HIPSTER

Autonomous **R**eaming for **T**otal **H**ip **R**eplacement **(ARTHuR)**

Preliminary Design Review

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Contents

Meet the Team

Kaushik Balasundar

Perception and Sensing Lead

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Mechanical Systems Engineering Lead

Anthony Kyu

Controls and Actuation Lead

Gunjan Sethi

Software Engineering Lead

Sundaram Seivur

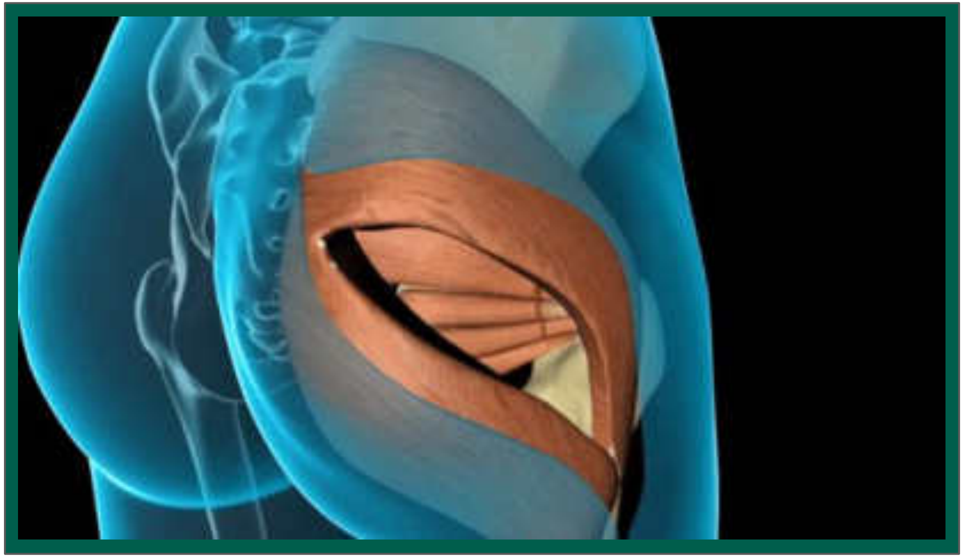
Trajectory Planning Lead

Project Description

Project Description

A doctor may recommend hip replacement if there exists significant ***pain***, ***inflammation*** and ***damage to the hip joint*** due to conditions such as:

- Osteoarthritis (most common)
- Rheumatoid arthritis
- Osteonecrosis (avascular necrosis)
- Injury such as hip fracture
- Tumor in the hip joint



Total Hip Arthroplasty Overview

Factors and Barriers of Success

Steps in Total Hip Replacement:

- *Reaming the acetabulum*
- Cutting and drilling into the femur
- Impacting the acetabular cup into the acetabulum
- Impacting the femoral implant into the femur

Femoral Stem and Acetabular Component Placement [1]

Success Criteria

- **Accuracy of acetabular cup position and orientation**
- Accuracy of Femoral Implant
- Surgical Time

Barriers

- Surgeons cannot see site of surgery very well
  - ***< 50%*** of manual surgeries are within the Lewinnek safe zone
- Modern systems lower this barrier but at the cost of surgical time and robustness

Femoral Stem and Acetabular Component Construction [4]

Our Solution: **ARTHuR** (**A**utonomous **R**eaming for **T**otal **H**ip **R**eplacement)

A ***fully autonomous robotic arm*** aimed at performing acetabular reaming with ***high accuracy***, eliminating the need of surgeons to use intuition to ***correctly position/angle the reamer***.

Use Case

Use Case

Patient has Osteoarthritis → Surgeon makes surgical plan with 3D Anatomical Model → Surgeon performs THA surgery with autonomous reaming robot → Acetabulum is reamed accurately according to surgical plan → Patient is happy! :)

Use Case Flow

Use Case

Use Case visualization and environment mockup

Requirements

Mandatory Performance Requirements

The System Will:

M.P.1.1 **Localize** the robot arm with a **latency less than or equal to 50 ms**

M.P.1.2.1 **Localize** the robot arm with respect to the pelvis with a **position error of less than 1 mm**

M.P.1.2.2 **Localize** the robot arm with respect to the pelvis with an **orientation error less than 1.5 deg**

M.P.2 **Plan** the trajectory based on the given surgical plan with a **latency less than or equal to 150 ms**

M.P.3.1 **Execute** surgical plan by reaming along the trajectory with an **position error of less than 1 mm**

M.P.3.2 **Execute** surgical plan by reaming along the trajectory with an **orientation error of less than 1.5-degrees**

M.P.4.1 **Compute** error and interpret the movement of the pelvis with a **latency less than or equal to 50 ms**

M.P.4.2 **Generate** a new trajectory **if the errors are greater than 1 mm or greater than 1.5-degrees**

M.P.5 **Adapt and compensate** for movement by generating a new trajectory with **latency less than or equal to 150 ms**

M.P.6 **Allow** the surgeon **to place the robot arm** to an initial position by **back-driving the robotic arm**

M.P.7 **Provide** the surgeon with **visual feedback** with a **latency less than or equal to 150 ms**

M.P.8 **Allow** the surgeon to **e-stop** the system, stopping the system **within 500 ms**

Detailed Functional Requirements

Mandatory Non-Functional Requirements

The System Will:

M.N.1 **Produce forces low enough** for it to be safe around humans

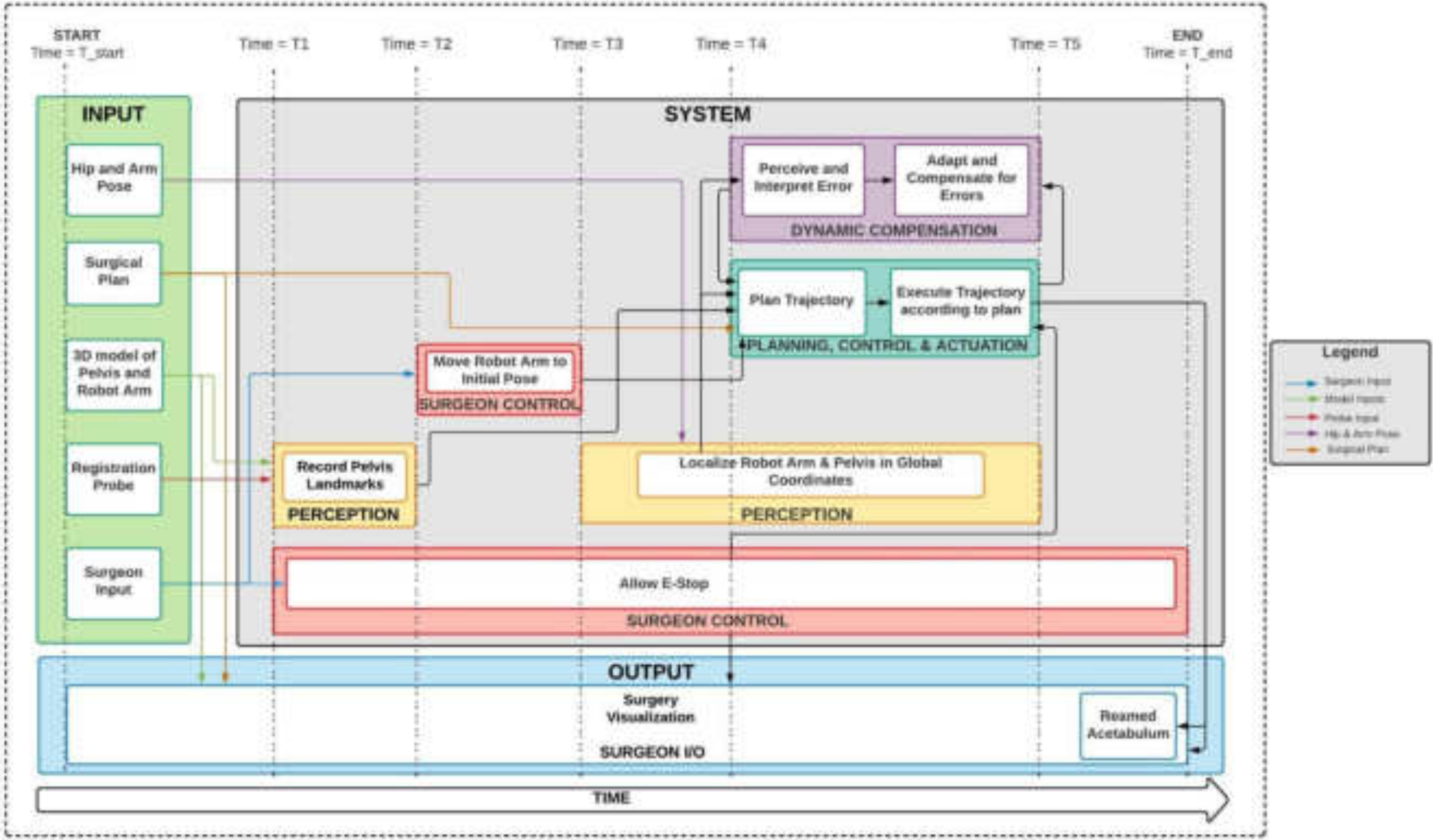
M.N.2 **Provide** a minimal and easy-to-interpret **user interface** design for surgeons

M.N.3 **Autonomously detect malfunctions** and errors and notify user accordingly

Detailed Non-Functional Requirements

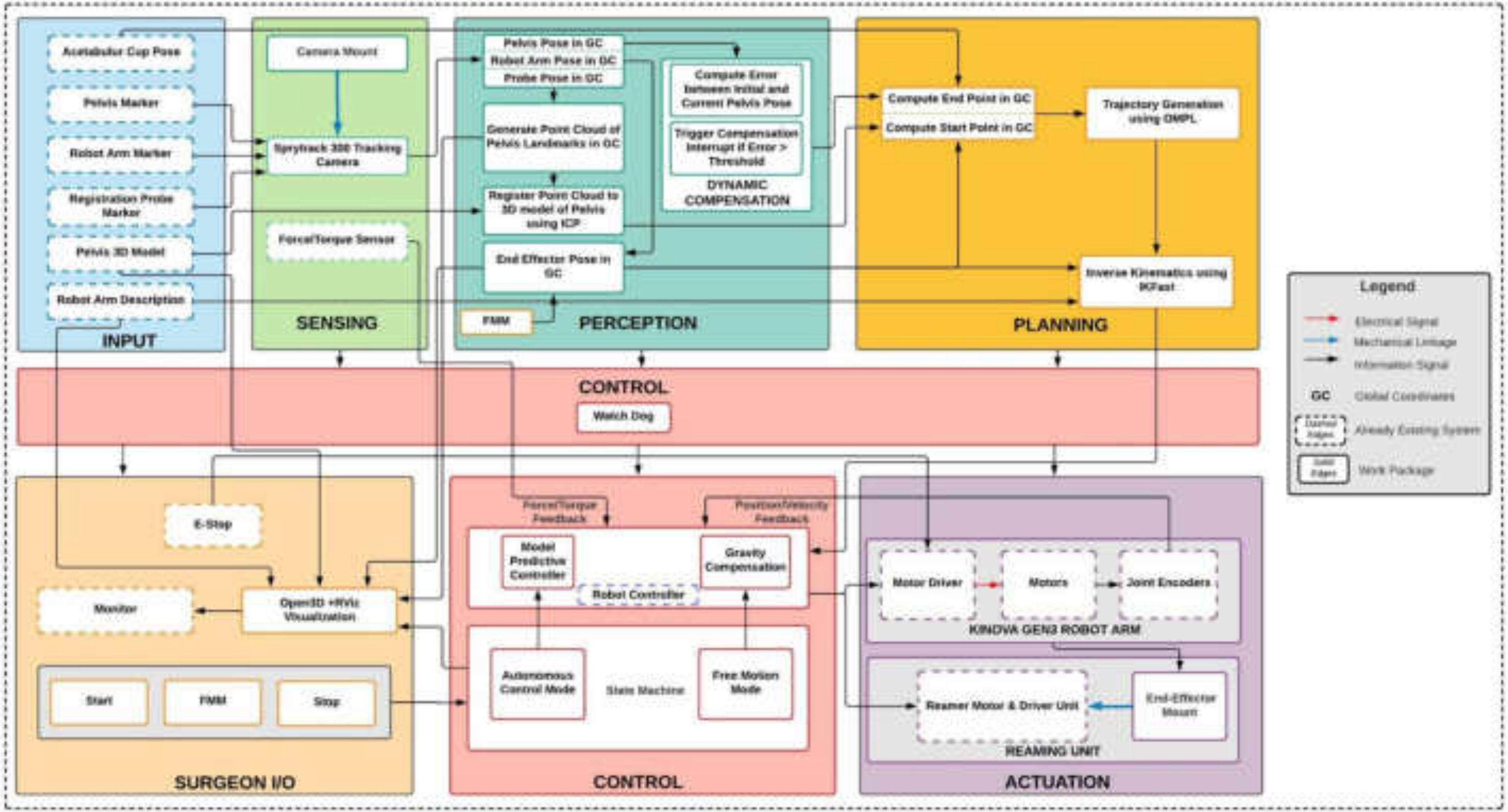
Functional Architecture

Functional Architecture



Cyberphysical Architecture

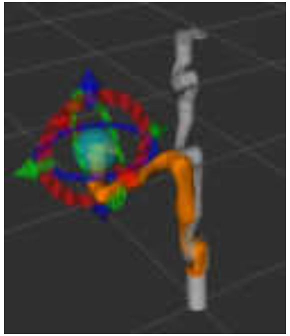
Cyberphysical Architecture



Subsystem Descriptions

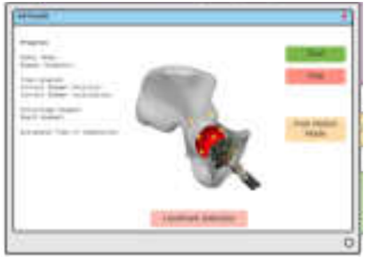
Major Subsystems

Sensing & Perception



Planning & Controls

Hardware & Actuation



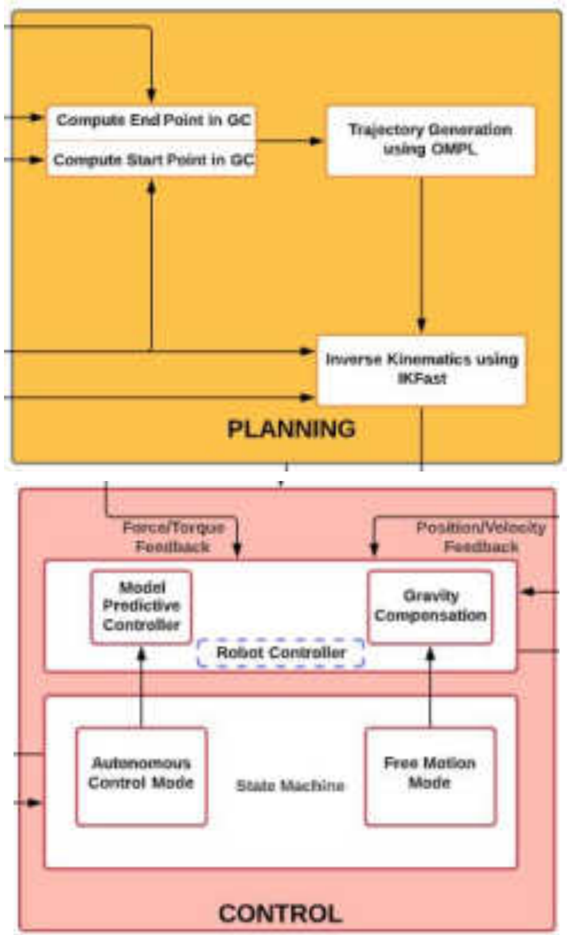
Surgeon I/O

Planning and Controls

Planning and Controls

Modifications:

- Not using CHOMP
- Using Model Predictive Control
- Gravity Compensation built into Kinova Gen 3 Arm



Model Predictive Control: Current Progress

$$s = \begin{bmatrix} q \\ \dot{q} \\ x \\ \dot{x} \\ F_{External} \end{bmatrix}$$

$$\min_{s_k, u_k, k\in[1,H]} \quad \frac{1}{2}(s_H - s_d)^T Q_H (s_H - s_d) + \sum_{k=1}^{H-1} \frac{1}{2}(s_k - s_d)^T Q (s_k - s_d) + \frac{1}{2} u_k^T R u_k$$

$$\text{s.t.} \quad \begin{bmatrix} \dot{q} \\ \ddot{q} \\ \dot{x} \\ \ddot{x} \\ \dot{F}_{External} \end{bmatrix} = \begin{bmatrix} \ddot{q} \\ M^{-1}(u - \tau_{External} - C\dot{q} - G) \\ J\dot{q} \\ \dot{J}\dot{q} + J\ddot{q} \\ B_{External}(\dot{J}\dot{q} + J\ddot{q}) \end{bmatrix}$$

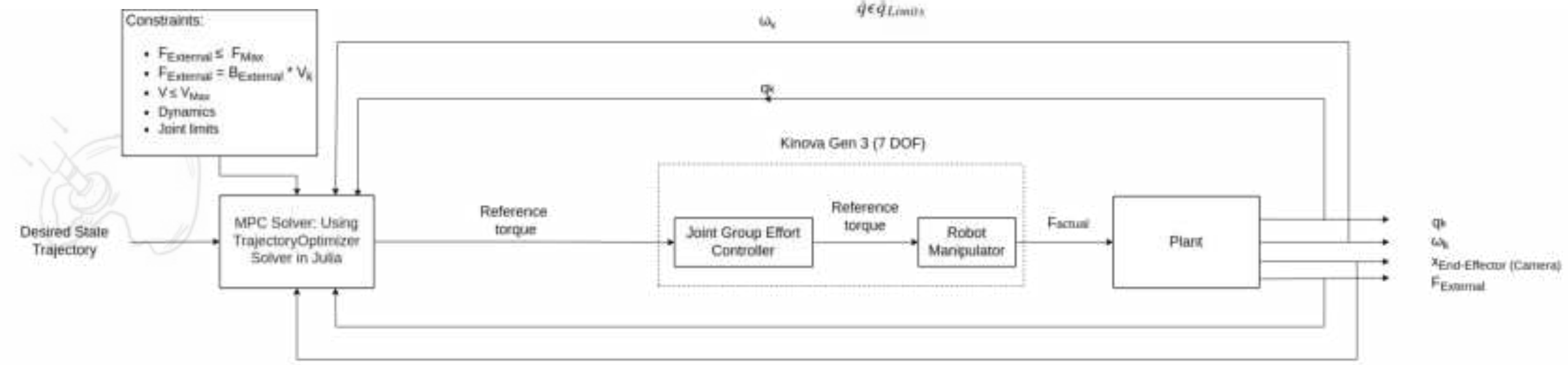
$$u = \tau_{Applied} \leq \tau_{Max}$$

$$||F_{External}|| = ||B_{External} J\dot{q}|| \leq F_{Max}$$

$$||\dot{x}|| = ||J\dot{q}|| \leq \dot{x}_{Max}$$

$$q \epsilon q_{Limits}$$

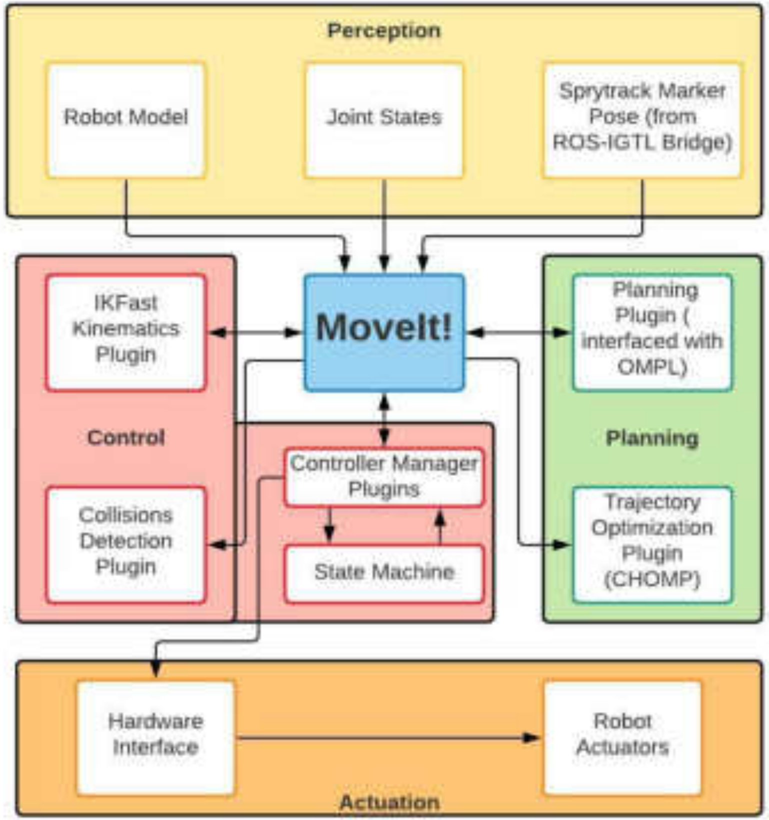
$$\dot{q} \epsilon \dot{q}_{Limits}$$



Free Motion Mode (FMM)

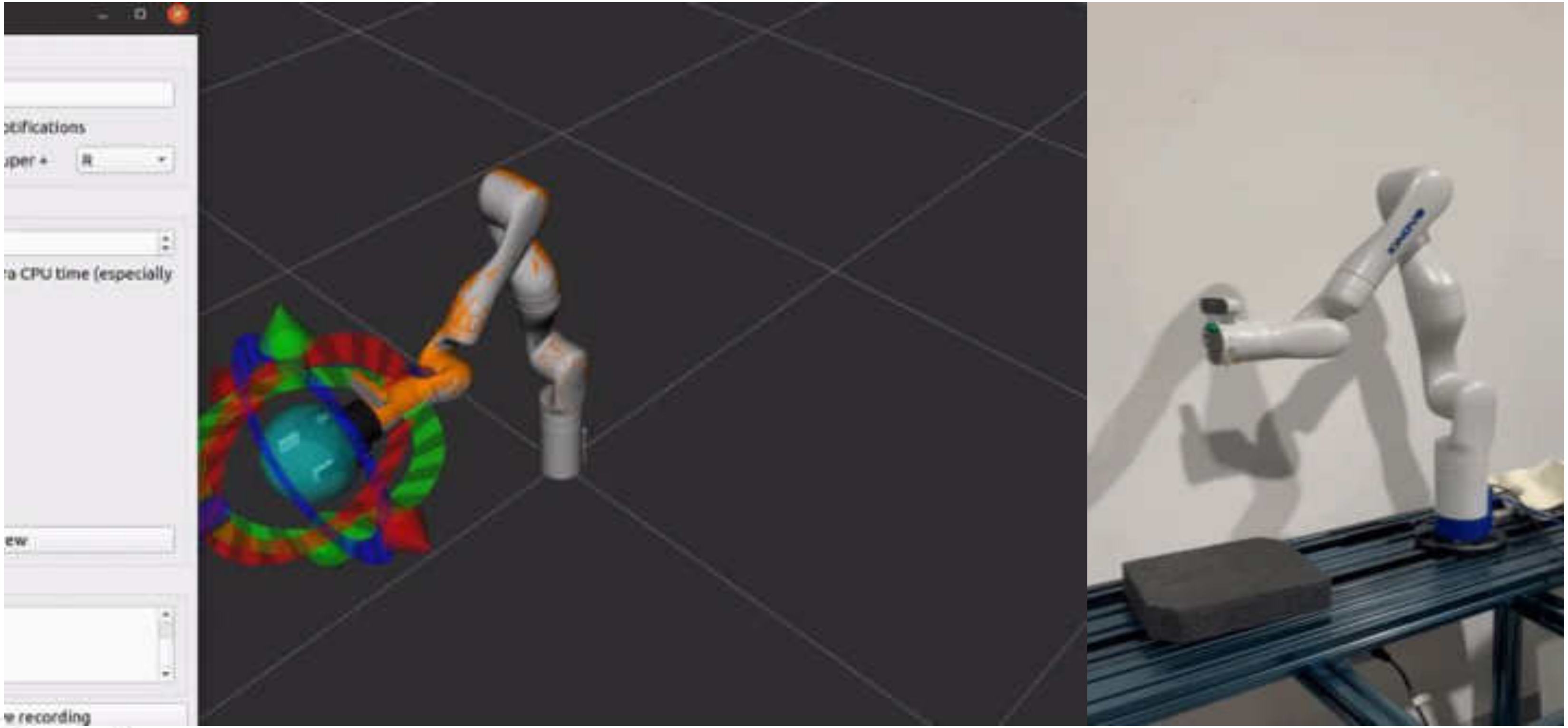
Example of Gravity Compensation in FMM

Using ROS for Planning & Control



MoveIt! Dependencies

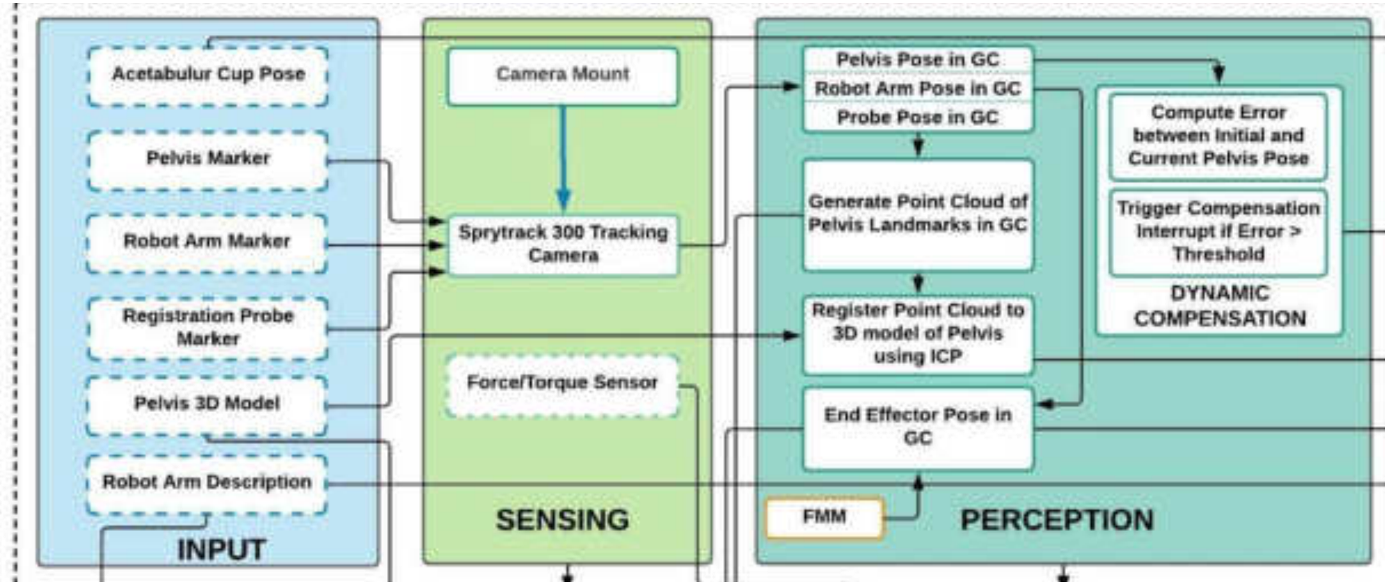
Motion Planning: Current Progress

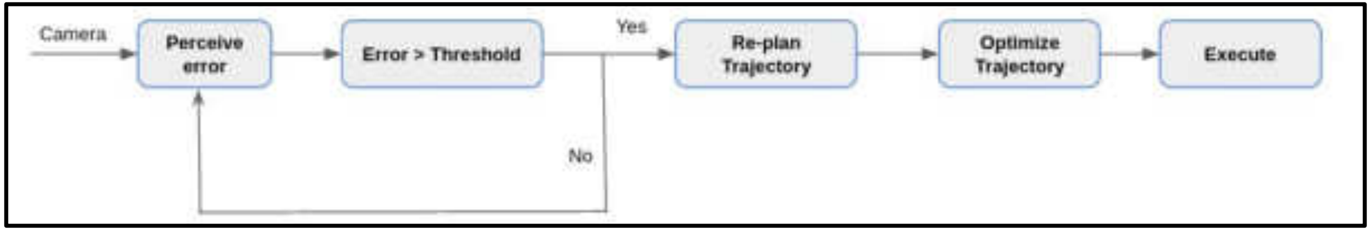


Motion planning using MoveIt! and IKFast solver

Perception and Sensing

Input, Sensing, and Perception

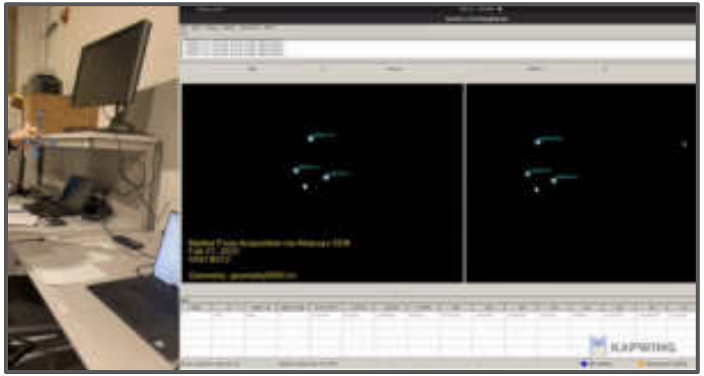




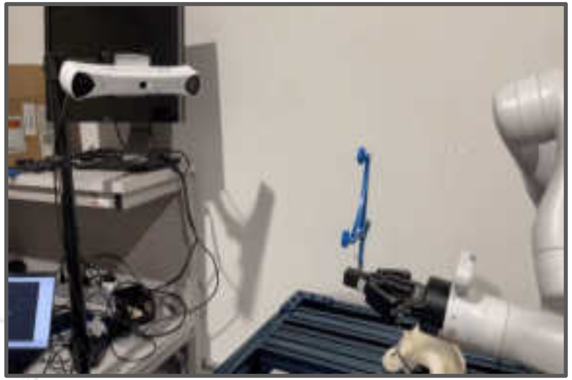
Functioning of Dynamic Compensation

Marker Tracking: Current Progress

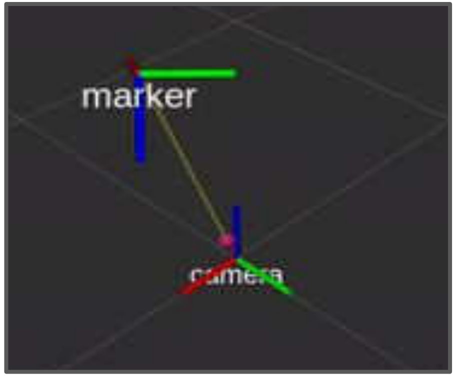
Camera Setup



Marker Tracking Using Atracsys SDK

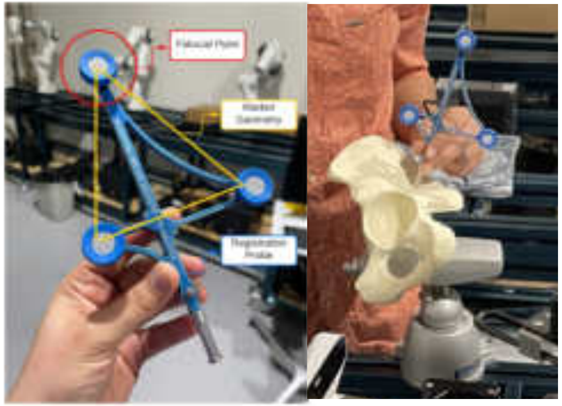


Robot Arm Moving the Marker Probe for Test

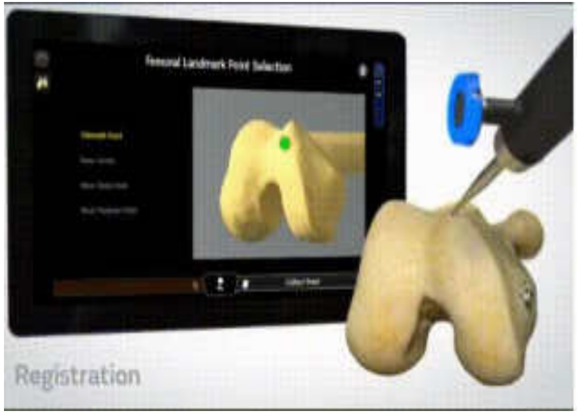


Marker Tracking Using ROS

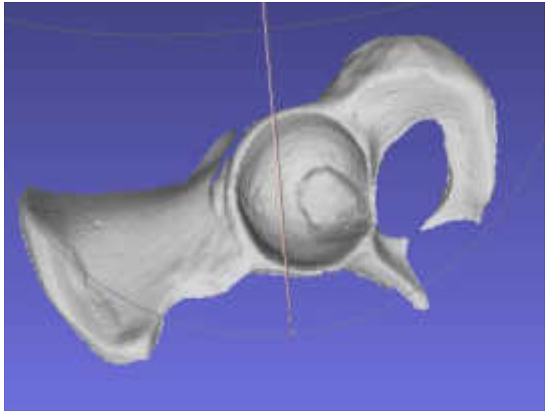
Registration: Current Progress



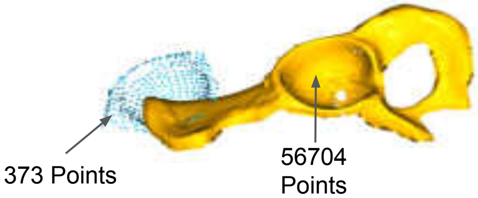
Marker (left) Usage of Marker on Registration Probe (right)



Point Collection on Commercial System



3D scan from Konica Minolta Vivid 9i



Source and target pointclouds

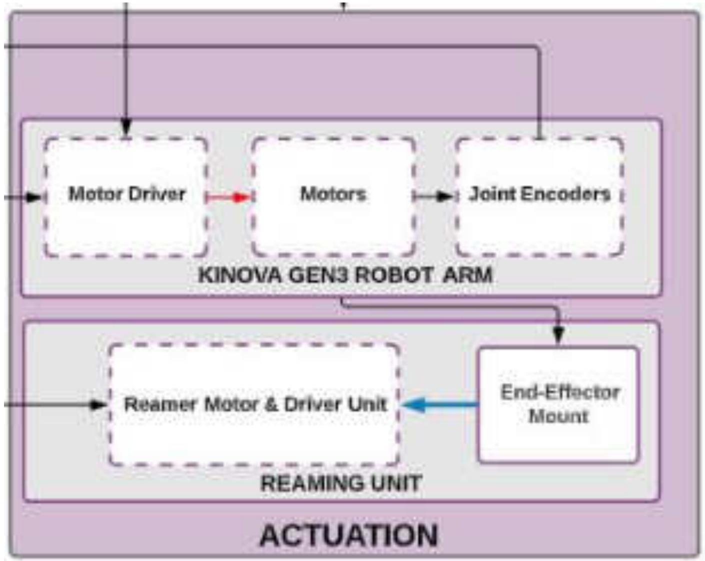
Downsampled pointclouds after initial registration

Point-to-point distance cost function results after RANSAC refinement

Hardware and Actuation

Subsystem Description: Hardware and Actuation

Work Environment Mock-up



Reamer and Kinova Gen-3

Surgical Reamer

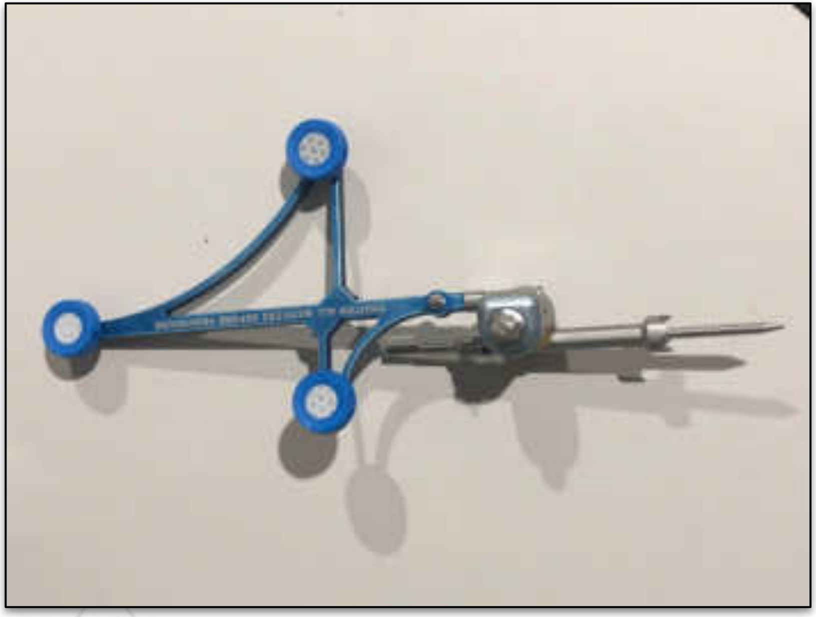
+

Kinova Gen-3 Robot Arm

Current Progress: Kinova Gen-3

Kinova Gen-3 Working

Current Progress: Pelvis Screw Mount and Reaming Handle



Pelvis Screw Mount

Reaming Handle

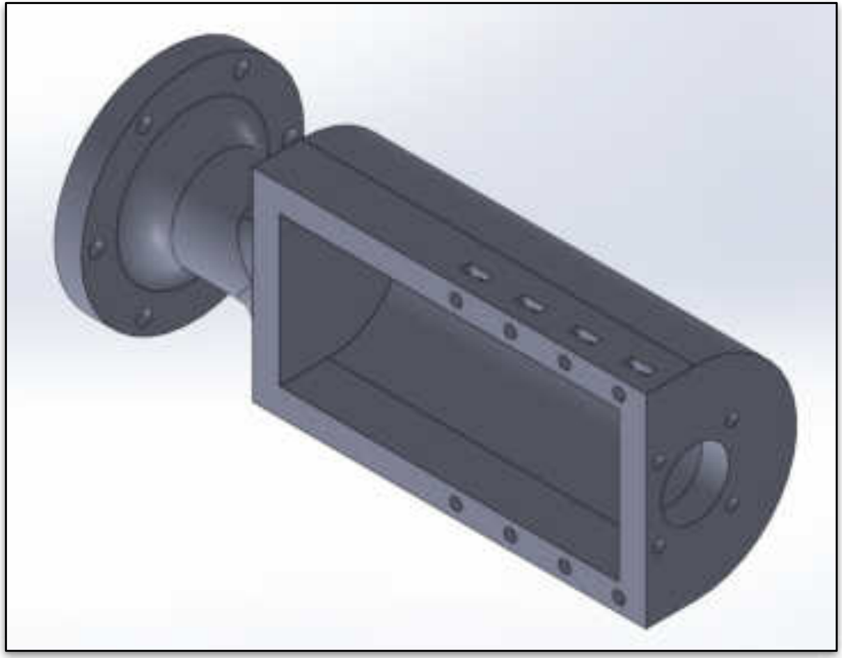
Current Progress: End-Effector Adapter

Solidworks Clamping Design

Clamping 3D-Print Prototype

Current Progress: End-Effector Adapter

ServoCity Motor

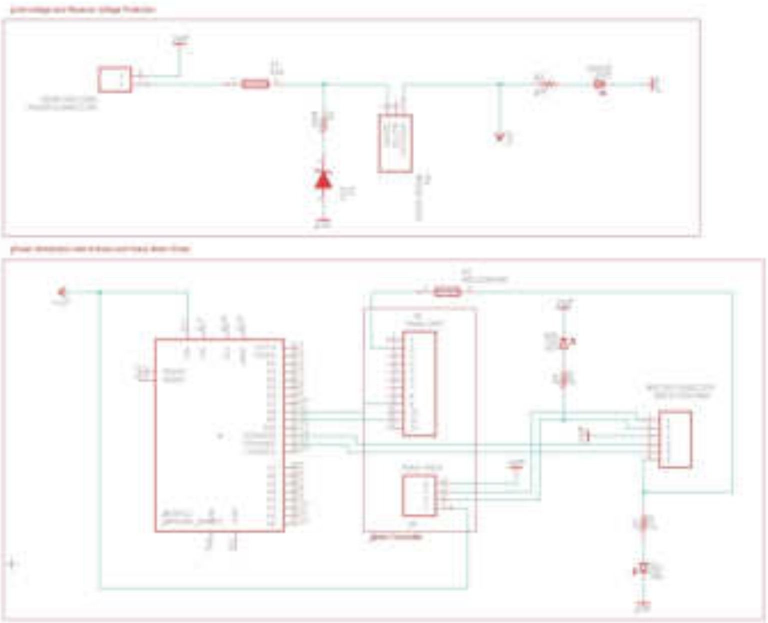


End-Effector Adapter

Current Progress: End-Effector Adapter

Full End-Effector Assembly

Current Progress: Motor-Control PCB



PCB Schematic

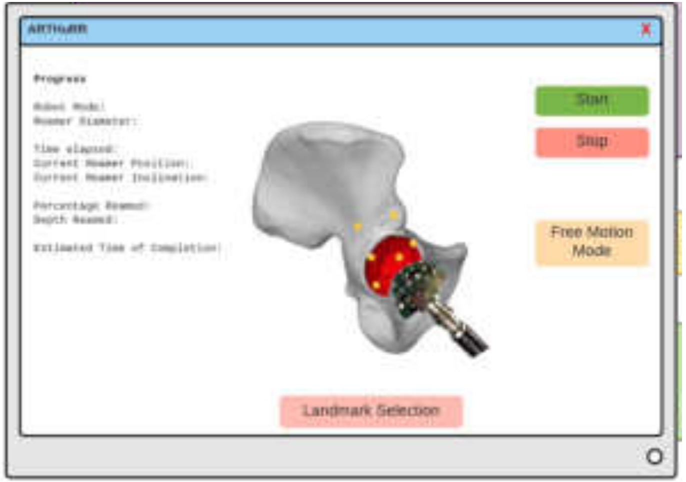
Pololu Motor Driver, Power Supply, Arduino Nano

Current Progress: Completed Setup

Full Setup

Surgeon I/O

Surgeon I/O and Visualization



IGSTK Visualization Screen

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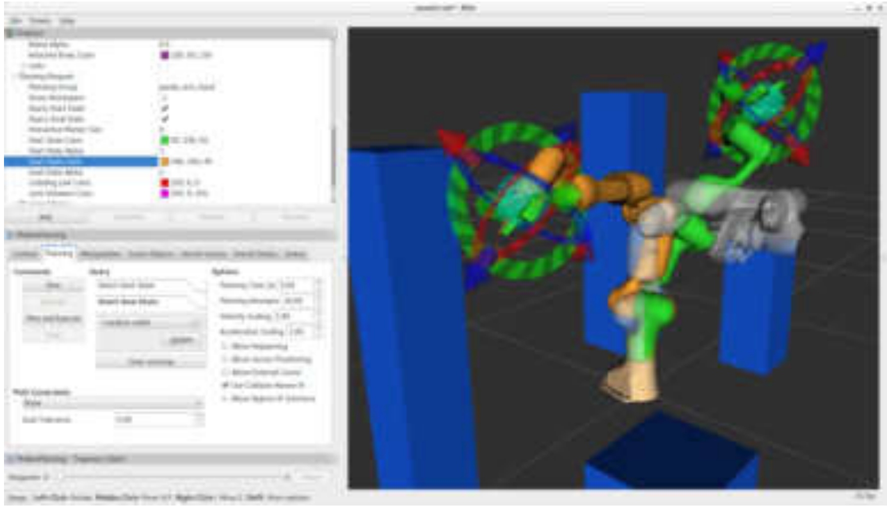
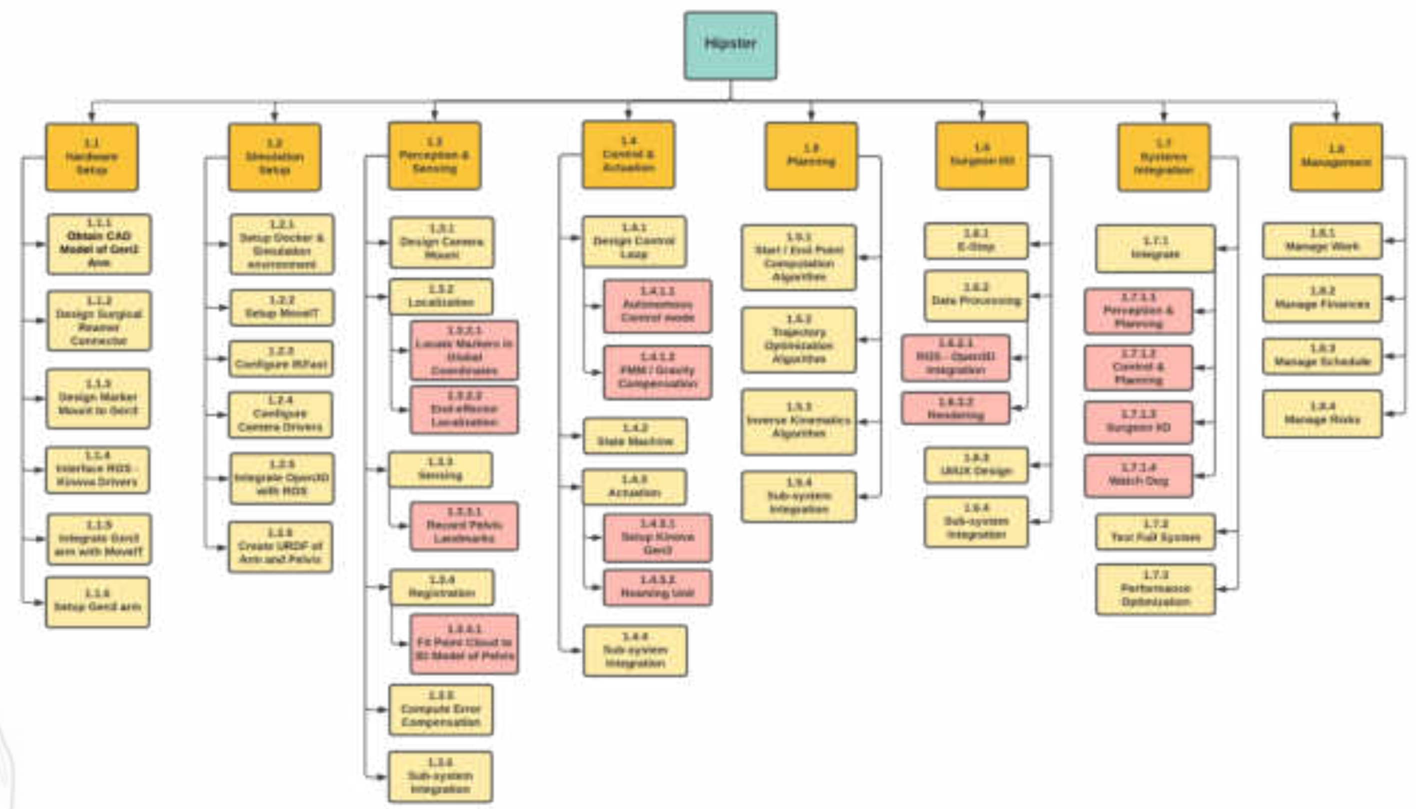


RViz Visualization Screen [8]

Project Management

Work-Breakdown Structure



Schedule

Epic
FEB
MAR
APR
MAY
Progress Review 2
Progress Review 3
Progress Review 4
Progress Review 5
Report
HRR-182 Environment Setup
HRR-82 Hardware Setup
HRR-91 Perception and Sensing
HRR-92 Controls and Actuation
HRR-93 Motion Planning
HRR-101 Project Course
HRR-108 Business Course
HRR-179 Project Management

High-Level Test Plan: Progress Reviews

Identifier	Capability Milestone(s)	Associated Tests	System Requirements
Progress Review 3 **3/23/2022**	- Probe is able to be used to create a point cloud which can be visualized - Control method is capable of being used with robot manipulator virtually - Waypoint and trajectory generation working in ROS - Hardware verified for use in reamer assembly	Test 5 Test 11 Test 13 Test 17	M.F.1 M.F.2
Progress Review 4 **4/6/2022**	- Probe is able to create a point cloud which is comparable to the pelvis geometry - Waypoint generation compensation is implemented virtually - Control method is capable of being used with robot manipulator physically - Robot manipulator end-effector and setup is fully assembly	Test 6 Test 12 Test 14 Test 16	M.F.1 M.F.2 M.F.3 M.F.5 M.N.1
Progress Review 5 **4/20/2022**	- Probe is able to create a point cloud which is sufficient for use in generating waypoints according to surgical plan - Control method and motion planning fully integrated - Detect all movement of the pelvis - Manipulator able to be maneuvered in free motion mode	Test 8 Test 9 Test 10 Test 15	M.F.1 M.F.2 M.F.3 M.F.4 M.F.6

High-Level Test Plan: Fall Semester Plan [Tentative]

Month	Capability Milestone	Validation Metrics
August	Free Motion Mode	Personnel can move robot arm around freely
September	Perception + Planning Subsystem Integration	Robot can determine its pose with respect to the pelvis within 50ms, within a pose and orientation error of 1mm and 1.5 degrees respectively
	Dynamic Compensation	This latency in computing error must be within 50ms and must generate a new plan within 150ms.
October	Perception + Planning + Controls Subsystem Integration	The trajectory must be followed within the defined root mean square error threshold.
	E-Stop	Must stop the system within 500 ms
November	Full System Integration + Test	1. Run the procedure start script. 2. Record the latency of the initial pose localization. 3. Record the time taken for the motion plan to be generated 4. Robot follows the trajectory. 5. Run Quantitative Trajectory Evaluator
	Surgeon I/O	Latency within 150 ms

High-Level Test Plan: Progress Review 5 & 6 [SVD]

Test 8 : Surgical Plan Tranformation Test	
Surgical Plan Transformation Test	
Objective	
To test the ability of the system to convert a surgical plan specified in thepelvis model to world coordinates that can be taken as input	
Equipment	Atracys Sprytrack 300 Camera, Markers, MRSD System 2, Model Pelvis
Elements	Perception Subsystem
Personnel	Gunjan
Location	NSH B
1. Use the registration p of view of the camera to 2. Specify the pose of th pelvis marker's centroid. 3. Run ROS script to tra	
- The ROS script's pose by the Sprytrack camera orientation combined.	

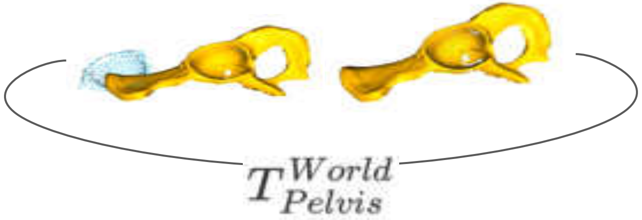
Test 9 :	
Pelvis Motion Detection Test	
Objective	
Test to verify that perception subsystem is capable of processing data to determine if the pelvis has moved past a specified error threshold	
Equipment	Atracys Sprytrack 300 Camera, Markers, MRSD System 2, Sawbone Pelvis
Elements	Perception Subsystem
Personnel	Gunjan Sethi & Kaushik Balasundar
Location	NSH Basement
Procedure	
1. Place the pelvis in the field of vision of the camera. 2.Specify the surgical plan as a 6D pose and convert to world coordinates. 3. Manually move/tilt pelvis beyond the specified error threshold while ensuring that the pelvis marker remains the camera field of vision.	
Validation	
- The ROS script must detect and notify user on change in pelvis position when threshold is exceeded with a latency of <500ms.	

Test 10:	
Motion Planning and Controls Integration Test	
Objective	
To integrate the planning and control subsystems such that the end effector follows the trajectory generated without exceeding the force threshold	
Equipment	MRSD
Elements	Plannin
Personnel	Sundar
Location	NSH Ba
1. Move end-effetor close 2. Call node to generate point. 3. Call control node to m 4. Measure and analyze within stated error limits	
- Check visually and in si - Read force-torque sens stated limits.	

Test 15 :	
Free Motion Mode Test	
Objective	
To test the ability of the manipulator to allow the an external agent to move the end effector freely, moving the arm without gravitational resistance, and without the controller trying to hold a single position	
Equipment	Robotic Manipulator, Force/Torque Sensor, System with Hipster Test Environment (MRSD Desktop 2)
Elements	Controls & Actuation Subsystem, State Machine Design
Personnel	Anthony Kyu
Location	NSH Basement
Procedure	
1. Set up UR5 with Free Motion Mode. 2. Have personnel push the end-effector in random directions within the workspace. 3. Qualitatively assess whether the end-effector moves without resistance (except for possible arm momentum), and without the need for the personnel to provide gravitational assistance.	
Validation	
- The robot end-effector moved with ease or without resistance (qualitatively). - The robot arm didn't need gravitational assistance from the personnel (qualitatively). - The joints of the arm moved in a predictable manner (qualitatively).	

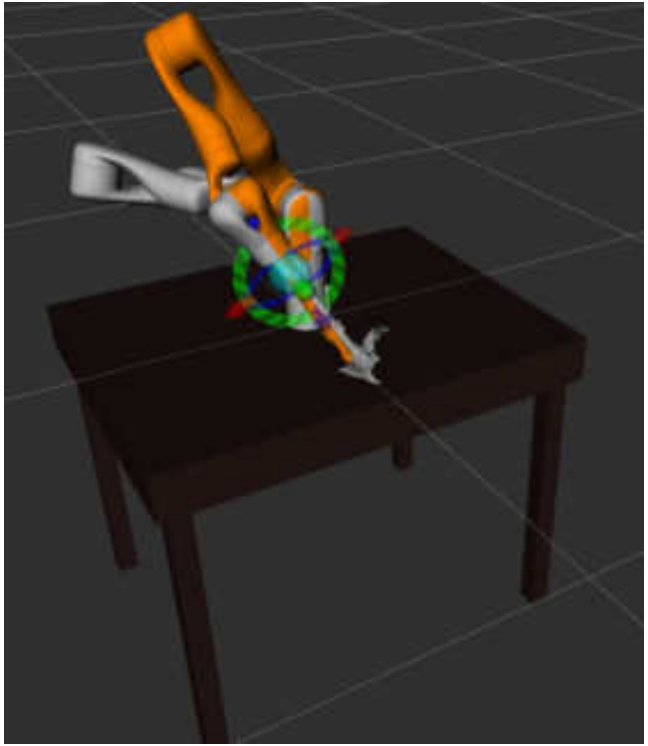
High-Level Test Plan: Progress Review 5 & 6 [SVD]

Test 8 : Surgical Plan Tranformation Test	
Surgical Plan Transformation Test	
Objective	
To test the ability of the system to convert a surgical plan specified in thepelvis model to world coordinates that can be taken as input	
Equipment	Atracys Sprytrack 300 Camera, Markers, MRSD System 2, Model Pelvis
Elements	Perception Subsystem
Personnel	Gunjan Sethi & Kaushik Balasundar
Location	NSH Basement
Procedure	
1. Use the registration probe to slide through the acetabuluar surface in the field of view of the camera to register the pelvis acetabulum with the 3D model. 2. Specify the pose of the acetabular implant (x,y,z,roll,pitch,yaw) to be at the pelvis marker's centroid. 3. Run ROS script to transform to world frame coodinates with registration result	
Validation	
- The ROS script's pose output must be the same as the pelvis marker reading read by the Sprytrack camera with a maximum error of 3 mm in position and 3 degrees in orientation combined.	



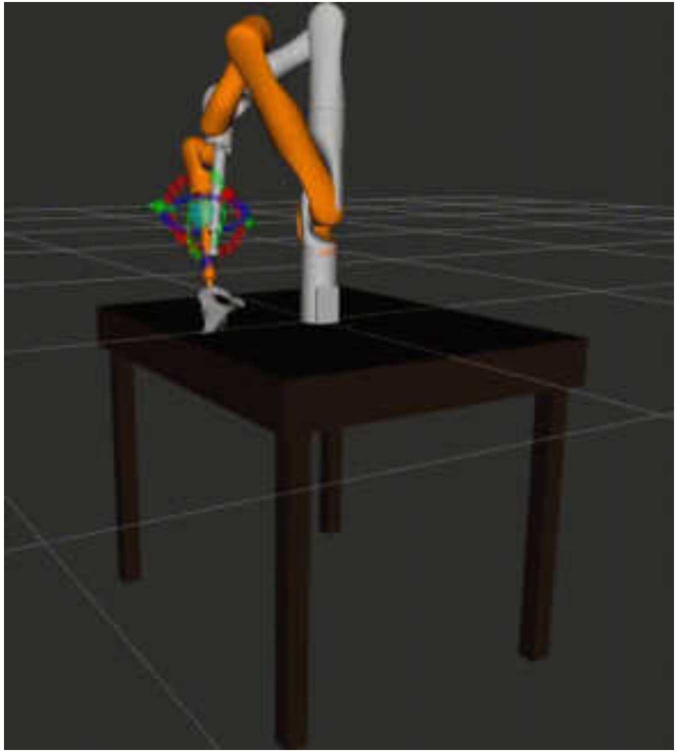
High-Level Test Plan: Progress Review 5 & 6 [SVD]

Test 9 :	
Pelvis Motion Detection Test	
Objective	
Test to verify that perception subsystem is capable of processing data to determine if the pelvis has moved past a specified error threshold	
Equipment	Atracys Sprytrack 300 Camera, Markers, MRSD System 2, Sawbone Pelvis
Elements	Perception Subsystem
Personnel	Gunjan Sethi & Kaushik Balasundar
Location	NSH Basement
Procedure	
1. Place the pelvis in the field of vision of the camera. 2.Specify the surgical plan as a 6D pose and convert to world coordinates. 3. Manually move/tilt pelvis beyond the specified error threshold while ensuring that the pelvis marker remains the camera field of vision.	
Validation	
- The ROS script must detect and notify user on change in pelvis position when threshold is exceeded with a latency of <500ms.	



High-Level Test Plan: Progress Review 5 & 6 [SVD]

Test 10:	
Motion Planning and Controls Integration Test	
Objective	
To integrate the planning and control subsystems such that the end effector follows the trajectory generated without exceeding the force threshold	
Equipment	MRSD System 2. Robot Manipulator, Markers, Reaming tool
Elements	Planning & Controls
Personnel	Sundaram Seivur
Location	NSH Basement
Procedure	
1. Move end-effector close to the site of operation. 2. Call node to generate trajectory using MoveIt between current point and end point. 3. Call control node to make the arm move along generated waypoints. 4. Measure and analyze if manipulator follows trajectory and reaches goal state within stated error limits and not exceeding force limits.	
Validation	
- Check visually and in simulation if arm starts following generated trajectory. - Read force-torque sensor readings to validate that the applied forces are within the stated limits of <20N. - Comparing the generated trajectory with the trajectory followed in reality using the RPG Trajectory Evaluation package to validate that the positional error is within 3mm.	



High-Level Test Plan: Progress Review 5 & 6 [SVD]

Test 15 :	
Free Motion Mode Test	
Objective	
To test the ability of the manipulator to allow the an external agent to move the end effector freely, moving the arm without gravitational resistance, and without the controller trying to hold a single position	
Equipment	Robotic Manipulator, Force/Torque Sensor, System with Hipster Test Environment (MRSD Desktop 2)
Elements	Controls & Actuation Subsystem, State Machine Design
Personnel	Anthony Kyu
Location	NSH Basement
Procedure	
1. Set up Kinova Gen 3 in Free Motion Mode. 2. Have personnel push the end-effector in random directions within the workspace. 3. Qualitatively assess whether the end-effector moves without resistance (except for possible arm momentum), and without the need for the personnel to provide gravitational assistance.	
Validation	
- The robot end-effector moved with ease or without resistance (qualitatively). - The robot arm didn't need gravitational assistance from the personnel (qualitatively). - The joints of the arm moved in a predictable manner (qualitatively).	

High-Level Test Plan: FVD

Test Number	Capability Milestone	Location	Sequence of Events	Metrics	Performance Requirements
1	Free Motion Mode	NSH Basement	1. Place pelvis onto the table 2. Power on the robot arm 3. Hold the end-effector and gently manouver it to bring it close to the pelvis	Personnel can move robot arm around freely	M.P.6
2	Subsystem Integration (Percpetion + Planning + Controls)	NSH Basement	1. Run the procedure start script 2. Record the latency of the initial pose localization	Robot can determine its pose with respect to the pelvis within 50ms, within a pose and orientation error of 1mm and 1.5 degrees respectively	M.P.1.1 M.P.1.2.1 M.P.1.2.2 M.P.4.2
			3. Record the time taken for the motion plan to be generated	The latency must be within 150ms	M.P.2
			4. Robot follows the trajectory 5. Run Quantitative Trajectory Evaluator	The trajectory must be followed within the defined root mean square error threshold	M.P.3.1 M.P.3.2
3	Dynamic Compensation	NSH Basement	1. As a continuation to Test 2, move the pelvis' position and orientation from its initial pose 2. Record the latency of the robot indicating an error value between the two points and generating a new plan	This latency in computing error must be within 50ms and must generate a new plan within 150ms	M.P.4.1 M.P.5
4	Surgeon I/O	NSH Basement	1. Start the surgeon I/O during each test 2. The robot and the pelvis, in their current states, must be visible on the surgeon I/O	Latency within 150 ms	M.P.7
5	E-Stop	NSH Basement	1. Run the procedure start script 2. Press the e-stop button mid-execution	Must stop the system within 500 ms	M.P.8

Budget

Total Budget	5000						
Total Spent	369.93						
Balance	4630.07						
Sr. No	Owner	Description	Month	Amount	Tax	Delivery	Total
1	Sundaram	Hemi Pelvis 48mm - Solid foam	Nov	40	4.805	9.3	54.105
2	Sundaram	Hemi Pelvis 56mm with vise attachment - Solid foam	Nov	40	4.805	9.3	54.105
3	Sundaram	Monitor Desk Mount Vesa	Nov	40	2.4	0	42.4
4	Sundaram	Panavise Mount for holding sawbones	Nov	90	6.3	0	96.3
5	Gurjan	LENTION USB-C Multi-Port Hub with 4K HDMI Output, 4 USB 3.0, Type C Charging Compatible 2021-2016 MacBook Pro, New Mac Air & Surface, Chromebook, More, Stable Driver Adapter (CB-C35, Space Gray)	Jan	35.99	2.16	0	38.15
6	Sundaram	Dry-erase markers	March	6.92			6.92
7	Parker	Servocity Planetary Gear Motor	March	59.99			59.99
8	Parker	HD Premium Planetary Gear Motor Mount, Face Tapped	March	4.99			4.99
9	Parker	6mm to 8mm Flexible Clamping Shaft Coupler	March	5.99			5.99
10	Parker	6mm to 0.250" Flexible Clamping Shaft Coupler	March	5.99			5.99
11	Parker	PH Series JST 6-pin connector (2mm Pitch)	March	0.99			0.99

Total Budget	Total Spent	Balance
$5000	$369.93	$4630.07

Risk Management

Risk #	Risk	Type	Likelihood #	Consequence #	Risk Mitigation Action
1	Robot arm does not arrive on time	Schedule	2	4	• Follow-up with sponsor to get robot arm ordered as soon as possible • Plan project to focus on simulation early
2	Robot arm breaks	Technical	2	5	• Implement code on robot arm only after it has proven safe in simulation • Store robot arm in safe environment • Talk with other professors to see if we could use their robot arms as a backup
3	ROS simulation does not match up to reality	Technical	4	2	• Schedule project to include time to find and fix problems in transition from simulation • Discuss differences in simulation and reality in end of sprint meetings
4	Too many requirements	Schedule	3	3	• Determine requirements that are necessary and that are desirable • Individually check progress on requirements in end of sprint meetings
5	Performance requirements not met	Programmatic	4	4	• Conduct research to re-evaluate quantification of performance requirements • Revisit performance requirements every sprint meeting • Have a project manager who checks our performance against requirements
6	Integration issues between subsystems	Technical	5	4	• Define clear inputs and outputs of each subsystem in work breakdown structure • Host end-of-sprint meetings • Create documentation at the end of every sprint
7	Camera hardware fails	Technical	2	4	• Store camera in a safe location • Design pipeline for the use of the camera • Ask sponsor for a backup camera to use in an emergency • Find another camera online to order in case of emergency
8	ROS and IGSTK data conversion difficulties	Technical	4	2	• Schedule project to have enough time to determine and fix potential problems • Research data types needed for ROS and IGSTK visualization
9	Team member has difficulties working on their part of the project	Programmatic	5	2	• Schedule primary and secondary roles, so all work tasks have two owners • Have time during end-of-sprint meetings to communicate issues
10	Development Environment Incompatibility	Technical	5	1	• Use Docker so that everyone's ROS environment is set up the same • Train on ROS and Docker during the winter break
11	Unable to access workspace	Programmatic	1	5	• Set up simulation environment on everyone's personal computer • Discuss with sponsor potential back-up workspace

*Red indicates biggest risks

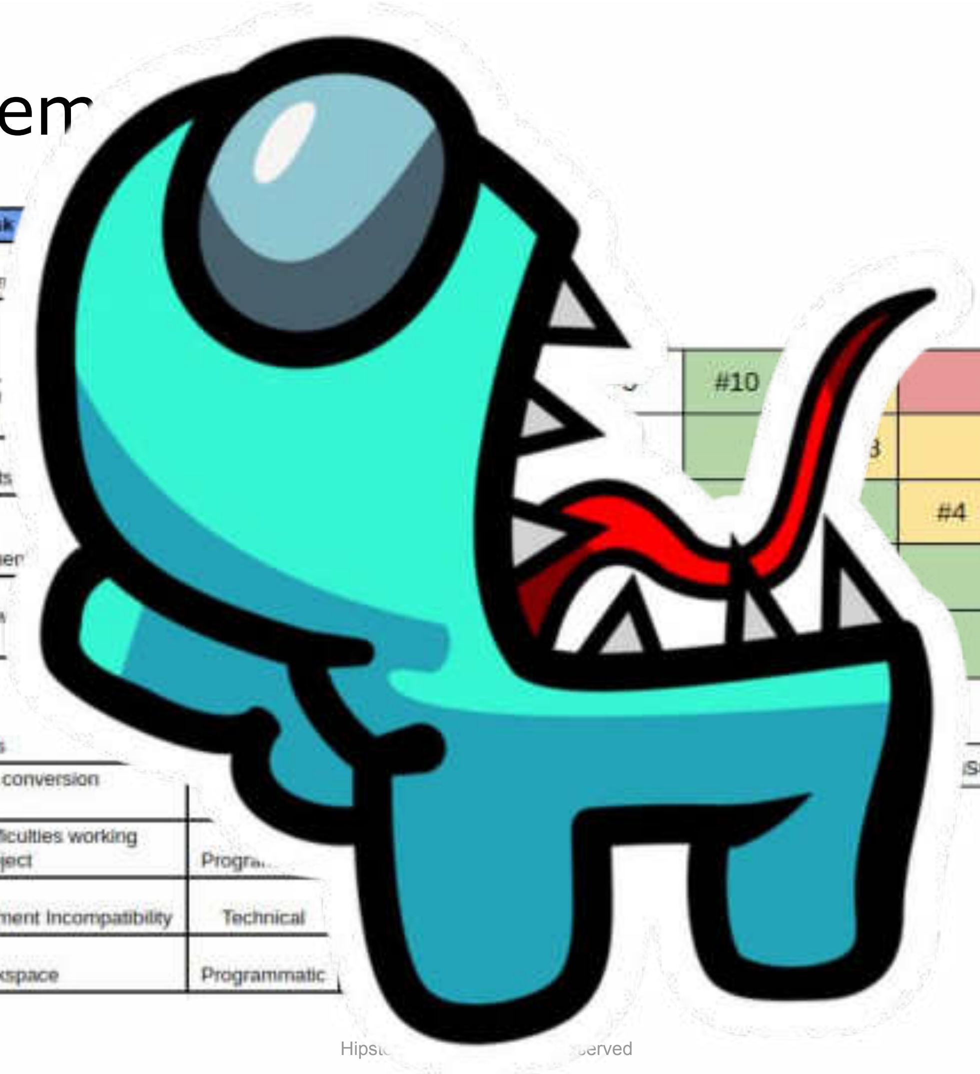
Risk Management

Risk #	Risk	Type
1	Robot arm does not arrive on time	Schedule
2	Robot arm breaks	Technical
3	ROS simulation does not match up to reality	Technical
4	Too many requirements	Schedule
5	Performance requirements not met	Programmatic
6	Integration issues between subsystems	Technical
7	Camera hardware fails	Technical
8	ROS and IGSTK data conversion difficulties	Technical
9	Team member has difficulties working on their part of the project	Programmatic
10	Development Environment Incompatibility	Technical
11	Unable to access workspace	Programmatic

Likelihood	5	#10	#9			
	4		#3, #8		#5	#6
	3			#4		
	2				#1, #7	#2
	1					#11
		1	2	3	4	5
		Consequence				

Risk Managem

Risk #	Risk	
1	Robot arm does not ar	
2	Robot arm breaks	
3	ROS simulation does reality	
4	Too many requirements	
5	Performance requiremen	
6	Integration issues betw subsystems	
7	Camera hardware fails	
8	ROS and IGSTK data conversion difficulties	
9	Team member has difficulties working on their part of the project	Progra
10	Development Environment Incompatibility	Technical
11	Unable to access workspace	Programmatic



#10				
			#5	#6
		#4		
			#1, #7	#2
				#11
			4	5
		sequence		

Risk Management

Risk #	Risk	Type
1	Robot arm does not arrive on time	Schedule
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Likelihood	5	#10	#9			
	4		#3, #8		#5	#6
	3			#4		
	2				#1, #7	#2
	1					#11
		1	2	3	4	5
		Consequence				

Thank You!

Questions?

References

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Mandatory Functional & Performance Requirements

Functional Requirement	Performance Requirement	Justification
M.F.1 The system shall **localize the robot arm** in real-time with respect to the pelvis before and during surgery	M.P.1.1 The system will localize the robot arm in real-time with respect to the pelvis before and during surgery with a **latency less than or equal to 50 ms**	Latency of Atracsys Sprytrack 300 is less than 25ms; Processing time ~ 25ms
	M.P.1.2.1 The system will localize the robot arm in real-time with respect to the pelvis before and during surgery with a **position error of less than 1 mm**	Survey sent to surgeons and literature review suggest a desired position error of less than 2 mm. Combining M.P.1.2.1 and M.P.3.1 will result in a combined position error of less than 2 mm.
	M.P.1.2.2 The system will localize the robot arm in real-time with respect to the pelvis before and during surgery with an **orientation error of less than 1.5-degrees**	Survey sent to surgeons and literature review suggest a desired orientation error of less than 3-degrees. Combining M.P.1.2.2 and M.P.3.2 will result in a combined orientation error of less than 3-degrees.

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Mandatory Functional & Performance Requirements

Functional Requirement	Performance Requirement	Justification
M.F.2 The system shall **plan the trajectory** of the robot arm based on the given surgical plan	M.P.2 The system will plan the trajectory of the robot arm based on the given surgical plan with a **latency less than or equal to 150 ms**	Total latency of the system should be less than 500 ms.
M.F.3 The system shall **execute surgical plan** by reaming along the generated trajectory	M.P.3.1 The system will execute surgical plan by reaming along the generated trajectory with an **position error of less than 1 mm**	Survey sent to surgeons and literature review suggest a desired position error of less than 2 mm. Combining M.P.1.2.1 and M.P.3.1 will result in a combined position error of less than 2 mm.
	M.P.3.2 The system will execute surgical plan by reaming along the generated trajectory with an **orientation error of less than 1.5-degrees**	Survey sent to surgeons and literature review suggest a desired orientation error of less than 3-degrees. Combining M.P.1.2.2 and M.P.3.2 will result in a combined orientation error of less than 3-degrees.

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Mandatory Functional & Performance Requirements

Functional Requirement	**Performance Requirement**	**Justification**
M.F.4 The system shall **compute error and interpret the movement** of the pelvis during reaming	M.P.4.1 The system will compute error and interpret the movement of the pelvis during reaming with a **latency less than or equal to 50 ms**	Latency similar to localization
	M.P.4.2 The system will **generate a new trajectory if** the interpreted position and orientation **errors are greater than 1 mm or greater than 1.5-degrees**	The thresholds for compensating for these errors should be less than the desired errors (2 mm and 3-degrees).
M.F.5 The system shall **adapt and compensate for movement** by generating a new trajectory	M.P.5 The system will adapt and compensate for movement by generating a new trajectory with a **latency less than or equal to 150 ms**	Latency similar to trajectory planning

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Mandatory Functional & Performance Requirements

Functional Requirement	Performance Requirement	Justification
M.F.6 The system shall allow the surgeon to **place the robot arm at an initial position**	M.P.6 The system will allow the surgeon to place the robot arm to an initial position by **back-driving the robotic arm**	Reduce system complexity by keeping path to be planned short
M.F.7 The system shall **provide the surgeon with visual feedback**	M.P.7 The system will provide the surgeon with visual feedback with a **latency less than or equal to 150 ms**	From literature on telesurgery, latency >150 ms is found to be noticeable to surgeons, and degrades performance of surgeon-performed tasks
M.F.8 The system shall **allow the surgeon to e-stop**	M.P.8 The system will allow the surgeon to e-stop the system, **stopping the system within 500 ms**	Competitor systems have similar quantification

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Desired Functional & Performance Requirements

Functional Requirement	Performance Requirement	Justification
D.F.1 The system shall **allow surgeon to change end-effector/tool**	D.P.1 The system will allow surgeon to change end-effector/tool in **3 steps or less**	During surgery, some surgeons would prefer to step up reamers sizes instead of using the final size. Allowing them to do this in 3 steps or will allow the surgeon to quickly and change tools during surgery.
D.F.2 The system shall **position acetabular cup for surgeon to impact** into reamed acetabulum	D.P.2 The system will position the acetabular cup for the surgeon to impact into reamed acetabulum with **less than a 3-degree error.**	According to surgeon surveys and literature review, 3-degree error is the maximum allowable error. Since the reaming determines positional error, positional error is not a concern for impaction.

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Mandatory & Desired Non-Functional Requirements

M.N.1 **The system *will*** produce forces low enough for it to be safe around humans

M.N.2 **The system *will*** provide a minimal and easy-to-interpret user interface design for surgeons

M.N.3 **The system *will*** autonomously detect malfunctions and errors and notify user accordingly

D.N.1 **The system *will*** allow for numerous successful surgeries, without the need for servicing and calibration

D.N.2 **The system *will*** have a cost comparable to similar systems on the market

D.N.3 **The system *will*** adhere to all relevant ISO standards pertaining to medical robotic systems

D.N.4 **The system *will*** be of a size and dimension that is ergonomic

D.N.5 **The system *will*** be designed such that it can be serviced easily

D.N.6 **The system *will*** be designed to be easily sterilizable or sterile in the sterile field

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