HIPSTER

Autonomous Reaming for Total Hip Replacement (ARTHuR)

Conceptual Design Review

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Meet the Team

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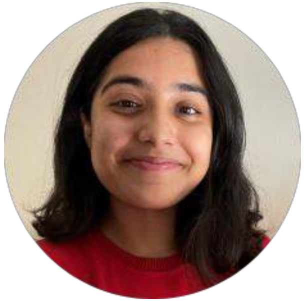

Gunjan Sethi

Software Engineering Lead

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Trajectory Planning Lead

Overview

Overview

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

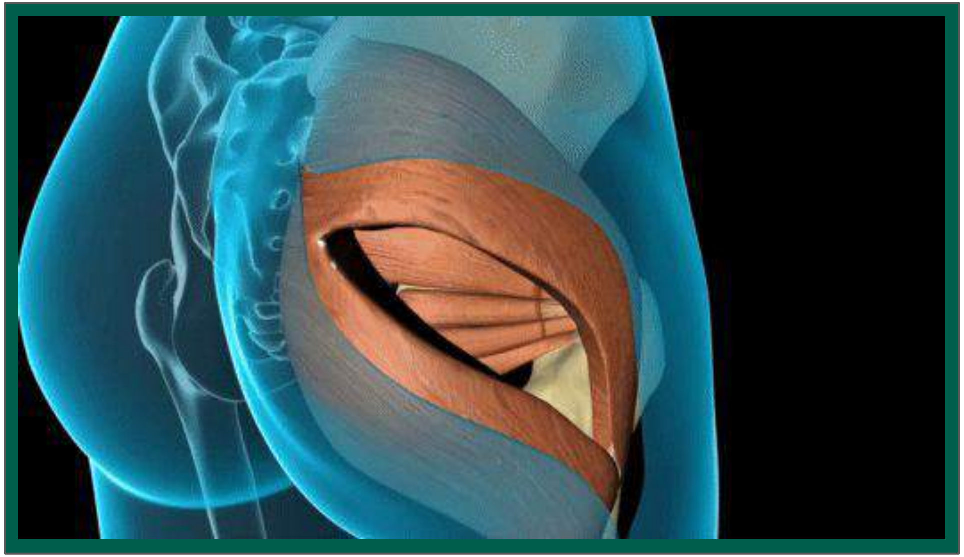


Fig 1: Total Hip Arthroplasty Overview [1]

Some Statistics

01

Of the 100 manual surgeries, **30-45% of them observed the implant within the Lewnnik safe zone** and of the 100 robotic-assisted surgeries, **77% were within the safe zone.**

02

Study on the future projections on the number of total joint replacements in the US, show that up until 2040, **we can expect an increase in the requirement of a THR for both sexes by approximately 280%.**

Fig 2: Statistics Overview [2], [3]

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

Fig 2: 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

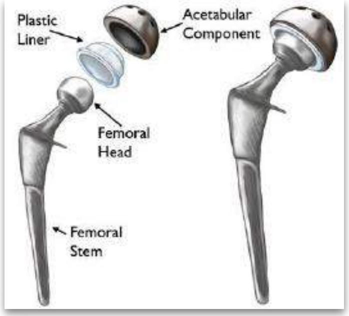


Fig 3: Femoral Stem and Acetabular Component Construction [4]

Our Solution: **ARTHuR**

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

A patient is suffering from osteoarthritis in their hip joint and is in need of a total hip replacement/arthroplasty. Before the surgery, a CT scan of the patient's pelvis is taken, and the data from the scan is used to create a 3D model of the patient's acetabulum. Based on the anatomical model, a hip implant prosthesis is chosen and the surgeon makes a plan on where the acetabular cup needs to be placed within the generated anatomical model.

During the surgery, the patient is oriented on their side. The surgeon exposes the joint and reflective markers are drilled into the pelvis. These markers are located in 3 dimensional space by a Sprytrack 300 camera, and the pelvis is localized to these reflective markers using a probe. The surgeon then moves the robotic arm close to the acetabulum after which the arm plans, optimizes and executes a trajectory to ream the acetabulum to fit the desired acetabular cup. As the robotic arm autonomously reams the acetabulum, the surgeon is provided with visual feedback on a monitor and has access to an emergency stop button to stop the procedure in case of system failure. Once the robotic arm has finished reaming, it can be removed from the surgical site, and the surgeon can analyze the acetabulum.

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! :)

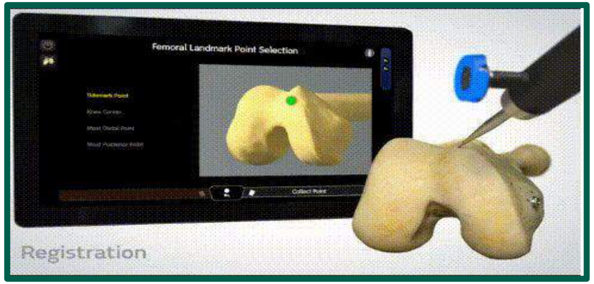


Fig 4: Use Case Flow

Requirements

Functional & Performance Requirements

Functional Requirement	**Performance Requirement**	**Justification**
H.F.1 The system shall **localize the robot arm** in real-time with respect to the pelvis before and during surgery	H.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
	H.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 H.P.1.2.1 and H.P.3.1 will result in a combined position error of less than 2 mm.
	H.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 H.P.1.2.2 and H.P.3.2 will result in a combined orientation error of less than 3-degrees.

Functional & Performance Requirements

Functional Requirement	Performance Requirement	Justification
H.F.2 The system shall **plan the trajectory** of the robot arm based on the given surgical plan	H.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.
H.F.3 The system shall **execute surgical plan** by reaming along the generated trajectory	H.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 H.P.1.2.1 and H.P.3.1 will result in a combined position error of less than 2 mm.
	H.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 H.P.1.2.2 and H.P.3.2 will result in a combined orientation error of less than 3-degrees.

Functional & Performance Requirements

Functional Requirement	**Performance Requirement**	**Justification**
H.F.4 The system shall **compute error and interpret the movement** of the pelvis during reaming	H.P.4 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
H.F.5 The system shall **adapt and compensate for movement** by generating a new trajectory	H.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

Functional & Performance Requirements

Functional Requirement	Performance Requirement	Justification
H.F.6 The system shall allow the surgeon to **place the robot arm at an initial position**	H.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
H.F.7 The system shall **provide the surgeon with visual feedback**	H.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
H.F.8 The system shall **allow the surgeon to e-stop**	H.P.8 The system will allow the surgeon to e-stop the system, **stopping the system within 500 ms**	Competitor systems have similar quantification

Non-Functional Requirements

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

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

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

H.N.4 **The system *will*** allow for numerous successful surgeries, without the need for servicing and calibration

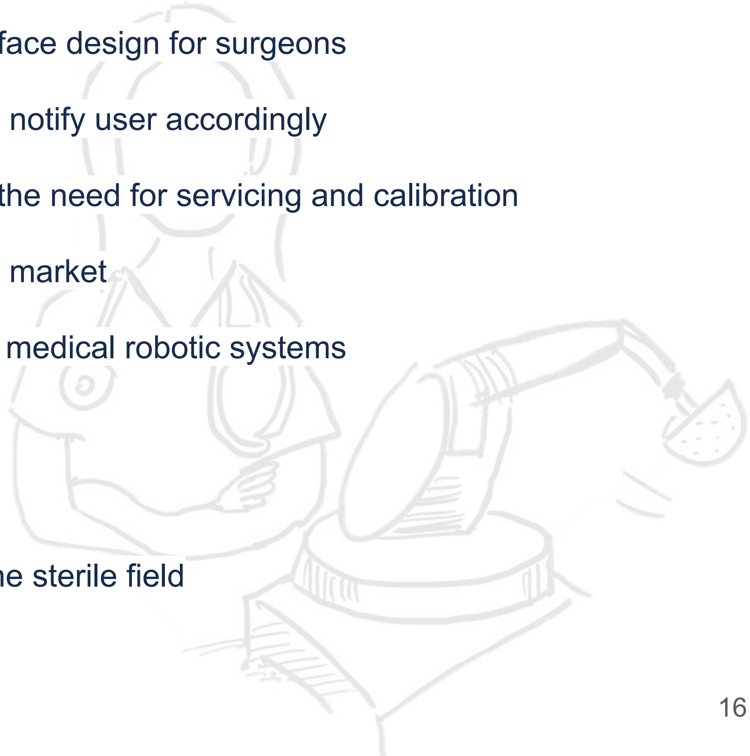
H.N.5 **The system *will*** have a cost comparable to similar systems on the market

H.N.6 **The system *will*** adhere to all relevant ISO standards pertaining to medical robotic systems

H.N.7 **The system *will*** be of a size and dimension that is ergonomic

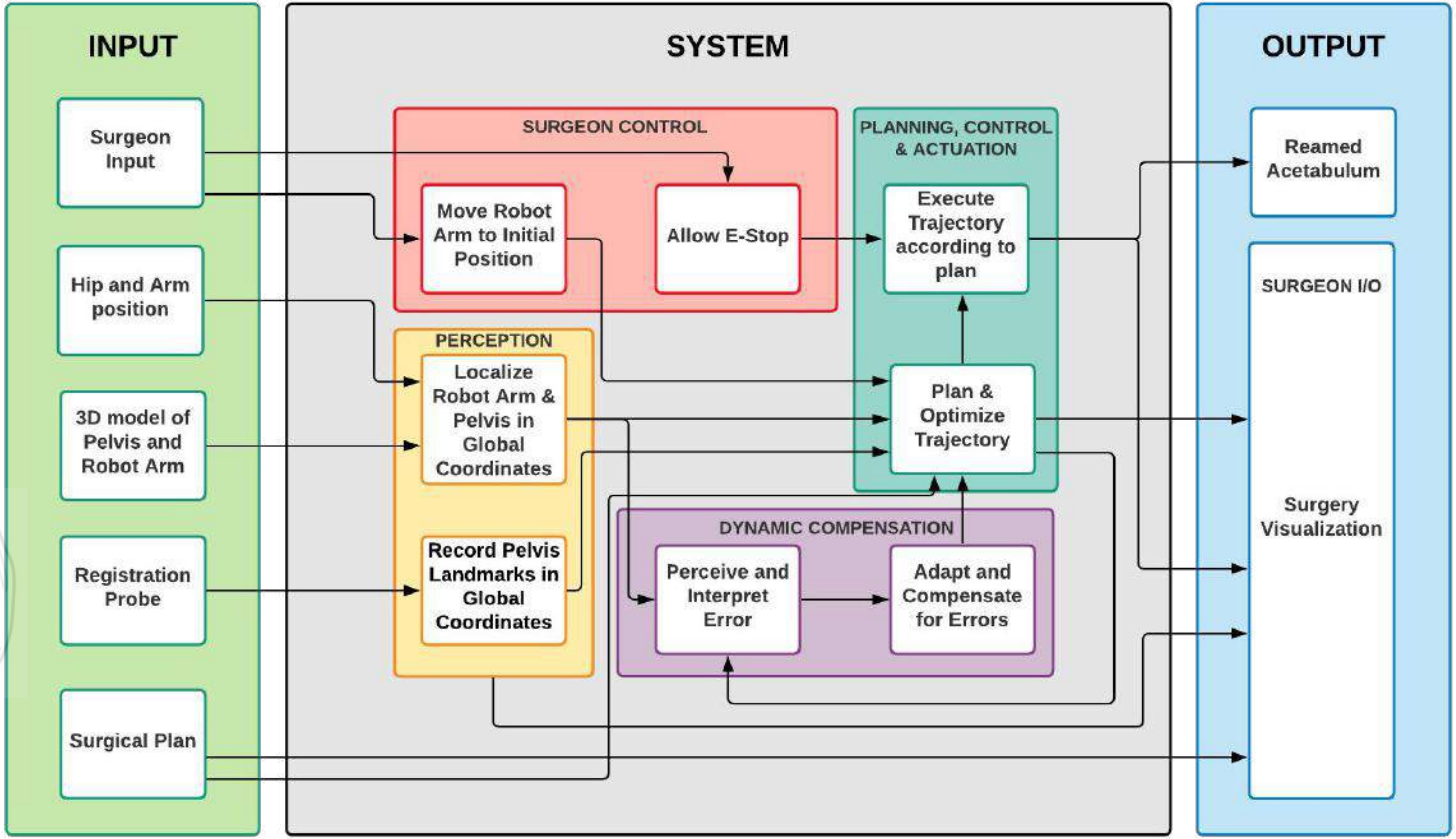
H.N.8 **The system *will*** be designed such that it can be serviced easily

H.N.9 **The system *will*** be designed to be easily sterilizable or sterile in the sterile field

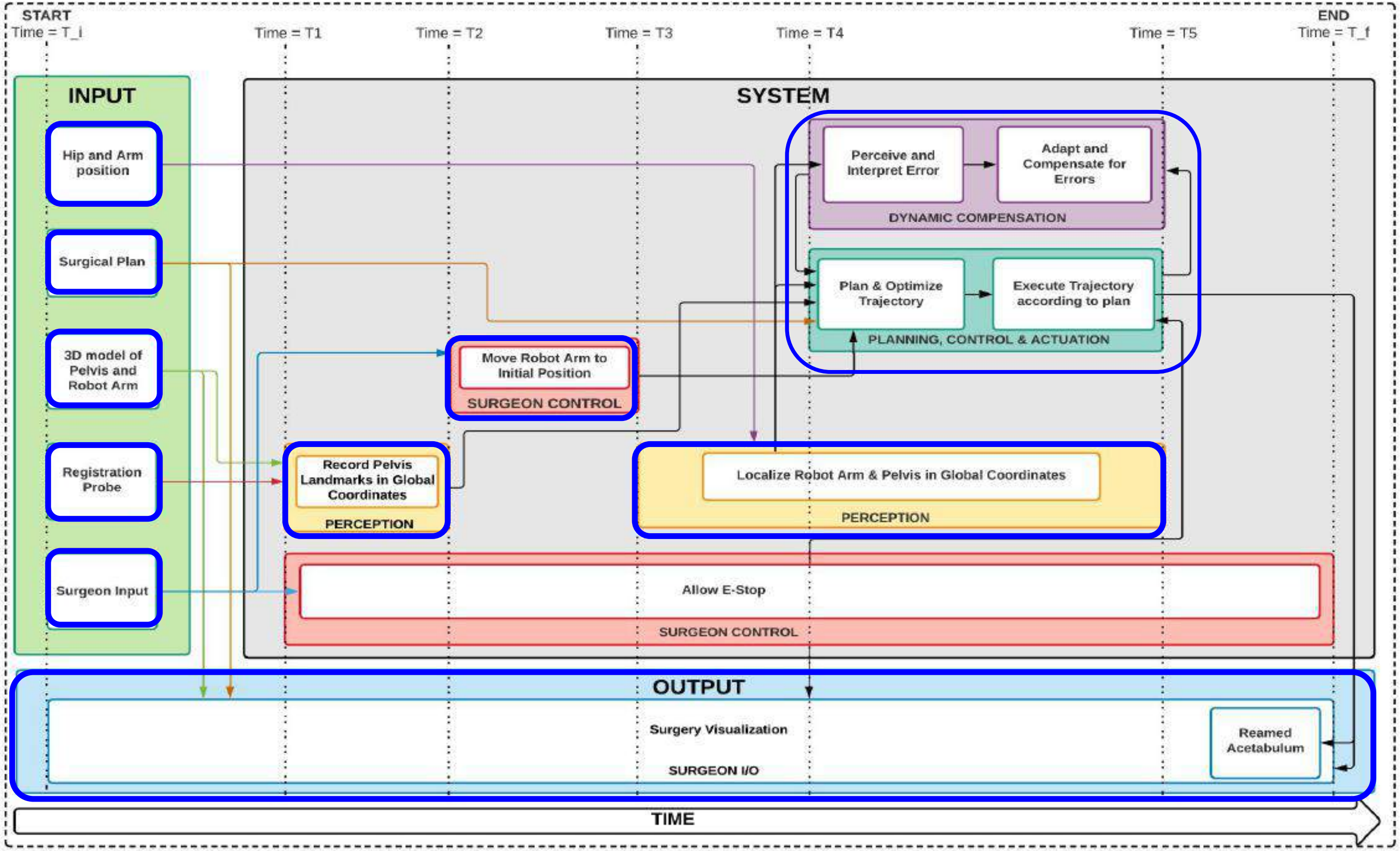


Functional Architecture

Functional Architecture: Version 1

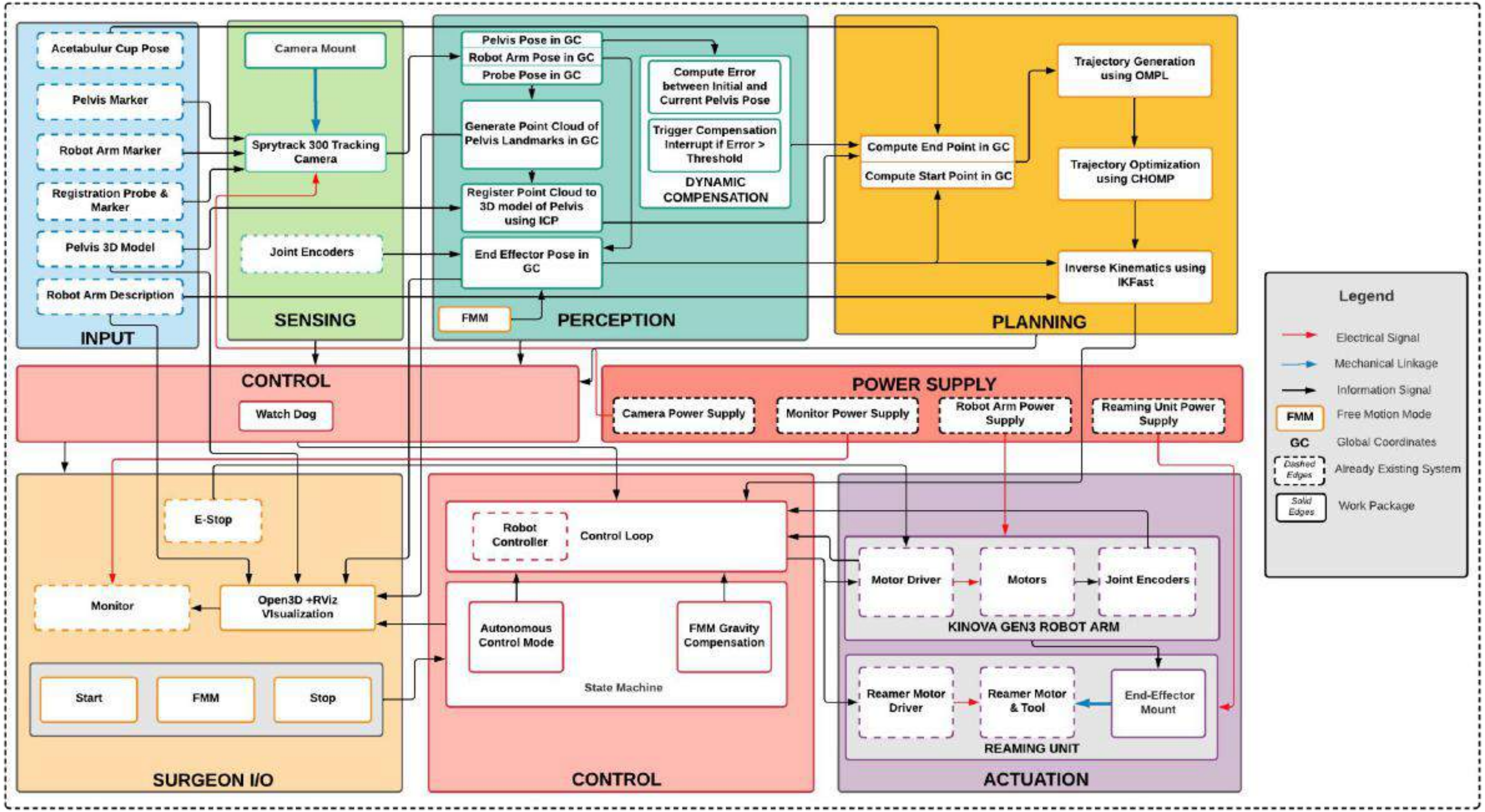


Functional Architecture: Revised

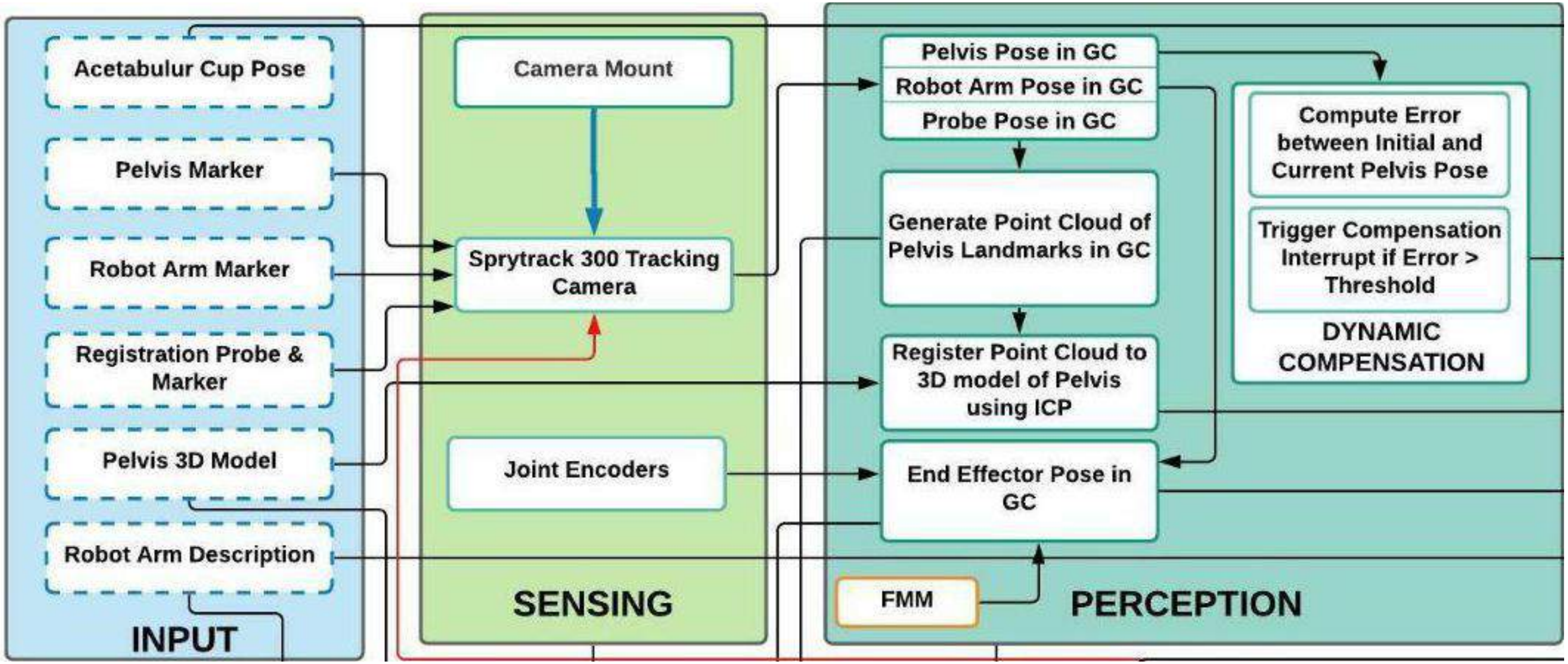


Cyberphysical Architecture

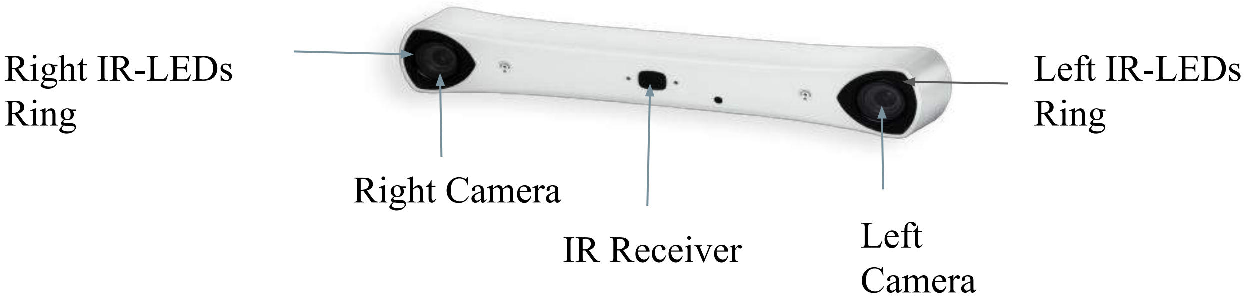
Cyberphysical Architecture



Input, Sensing, and Perception



Sprytrack 300 Camera



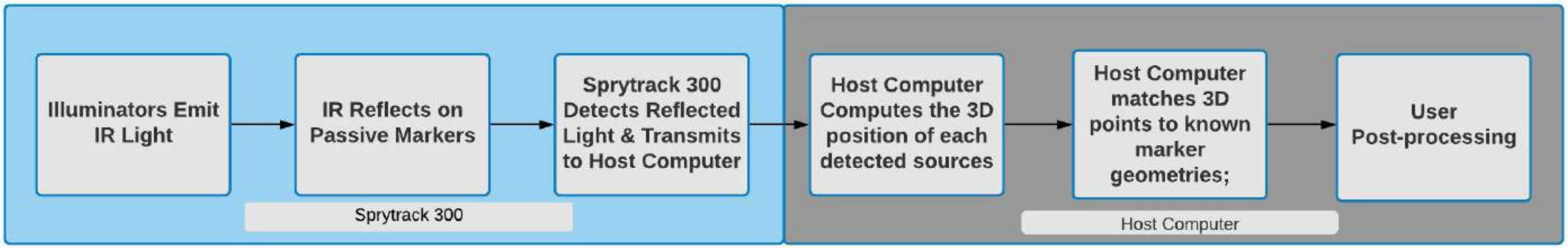


Fig 8: High Level Functionality of Sprytrack 300

Registration

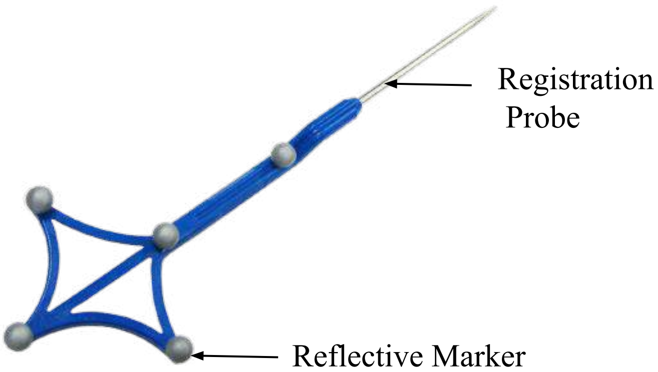


Fig 5: Registration Probe [5]

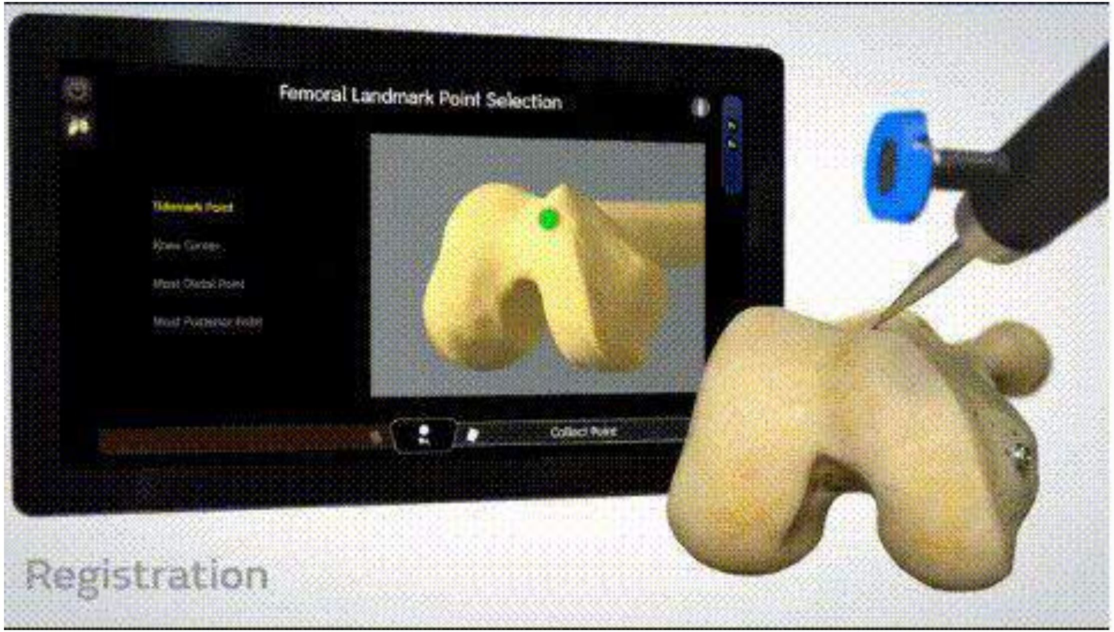


Fig 6: Registration Procedure on commercial products[6]

Dynamic Compensation

What is Dynamic Compensation?

- During THA, the forces acting on the patient while reaming makes the patient move
- This motion can lead to inaccuracies in position and orientation of the acetabular cup placement plan

Why Dynamic Compensation?

- Allows for adapting to the motion of the patient, hence, improving accuracy
- Competitor systems do not account for the problem in real-time

Dynamic compensation would require low-latency performance and optimized code

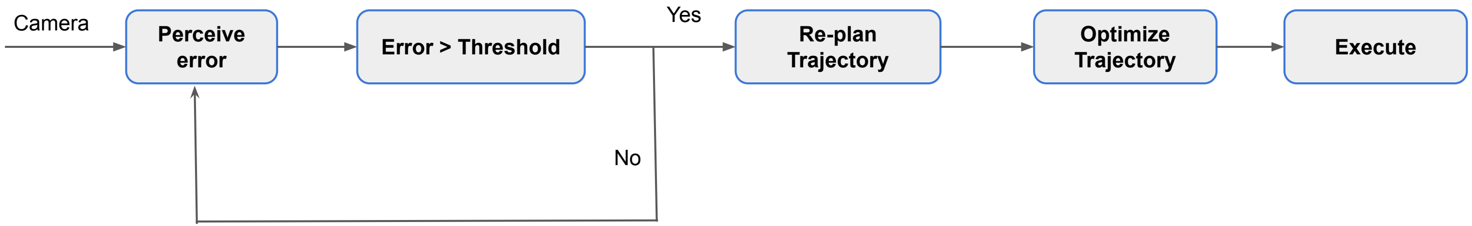
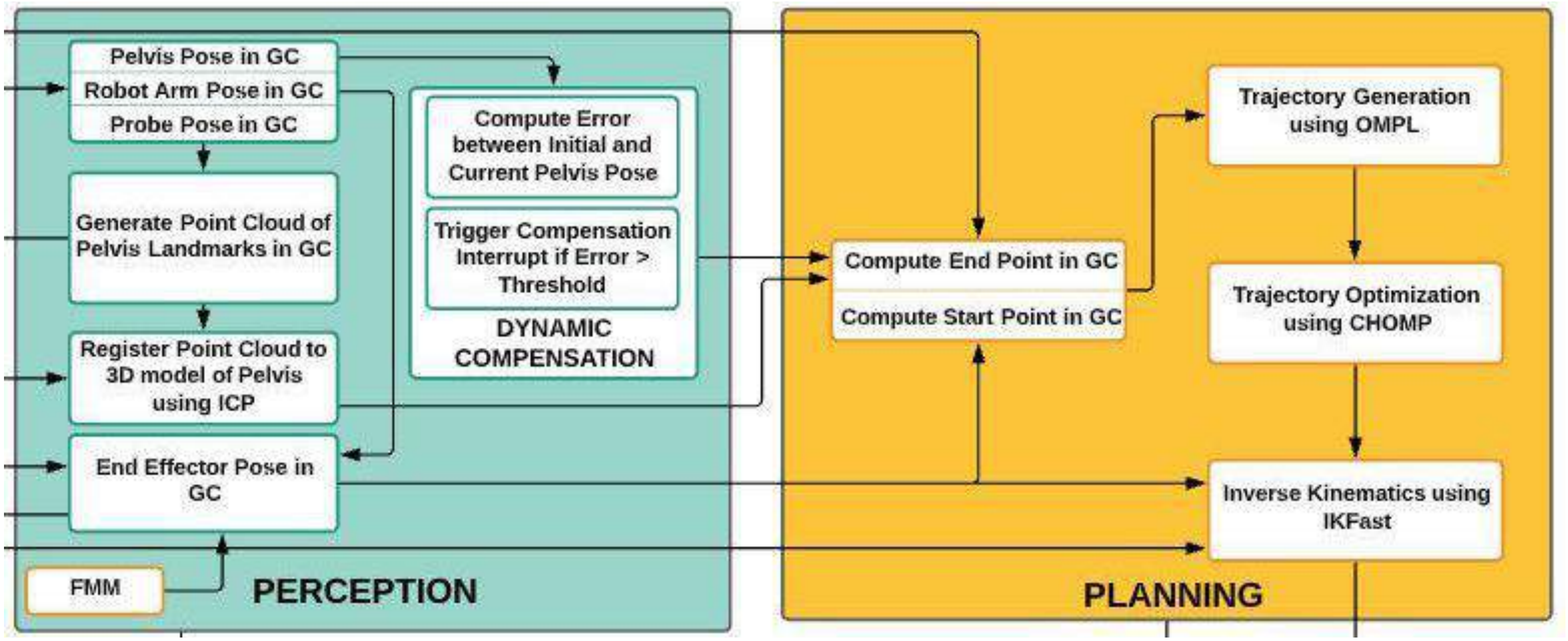
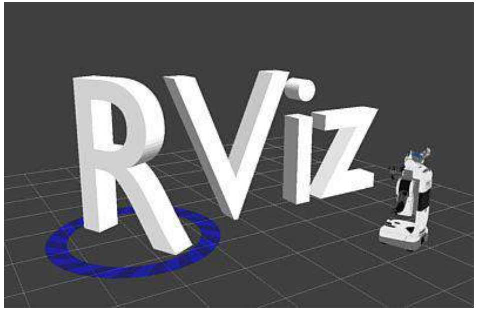


Fig 9: Functioning of Dynamic Compensation

Perception and Planning



Using ROS for Planning & Control



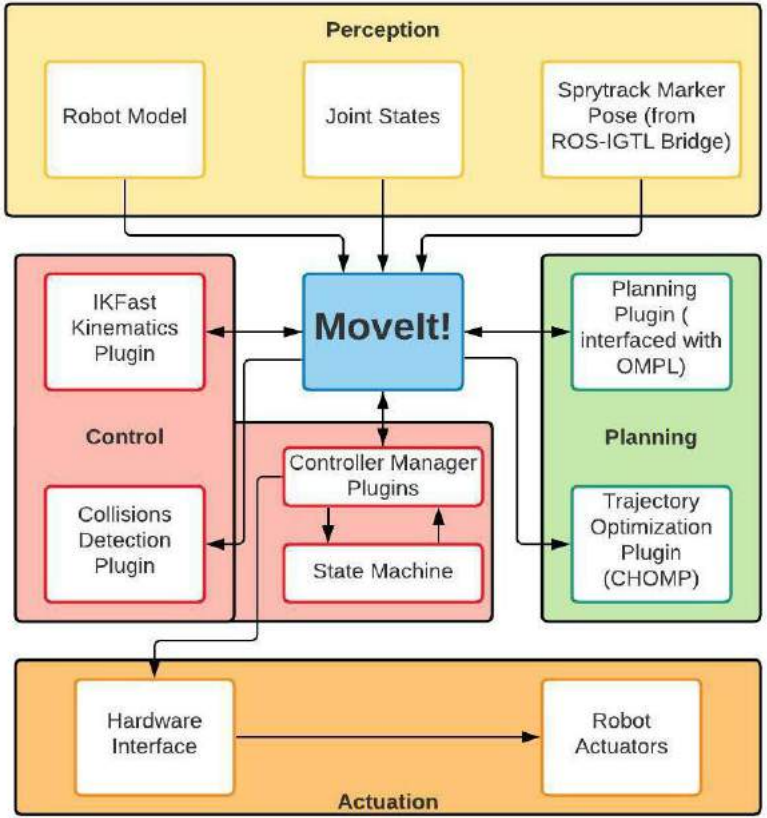
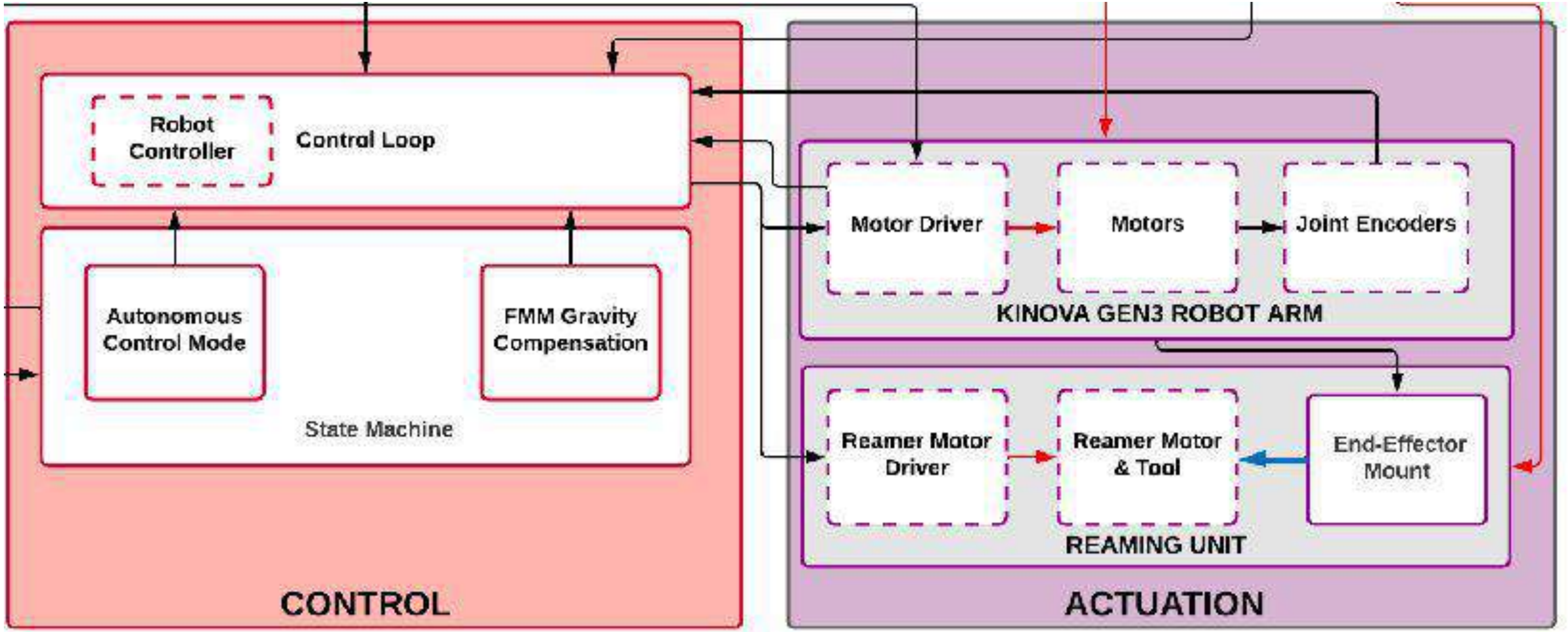


Fig 9: MoveIt! Dependencies

Control and Actuation



Free Motion Mode (FMM)

Fig 7: Example of Gravity Compensation in FMM [9]

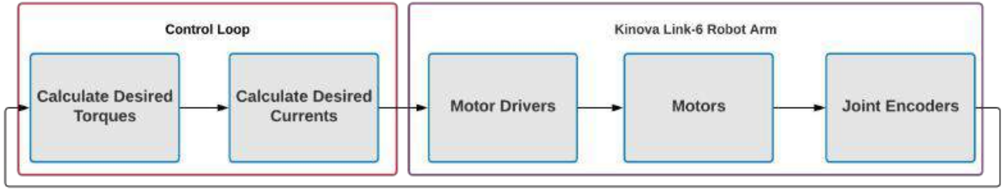
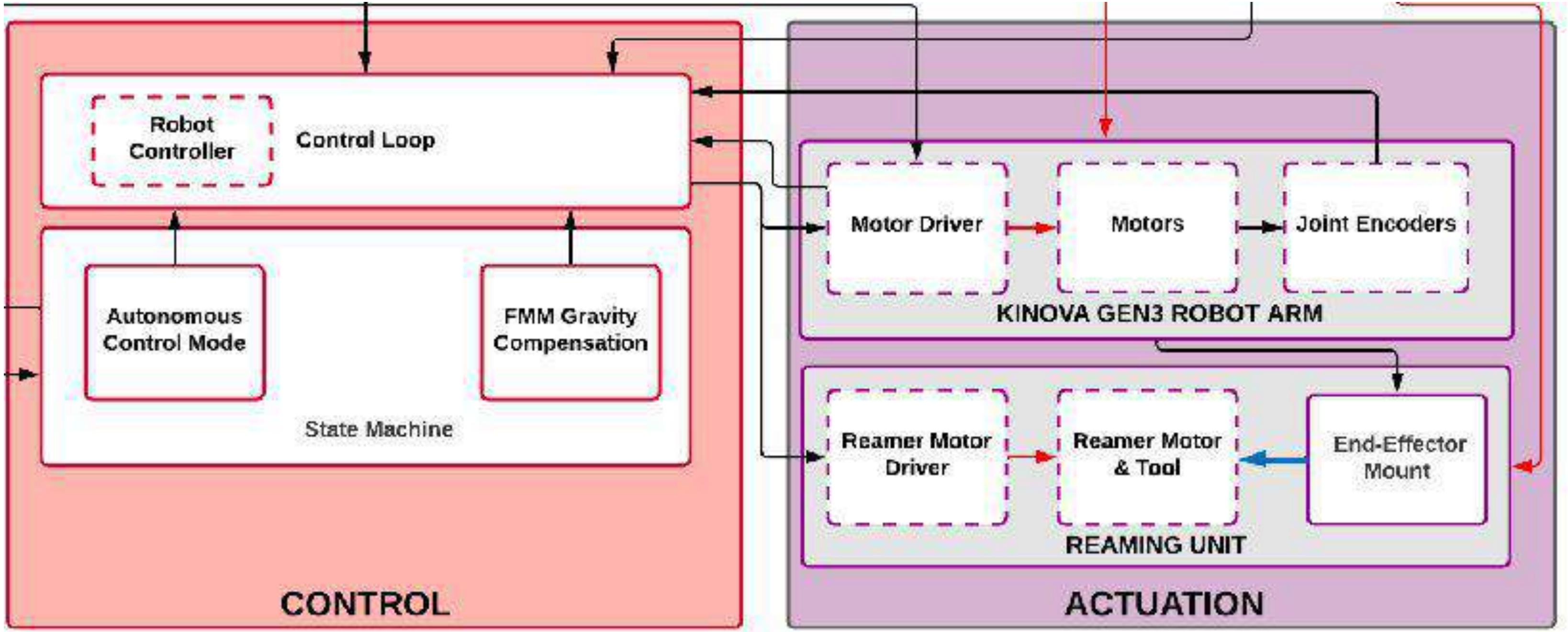


Fig 8: Flow Diagram for FMM

Control and Actuation



Reamer and Robot Arm Compatibility

Fig 9: Surgical Reamer [10]

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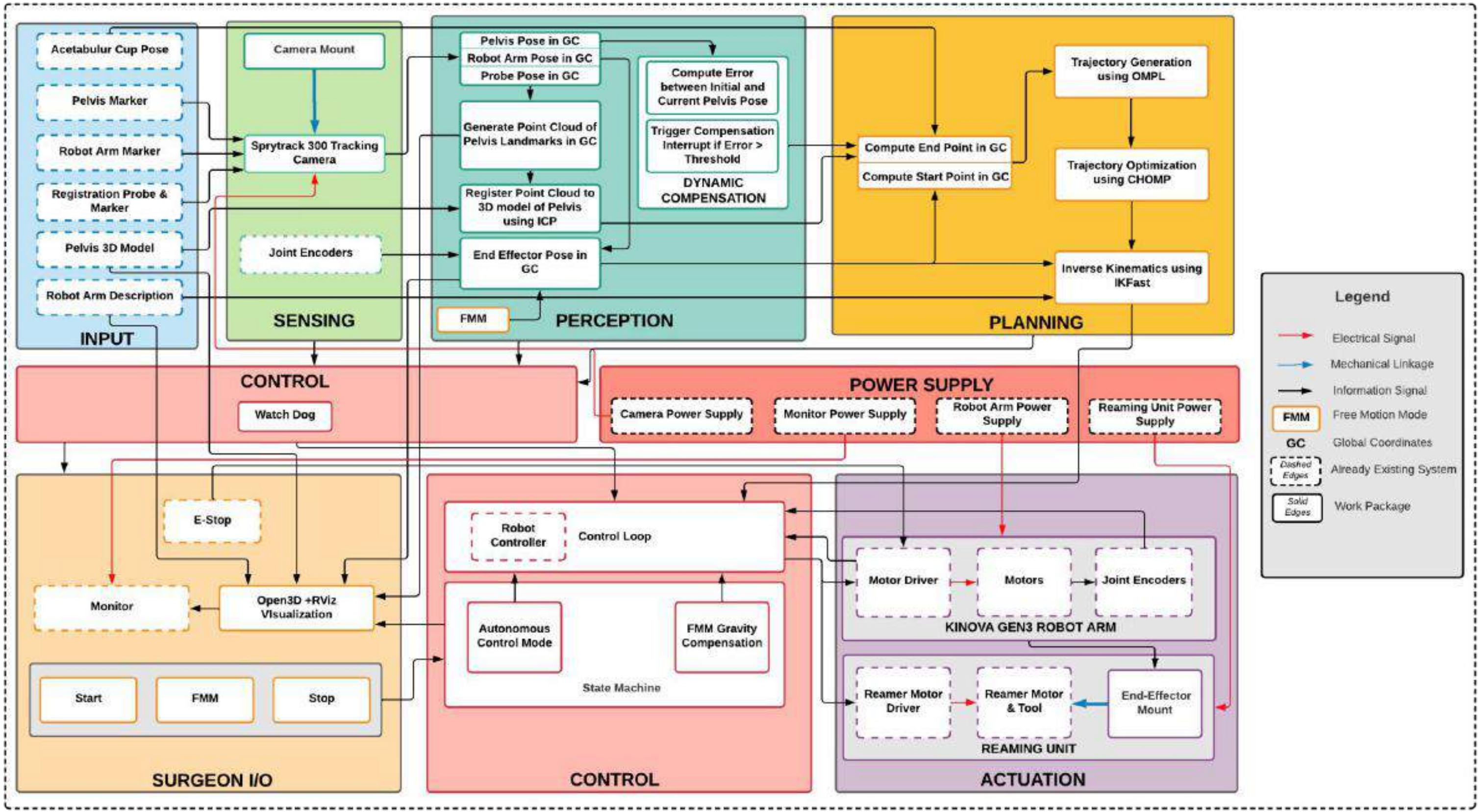
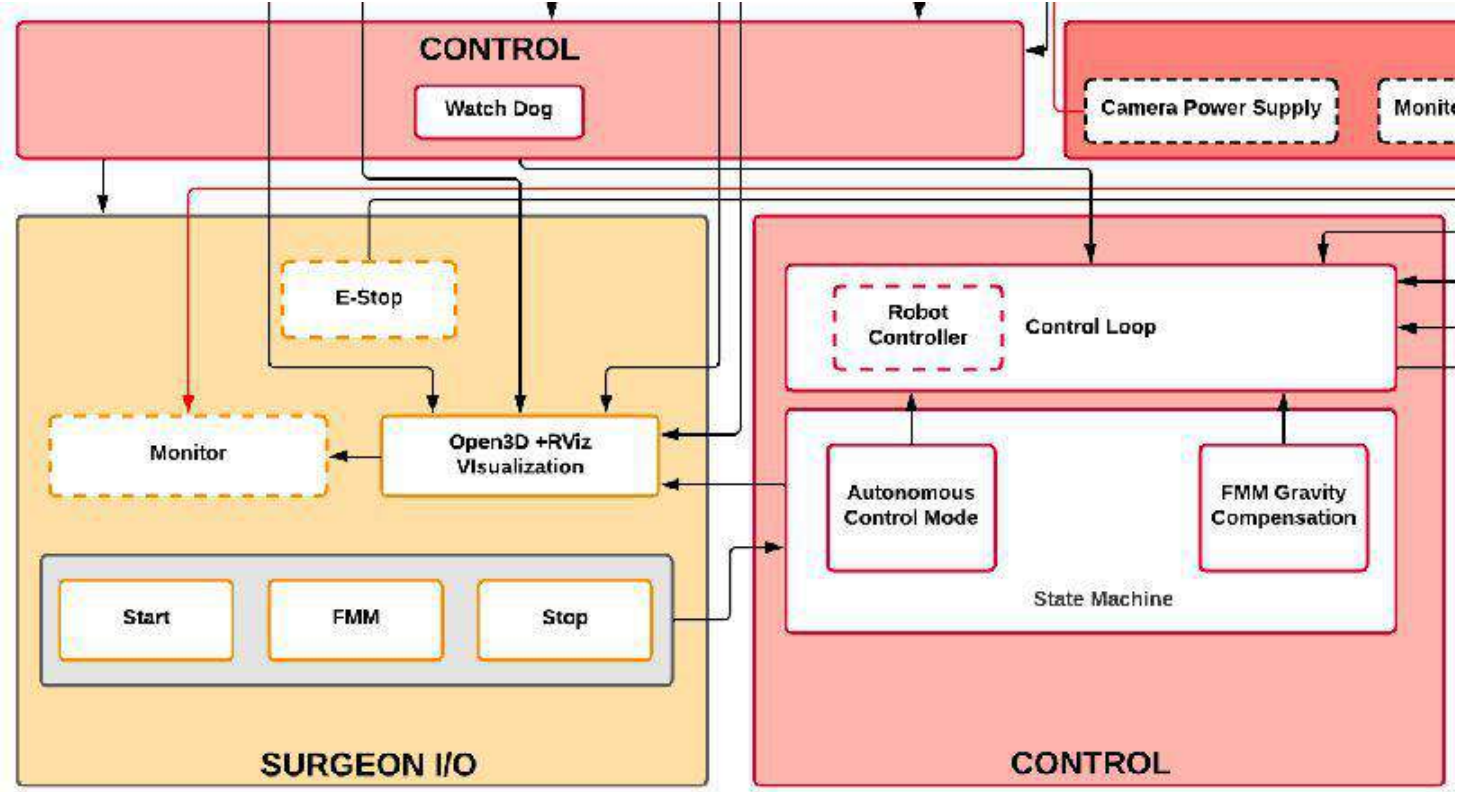
Fig 10: Kinova Gen-3 Robot Arm [11]

Cyberphysical Architecture



Surgeon IO and Control



Visualization

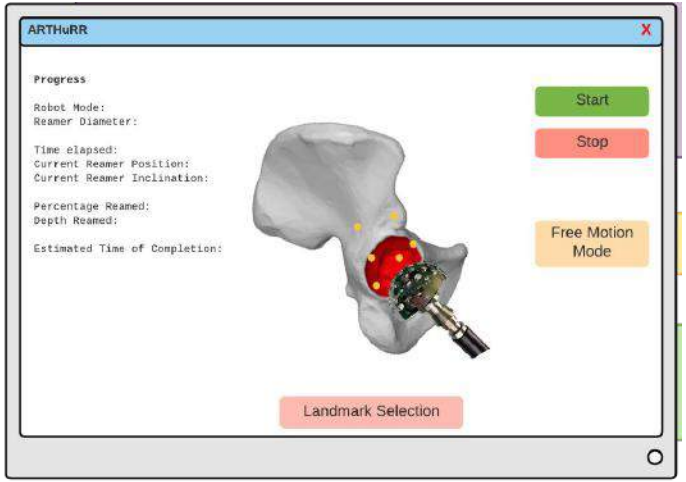


Fig 10: IGSTK Visualization Screen

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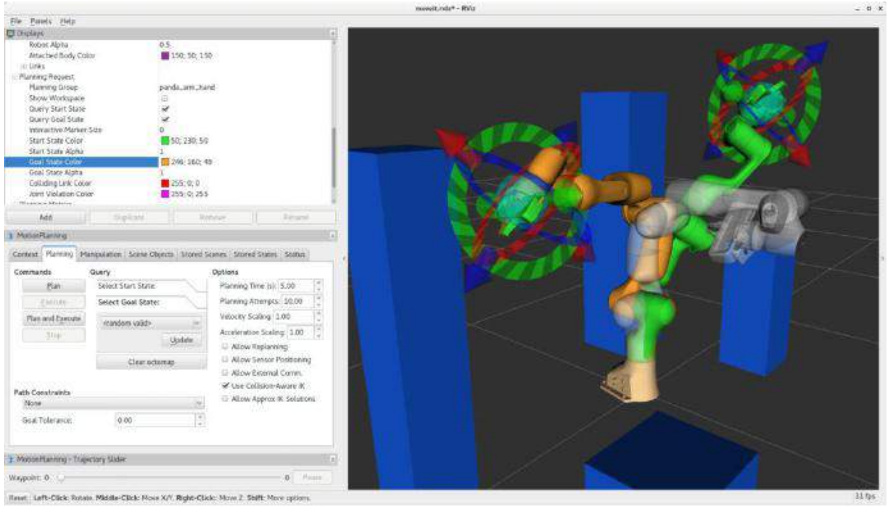
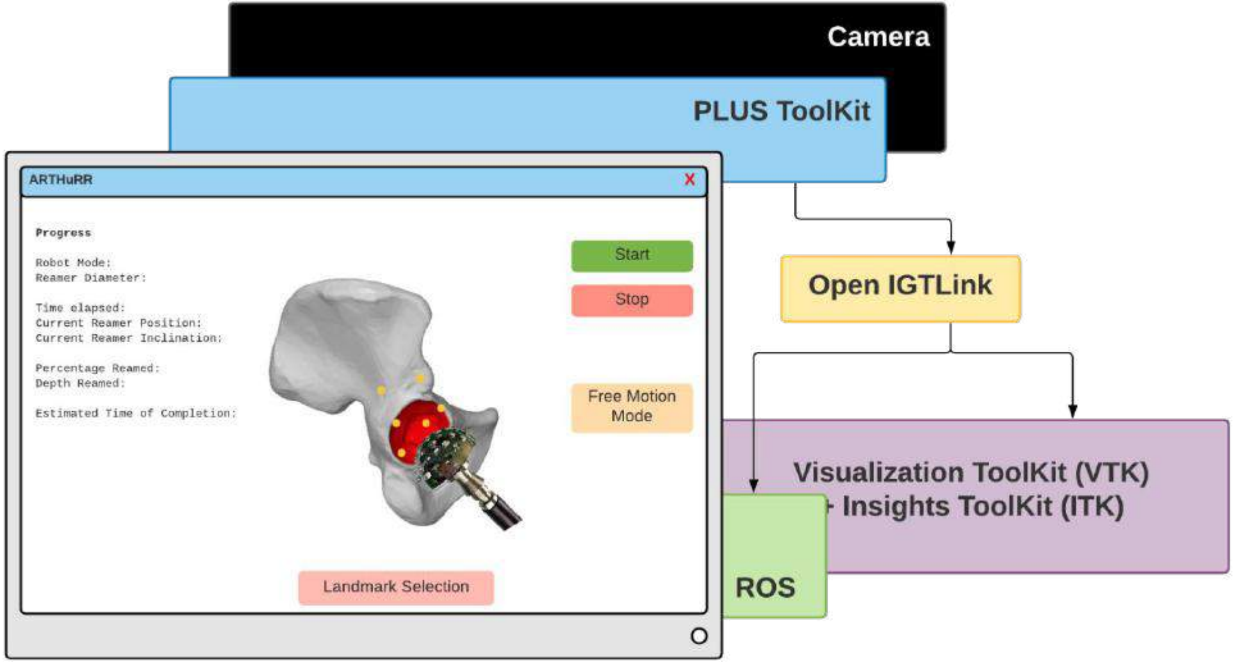


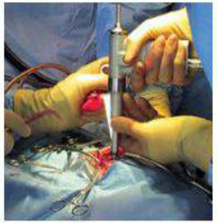
Fig 11: RViz Visualization Screen [8]

Software Tools and Packages



System-Level Trade Study

Investigating Levels of Autonomy

					
Concept		**Non-Robotic Hip Replacement**	**Computer-Guided Hip Replacement**	**Semi-Autonomous Robotic Hip Replacement**	**Fully-Autonomous Robotic Hip Replacement**
Description		Reaming the acetabulum using no additional technology	Reaming the acetabulum with technology that allows a surgeon to visualize the inclination and anteversion they are reaming at	Reaming the acetabulum with a robotic arm which allows surgeons to use push on a reaming tool which is kept along a specific axis as per the planned location of the acetabular cup	Reaming the acetabulum with a robotic arm with no external surgeon input aside from a planned location of an acetabular cup
Evaluation Criteria	**Weighting Factor %**	**Value: 1 - 10 Ranging from *Inadequate* (1) to *Excellent* (10)**			
Surgical Time	10.00%	5	4	4	5
Feedback to Surgeon	15.00%	5	7	7	4
Achievable Accuracy & Patient Outcome	45.00%	5	6	8	10
Probability of System Failure	5.00%	5	8	5	8
Severity of System Failure	2.50%	5	5	3	2
Detectibility of System Failure	2.50%	5	8	5	8
Longevity	7.00%	5	5	2	4
Time/Effort of Setup	7.00%	5	4	3	3
User Training	6.00%	5	4	2	4
Total:	**100.00%**	**5**	**5.745**	**5.97**	**6.98**

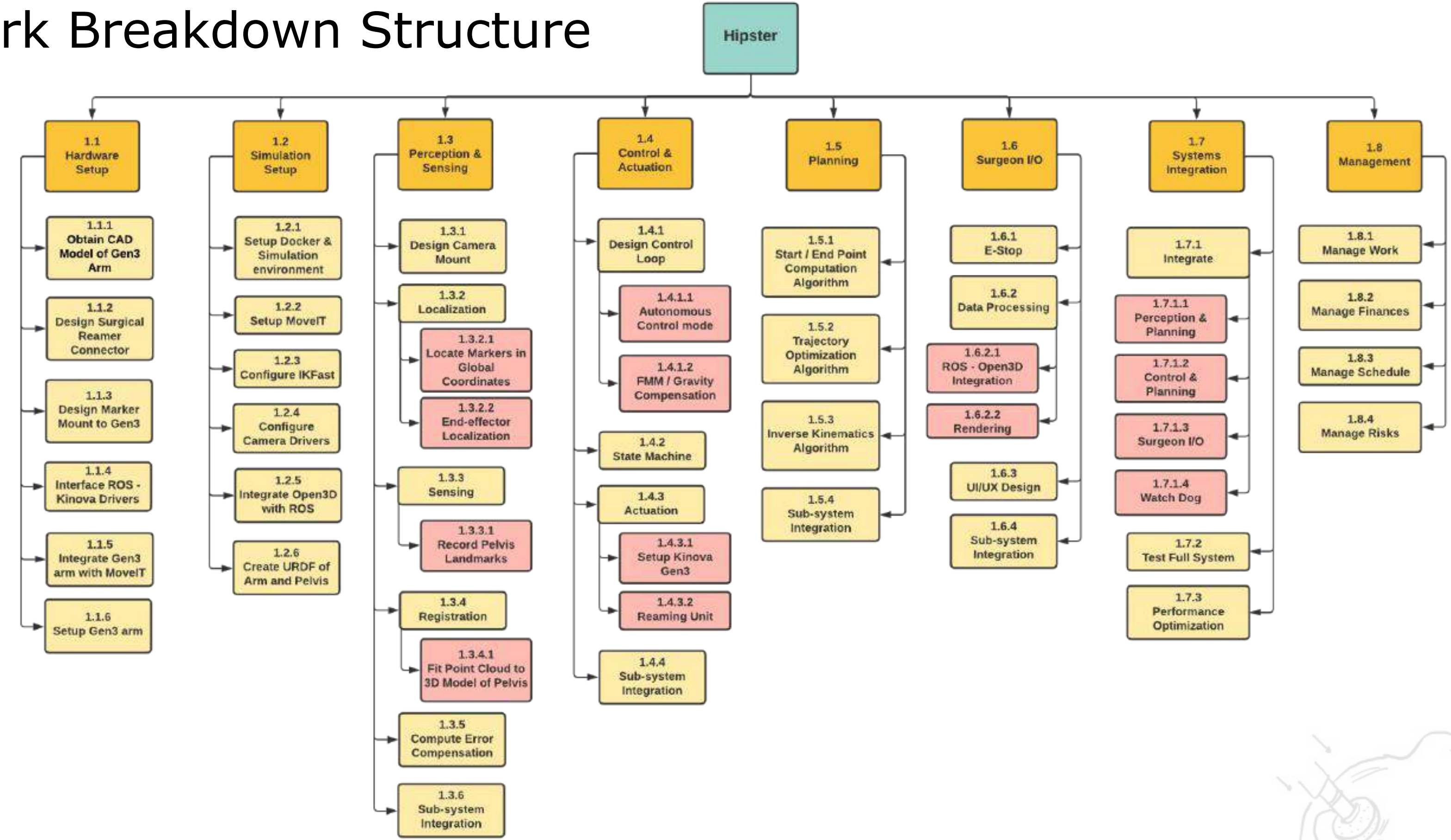
Subsystem-Level Trade Study

Choosing an Inverse Kinematics (IK) Package

	Concept	IKFast	KDL	TRAC-IK
	Description	IKFast, the Robot Kinematics Compiler, is a powerful inverse kinematics solver provided within Rosen Diankov's OpenRAVE motion planning software. Unlike most inverse kinematics solvers, IKFast can analytically solve the kinematics equations of any complex kinematics chain, and generate language-specific files (like C++) for later use. It gives extremely stable solutions that can run as fast as 5 microseconds.	The Kinematics and Dynamics Library (KDL) by OROCOS develops an application independent framework for modelling and computation of kinematic chains, such as robots, biomechanical human models, computer-animated figures, machine tools, etc.	TRAC-IK is an alternative Inverse Kinematics solver to Orocos' KDL. It varies from KDL in that it has two IK solver implementations. - one having an improved convergence algorithm to KDL and the second used SQP (Sequential Quadratic Programming) nonlinear optimization approach. By default, the IK search returns immediately when either of these algorithms converges to an answer.
	Type of Solver	Analytical	Numerical	Numerical
Evaluation Criteria	**Weighting Factor**	**Score: 1 - Inadequate, 2 - Tolerable, 3 - Adequate, 4 - Good, 5 - Excellent**		
Average Success Rate	30%	5	2.5	4
Number of Unique Solutions	20%	5	3	4
Speed of Solver	30%	5	3	4
Integration with ROS & Moveit!	15%	3.5	5	3
Documentation & Resources	5%	4	5	2
Total	**100%**	**4.725**	**3.65**	**3.95**

Work Breakdown Structure

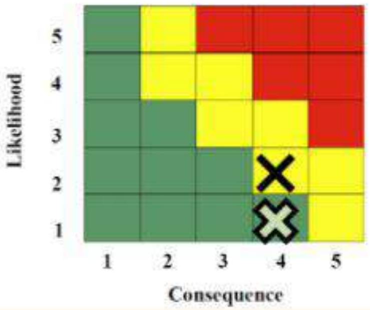
Work Breakdown Structure



Top Five Risks and Mitigation Plans

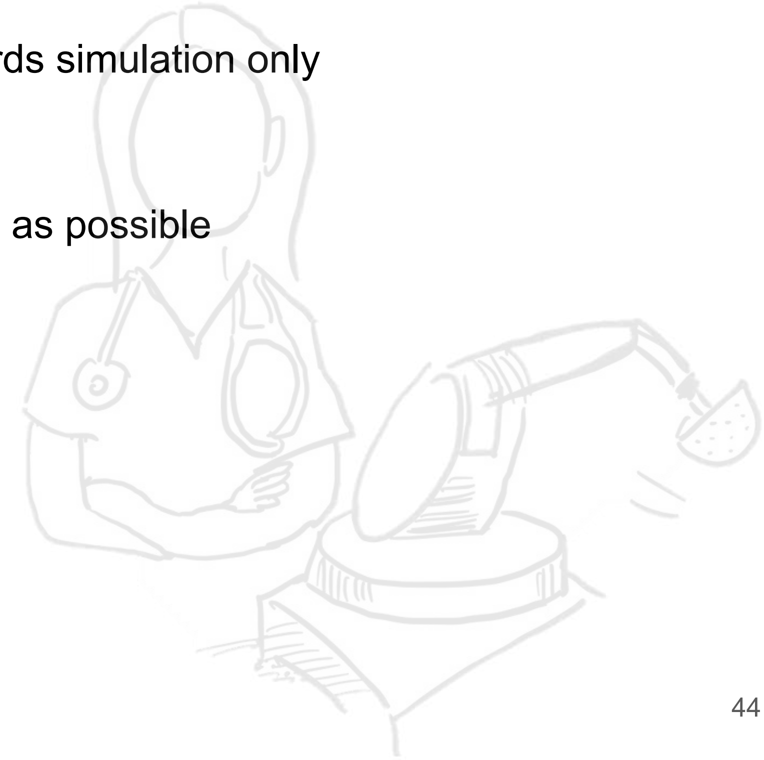
Risk 1: Robot arm does not arrive in time

Risk ID	Risk Title	Risk Owner	Date Submitted	Date Updated
1	Robot arm does not arrive in time	Mechanical Systems Engineer	11/19/2021	11/22/2021
Description		**Risk Type:** Schedule		
The robot arm does not arrive based on planned schedule				
Consequence				
The schedule would be impacted heavily, as a large portion of our project depends on moving from simulations to a physical system. With a delay it could halt our progress, or with a significant enough delay, lead to a necessary restructuring of the project				
Risk Reduction Plan Summary				
Action/Milestone		**Expected Outcome**	**Date Planned**	**Date Implemented**
Follow-up with sponsor to get arm ordered and set specific date for arm arrival		Arm ordered early	11/17/2021	11/17/2021
Plan project such that we focus on simulation early in the project		Any delays to the arm do not effect project schedule	11/19/2021	
Comments				
Talked with sponsor and got them to give us an ETA of January 20th, 2022 for the arm to arrive				



Risk 1: Robot arm does not arrive in time

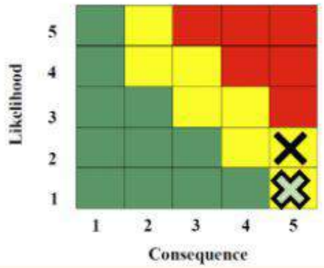
- Consequence:
  - Schedule heavily impacted, potential shift towards simulation only
- Risk mitigation steps:
  - Change schedule to focus on simulation first
  - Speak with sponsor to get arm ordered as soon as possible



Risk 2: Robot arm hardware failure

Risk ID	Risk Title	Risk Owner	Date Submitted	Date Updated
2	Robot arm hardware failure	Mechanical Systems Engineer	11/19/2021	11/22/2021

Description	Risk Type: Technical
As a result of testing of our system on the Kinova arm, a mechanical failure occurs and renders the robotic arm broken and unusable.	
Consequence	
The project would be unable to progress beyond simulation if the robot arm could not be fixed. If it could be fixed then we could expect significant delays to the project schedule.	



Risk Reduction Plan Summary

Action/Milestone	Expected Outcome	Date Planned	Date Implemented
Implement code on robotic arm after it has been proven safe and effective in simulation	Robot arm is unlikely to break as a result of code failure	11/19/2021	11/19/2021
Store robot arm in a safe environment	Robot won't be damaged by others or by flooding	10/27/2021	10/27/2021
Talk with other professors with access to robotic arms and ask if we could use their robotic arms in a worst case scenario	Potential backup arm to use	11/19/2021	

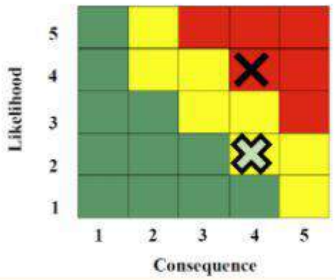
Comments
Workspace secured in the basement, so others have limited access to the arm, though flooding is still an issue unless we store it high above the ground

Risk 2: Robot arm hardware failure

- Consequence:
  - If fixable, the schedule would be heavily impacted
  - If unfixable, the project would need to be changed to be simulation only
- Risk mitigation steps:
  - Only test on robot arm after code has been verified in simulation
  - Store robot arm in safe environment
  - Speak with other professors to find other arms we could use in worst case scenario

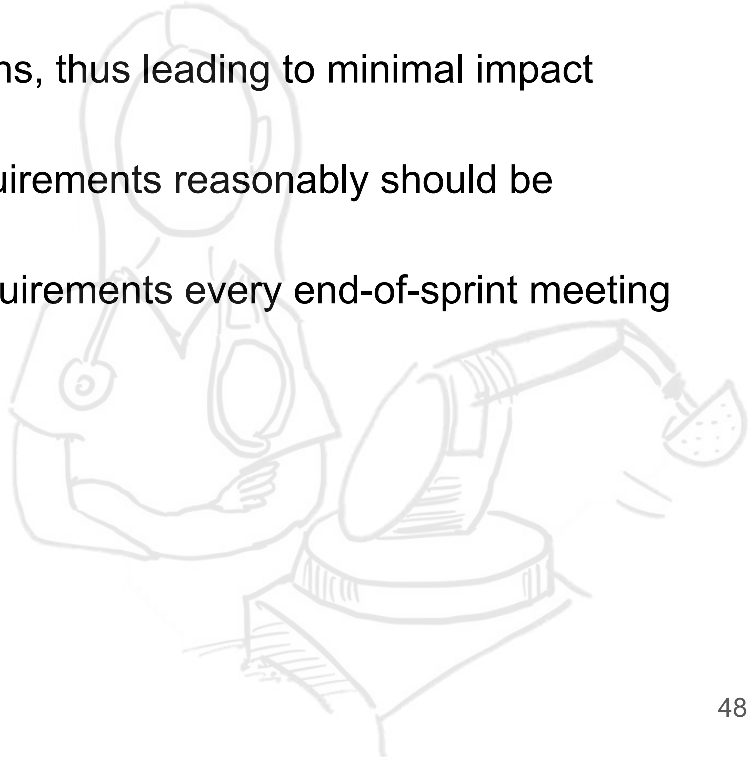
Risk 3: Performance requirements not met

Risk ID	Risk Title	Risk Owner	Date Submitted	Date Updated
5	Performance requirements not met	Project Manager	11/19/2021	11/22/2021
Description		**Risk Type:** Programmatic		
Some or all of the performance requirements we set for the system have not been met				
Consequence				
If the performance is bad enough the project could be considered a failure and not novel enough to make an impact in the medical industry after the conclusion of the project				
Risk Reduction Plan Summary				
Action/Milestone		**Expected Outcome**	**Date Planned**	**Date Implemented**
Conduct research on performance requirements to determine whether frequency or latency is better, and what the system would need to do as a minimum viable product		Accurate performance requirements that can feasibly be met	11/20/2021	11/22/2021
Consistently revisit and update performance requirements		Updated requirements as realities of project set in	11/20/2021	
Have a project manager role to keep on task		If project is completed in a timely manner then we have a lot of time to tune the system	11/20/2021	11/20/2021
Comments				
Discussion with sponsor led us to re-analyze our performance requirements to be latency based				
Plan on discussing performance requirements and feasibility every sprint meeting				



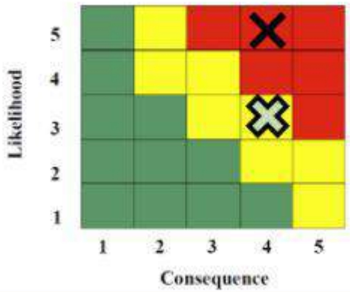
Risk 3: Performance requirements not met

- Consequence:
  - Project is not acceptable to sponsor and surgeons, thus leading to minimal impact
- Risk mitigation steps:
  - Conduct research on what our performance requirements reasonably should be
  - Have an internal project manager
  - Plan on revisiting and updating performance requirements every end-of-sprint meeting



Risk 4: System integration issues

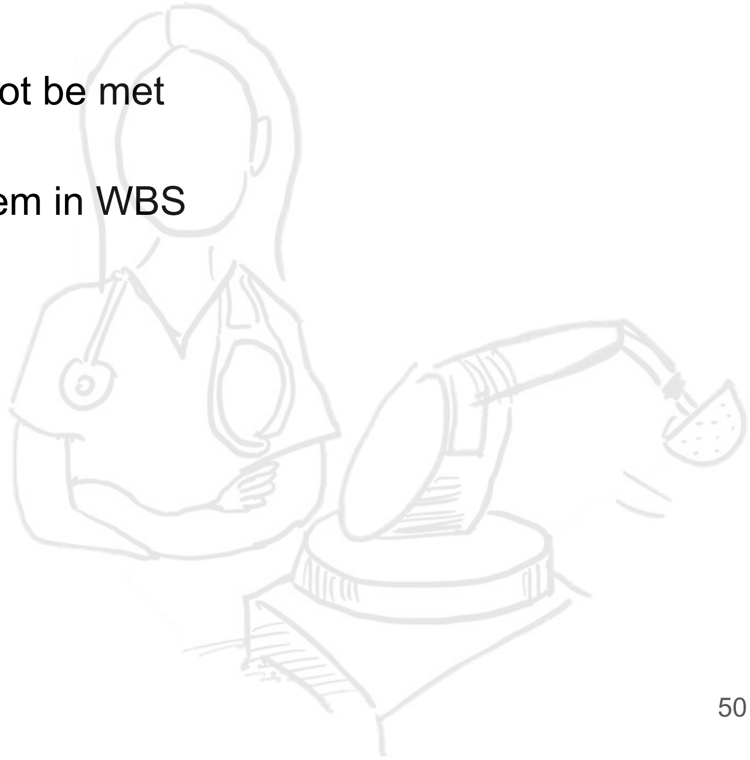
Risk ID	Risk Title	Risk Owner	Date Submitted	Date Updated
6	System integration issues	Software Integration Lead	11/19/2021	11/22/2021
Description		**Risk Type:** Technical		
Subsystems are tested and integrated individually, but issues exist when attempting to integrate all the subsystems together into a full system, either due to mechanical or software incompatibilities				
Consequence				
System integration takes longer than expected, leading to the schedule slip and potential requirements change				



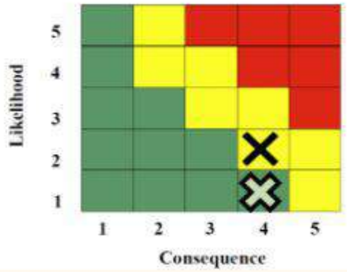
Risk Reduction Plan Summary			
Action/Milestone	**Expected Outcome**	**Date Planned**	**Date Implemented**
Host sprint meetings and demonstrations to break down the work completed during the last sprint	Knowledge of how other's systems are being built	11/20/2021	11/22/2021
Define clear inputs and outputs (data types, connectors, signals, etc) for all systems	Integration issues with regard to input/output mismatch will be largely mitigated	11/20/2021	
Generate documentation for every sprint that is validated by the project manager	Help debug issues quickly down the line	11/22/2021	
Comments			
Planning on hosting meetings on Monday and Friday, with Friday being the big summary meeting between the entire team			
Also will be working in close proximity in the same workspace often			

Risk 4: System integration issues

- Consequence:
    - Schedule heavily impacted, requirements may not be met
- Risk mitigation steps:
    - Define clear inputs and outputs of each subsystem in WBS
    - Host end-of-sprint meetings
    - Create documentation at the end of every sprint

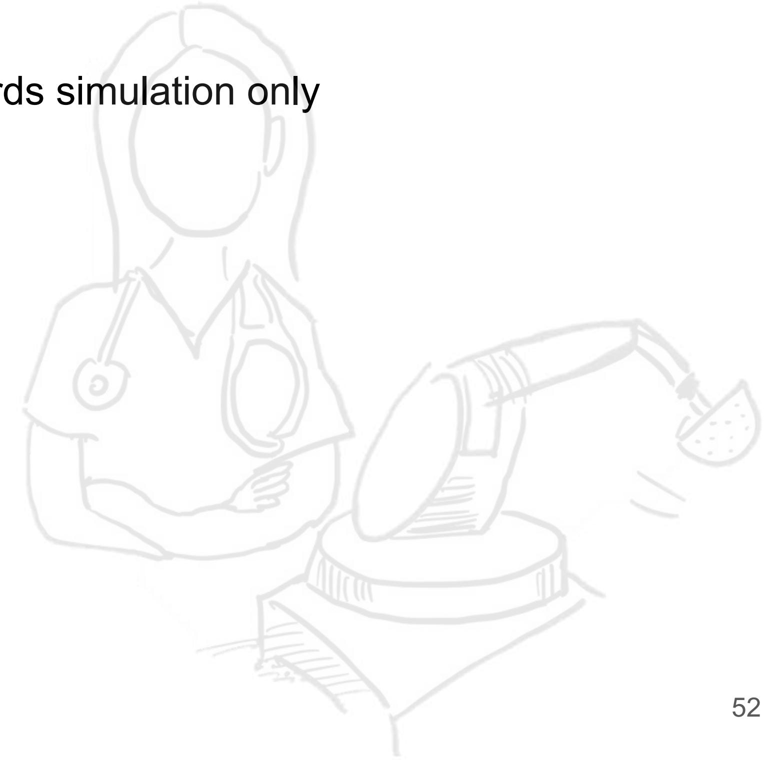


Risk 5: Camera hardware failure

Risk ID	Risk Title	Risk Owner	Date Submitted	Date Updated
7	Camera hardware failure	Perception Engineer	11/19/2021	11/22/2021
Description		**Risk Type:** Technical		
As a result of misuse, the Atracsys camera stops functioning as necessary for the completion of the project				
Consequence				
Significant delays to the schedule and a potential shift towards only using simulation				
Risk Reduction Plan Summary				
Action/Milestone		**Expected Outcome**	**Date Planned**	**Date Implemented**
Store camera in a safe environment		Camera won't be damaged by others or by flooding	11/19/2021	11/22/2021
Design a pipeline for camera use to limit chance of breakage		Limited chance of the camera breaking due to streamlined setup process	11/19/2021	
Ask sponsor for backup camera		Camera to use if the first is broken	11/22/2021	
Find another camera online and purchase asap if the Atracsys breaks and we cannot fix it		New camera for use, but will incur costs and delays as we learn to use new hardware	11/19/2021	
Comments				
Camera will be stored safely with robot arm in our workspace in the basement				

Risk 5: Camera hardware failure

- Consequence:
  - Schedule heavily impacted, potential shift towards simulation only
- Risk mitigation steps:
  - Store camera in a safe location
  - Design pipeline for use of camera
  - Ask sponsor for a backup camera
  - Find another camera online



Questions?

Thank You!

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