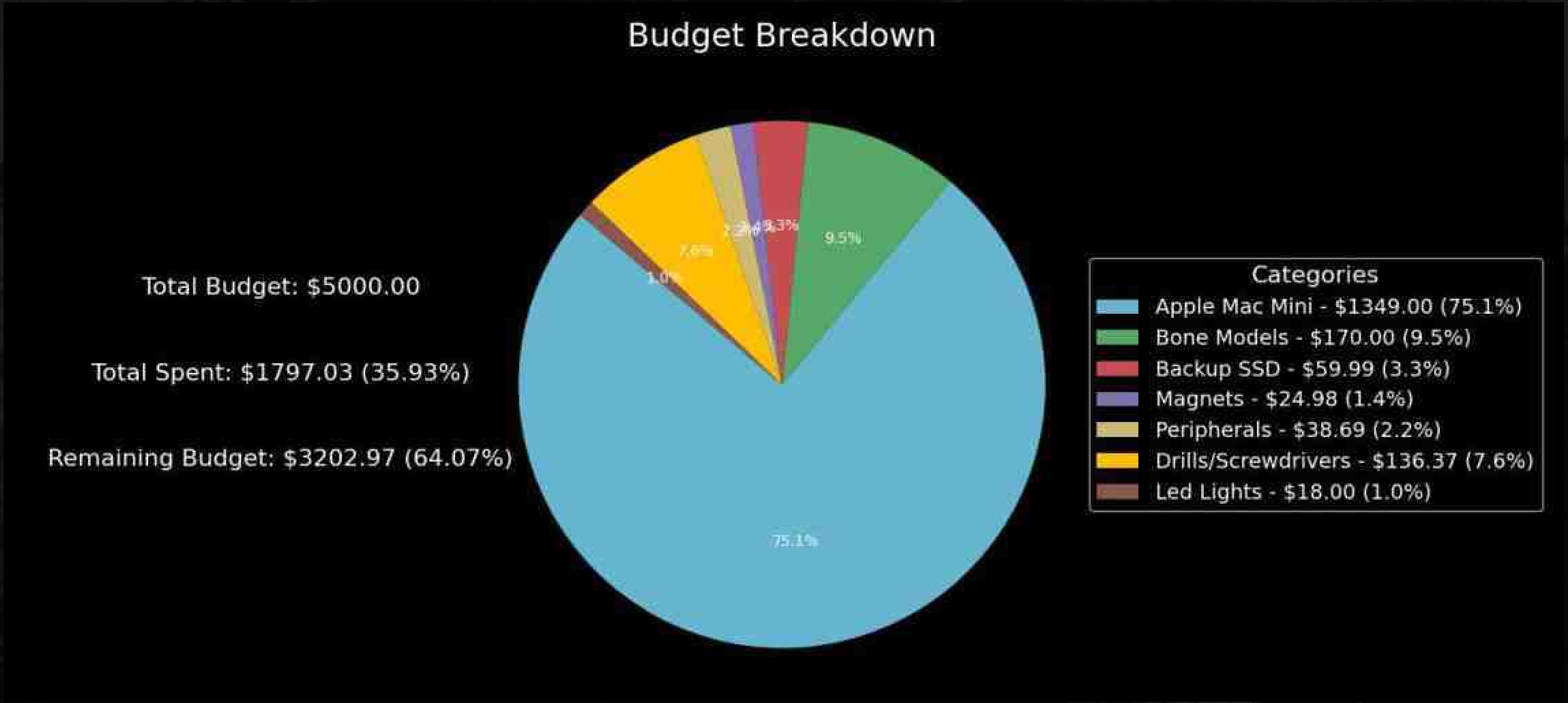
Budget Breakdown
Total Budget: $5000.00
Total Spent: $1797.03 (35.93%)
Remaining Budget: $3202.97 (64.07%)
9.5%
7.6%
75.1%
Categories
Apple Mac Mini - $1349.00 (75.1%)
Bone Models - $170.00 (9.5%)
Backup SSD - $59.99 (3.3%)
Magnets - $24.98 (1.4%)
Peripherals - $38.69 (2.2%)
Drills/Screwdrivers - $136.37 (7.6%)
Led Lights - $18.00 (1.0%)

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Risk Management

Improved Risk Management Analysis for AR-Enabled Robotic Surgery System

Risk ID	Risk Description	Likelihood	Impact	Mitigation Strategy
01	Vision Pro device failure or compatibility issues	3	4	Compatibility testing; backup devices; fallback functionality
02	AR development technical bottlenecks (rendering/tracking)	3	4	AR dev training; use mature frameworks; performance fallbacks
03	Robot end-effector failure	3	5	CNC redundant parts; modular design; stress testing
04	Camera calibration and spatial registration accuracy issues	3	5	Multi-sensor fusion; AprilTag calibration; dynamic recalibration
05	Point cloud processing and registration algorithm performance issues	3	4	GPU acceleration; multi-level registration; performance monitoring
06	Sensor data fusion instability	3	4	EKF data fusion; fault detection; sensor degradation plans
07	Workspace and equipment availability limitations	4	2	Early resource planning; clear communication; alternate equipment options
08	ROS and Vision Pro integration challenges	3	3	Custom middleware; error recovery; end-to-end testing
09	System real-time performance requirements not met	3	4	Code optimization; critical path analysis; performance benchmarking
10	User experience and human-machine interaction issues	2	3	Early user testing; iterative design; minimal UI approach

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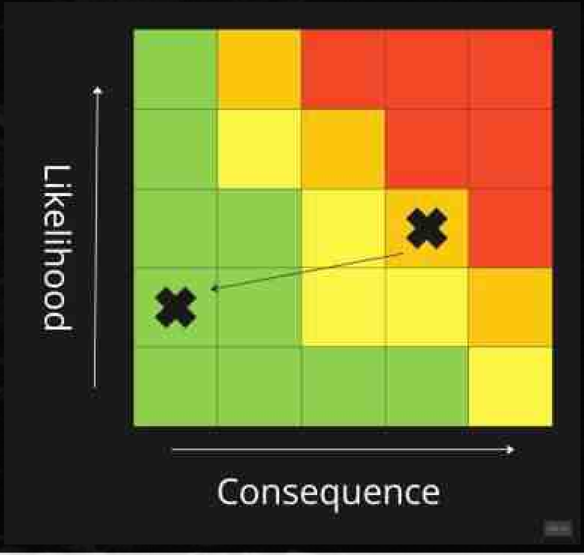
Risk: End-Effector breaks during testing

Impact: The pins aren’t screwed at the desired accuracy

Mitigation: Get the end-effector machined with the help of Tim Angert



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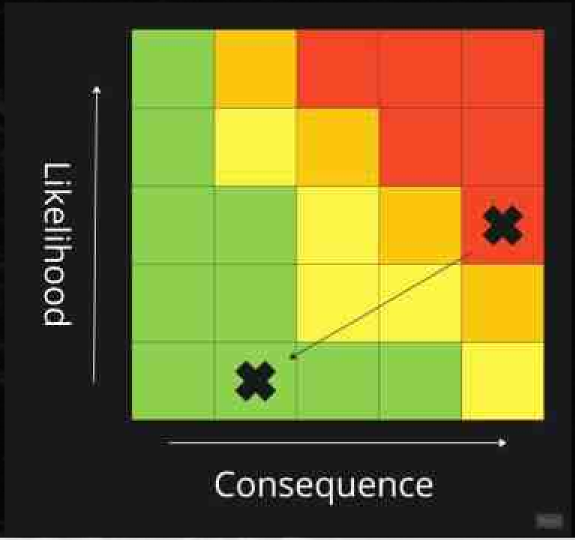
Risk: Loose wiring in the power delivery circuit

Impact: The drill malfunctions during operation

Mitigation: Create a PCB to ensure no loose wiring for the power delivery circuit



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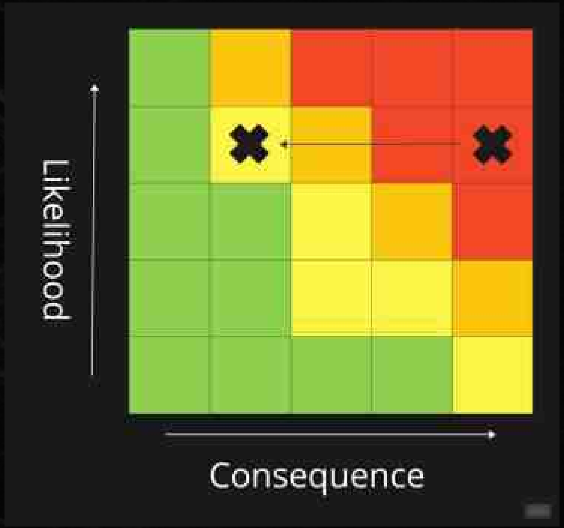
Risk: Apple Developer License lead time is longer than mentioned on the website

Impact: Unable to develop on the AVP without the license

Mitigation: Reach out to Apple Employees on LinkedIn and work on developing the ROS integration code in the meanwhile.



Risk: Loose wiring in the power delivery circuit

Impact: The drill malfunctions during operation

Mitigation: Create a PCB

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Issue Logs

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All Issues | By Status | Gantt | 1 more... | New

Issues Log

Name	Reported By	Assigned To	Status	Date Identified	Date Resolved	Priority	Tags
Unable to Build ParaDocs' Docker Container	Sreeharsha Paruc	Sreeharsha Paruchuri	Resolved	01/15/2025	02/26/2025	High	Perception, Planning
MagicLeap SDK-OpenXR Dependency Mismatch	Parth Singh	Parth Singh	Resolved	01/20/2025	01/26/2025	High	Augmented Reality
Ultrasonic Sensor not working with Final Code	Sreeharsha Paruc	Daksh Adhar	Resolved	02/01/2025	02/04/2025	Medium	Hardware, Project Course
Problem running HL2SS	Daksh Adhar	Sreeharsha Paruchuri, Daksh Adhar	Resolved	02/06/2025	02/14/2025	Medium	Augmented Reality
Lack of Rapid Prototyping Facilities	Parth Singh	Parth Singh	Resolved	02/09/2025	02/20/2025	Low	Hardware
Recalibration of D405	Daksh Adhar	Parth Singh	In progress	02/10/2025		Medium	Perception, Hardware
Gear material Flexing under stress	Parth Singh		Not started	02/20/2025		Medium	Hardware
ParaDocs Parasight rebuild error	Sreeharsha Paruc		Not started	02/27/2025		High	Perception
Get apple developer account under Kneepolean	wentacc	parthsin@andrew.cmu.edu	Not started	03/05/2025		High	Augmented Reality
LBR FRi Stack crashing	Daksh Adhar	Daksh Adhar	Not started	03/11/2025		Medium	Planning

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Thank You!
Questions?