October 26, 2022

HIPSTER

System Development Review

Autonomous Reaming for Total Hip Replacement
(ARTHuR)

The Team

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Contents

- Project description
- Use Case / System Graphics
- Requirements Modifications
- Current System Status
- Project Management: Schedule, Test Plan, Budget, Risks

Use Case

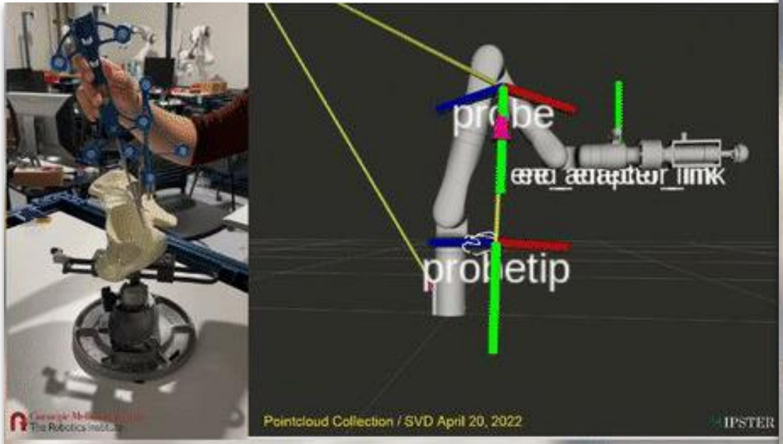
Why ARTHuR?

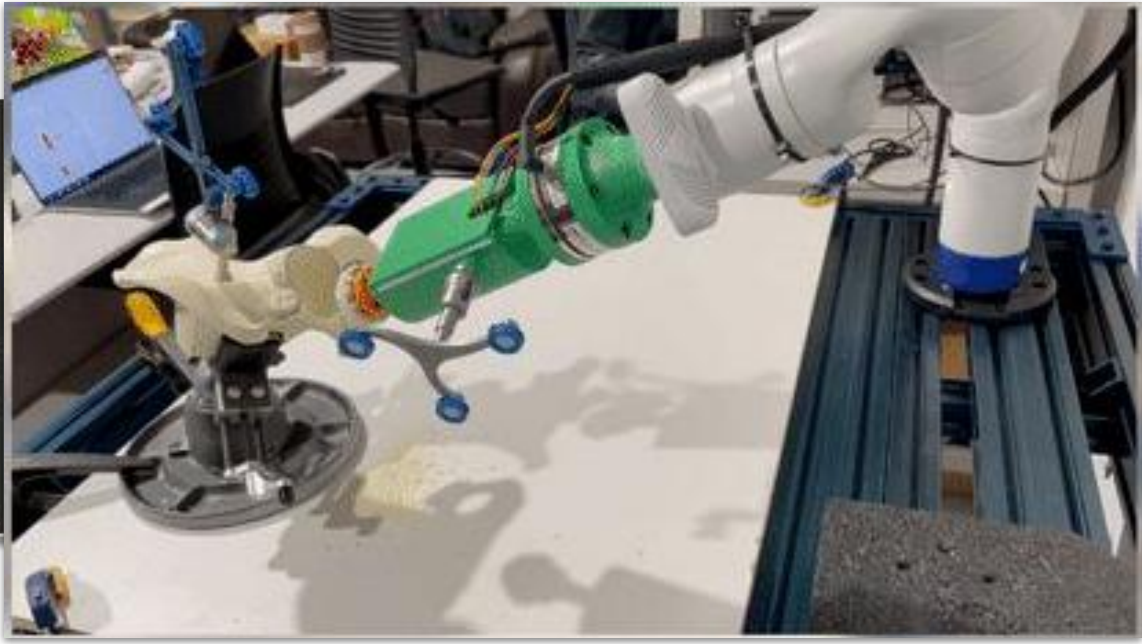
1. High accuracy required for reaming and implant placement
2. Surgeons heavily depend on intuition and prior experience
3. Large kickback from bone during manual operation

Project Description

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.

Spring 2022 System Status





Spring 2022 Challenges

– Large vibrations in the arm and end-effector during reaming –

– Planning subsystem was slow and dependent on arm configuration –

– Explore better control strategies –

– Need a way to monitor and interact with the system –

System Level Requirements: Changes

Mandatory Performance Requirements

The system will

Spring 2022	Fall 2022
M.P.1.1 **Localize** the robot arm with a **latency less than or equal to 50 ms**	M.P.1.1 **Use the Atracsys camera to track** the pelvis, registration probe, and robot arm markers with a frame rate greater than or equal to **50 Hz** or latency less than or equal to **20 milliseconds**
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 degrees**	M.P.1.2 **Use the Atracsys camera to track** the pelvis, registration probe, and robot arm **markers** with an accuracy of less than or equal to **0.55 mm**
	M.P.2.2 **Use the Atracsys camera to track** the pelvis and robot arm **error** with a **position accuracy** less than or equal to **2 mm**
	M.P.2.3 **Use the Atracsys camera to track** the pelvis and robot arm **error** with an **orientation accuracy** less than or equal to **1.5 degrees**
	M.P.3 **Perform registration** between the collected pointcloud and the given 3D pelvis scan with a root mean square **(RMS) error of 0.1 mm**

System Level Requirements: Changes

Mandatory Performance Requirements

The system will

Spring 2022	Fall 2022
M.P.2 **Plan** the trajectory based on the given surgical plan with a **latency less than or equal to 150 ms**	**Removed**
M.P.3.1 **Execute** surgical plan by reaming along the trajectory with an **position error of less than 3 mm**	M.P.5.1 **Ream** the pelvis based on the provided surgical plan with a **position accuracy** of **2 mm**
M.P.3.2 **Execute** surgical plan by reaming along the trajectory with an **orientation error of less than 3-degrees**	M.P.5.2 **Ream** the pelvis based on the provided surgical plan with an **orientation accuracy** of **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.2.1 **Continuously calculate the error** in pelvis movement with a frame rate greater than or equal to **50 Hz** or latency less than or equal to **20 milliseconds**
M.P.4.2 **Generate** a new trajectory **if the errors are greater than 1 mm or greater than 1.5 degrees**	**Removed**

System Level Requirements: Changes

Mandatory Performance Requirements

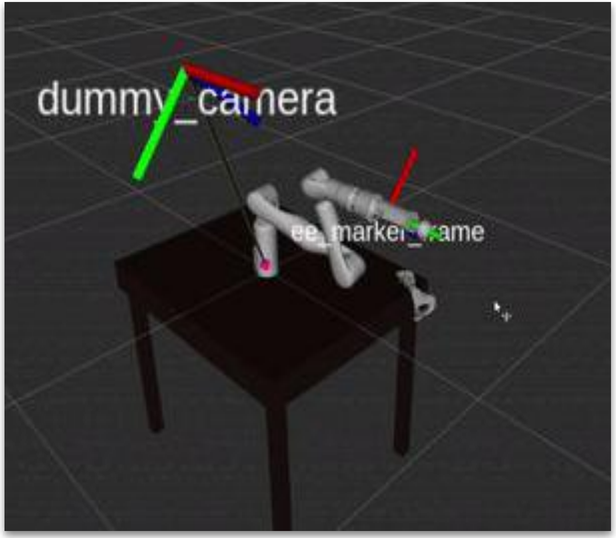
The system will

Spring 2022	Fall 2022
M.P.5 **Adapt and compensate** for movement by generating a new trajectory with **latency less than or equal to 150 ms**	M.P.4.1 **Dynamically compensate** for the movement of the pelvis by **retracting or powering off the reamer** with a **latency** of less than or equal to **25 ms**.
	M.P.4.2 **Dynamically compensate** for the movement of the pelvis by **realigning** the **reamer** with a **latency** of less than or equal to **50 ms**
M.P.6 **Allow** the surgeon **to place the robot arm** to an initial position by **back-driving the robotic arm**	M.P.6 **Allow** the surgeon **to place the robot arm** in 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.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**	M.P.8 **Allow** the surgeon to **e-stop** the system, stopping the system **within 500 ms**

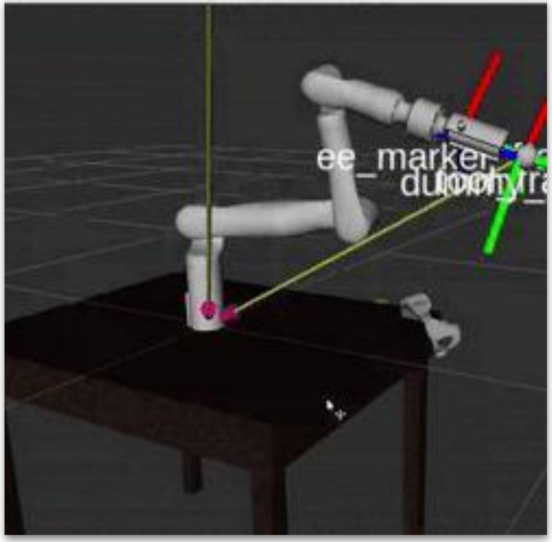
Current System Status

- Functional Descriptions
- Subsystem Depictions
- Current Functionality
- Modeling, Analysis, Test Results
- Challenges Faced
- Major Remaining Challenges

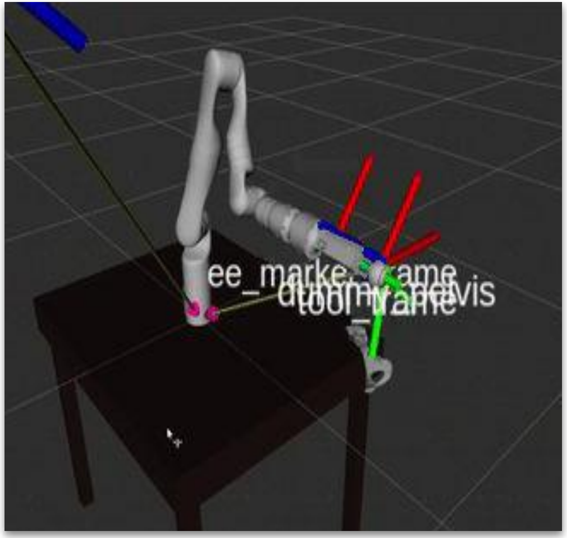
Controls



Camera Alignment Task



Joint Limit Avoidance



Singularity Avoidance

Controls

Pelvis Frame Alignment Task

Finished Test	Results	Outcome
Velocity Controller Tracking Test	1. Tracking frame at 40 Hz 2. Position Error < 2 mm 3. Orientation Error < 1.5 degrees	Success

Upcoming Tests	Description
Test 7	Verify system stability near singularities
Test 8	Verify system stability near joint limits
Test 9	Camera alignment using real arm
Test 11	Reamer controls integrated with arm controls

Controls

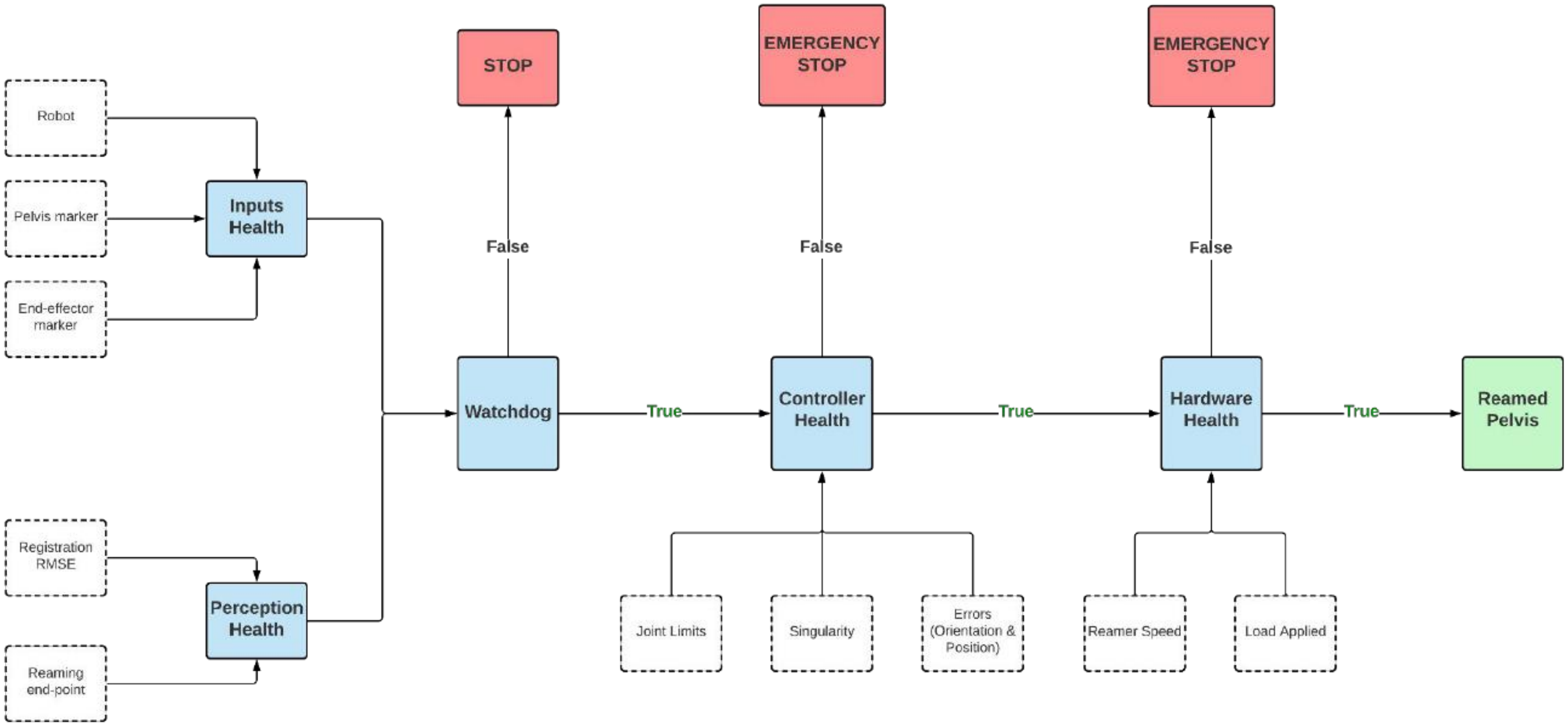
Challenges

1. 40 Hz bottleneck with Kinova ROS API
2. Enforcing collision boundaries between robot and environment
3. Framework architecture design
4. Combining several independent algorithms coherently
5. Many tunable parameters in the framework

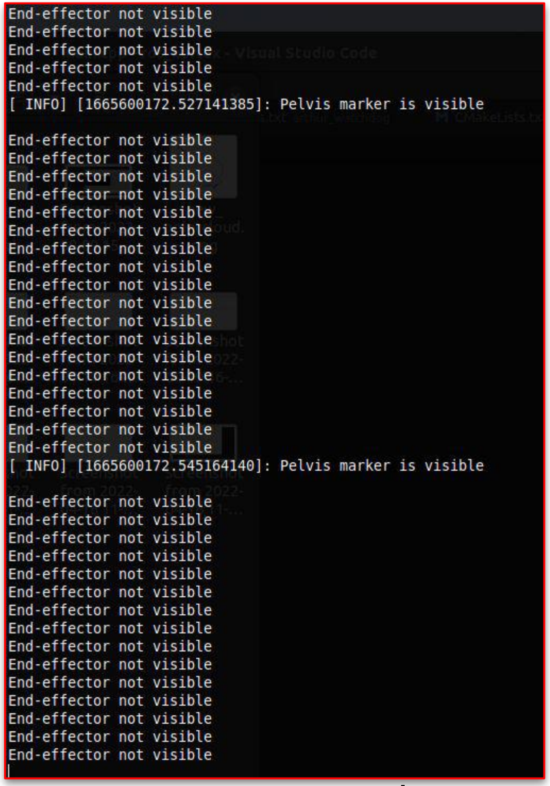
Next Steps & Remaining Challenges

1. Implementing singularity avoidance on real arm
2. Implementing camera-alignment task on real-arm
3. Integration with watchdog
4. Integration with UI
5. Testing & refinement

Watchdog


Robot
Pelvis marker
End-effector marker
Inputs Health
Registration RMSE
Reaming end-point
Perception Health
STOP
False
Watchdog
True
EMERGENCY STOP
False
Controller Health
True
Joint Limits
Singularity
Errors (Orientation & Position)
EMERGENCY STOP
False
Hardware Health
True
Reamer Speed
Load Applied
Reamed Pelvis

Watchdog



Current Functionality

Finished Test	Results	Outcome
Test 3 Test functioning of the watchdog version 1 as terminal logger	1. Check system inputs & hardware health 2. Check registration RMSE 3. Check controls health	Success In-progress

Upcoming Tests	Description
Test 10	Evaluate watchdog functionality and display all health parameters on the User Interface

Watchdog

Challenges

1. Integration still in progress as subsystems are still under development
2. Code structure and modularity
3. Rigorous testing and validation of watchdog performance
   a. Identifying edge case where any system could fail.

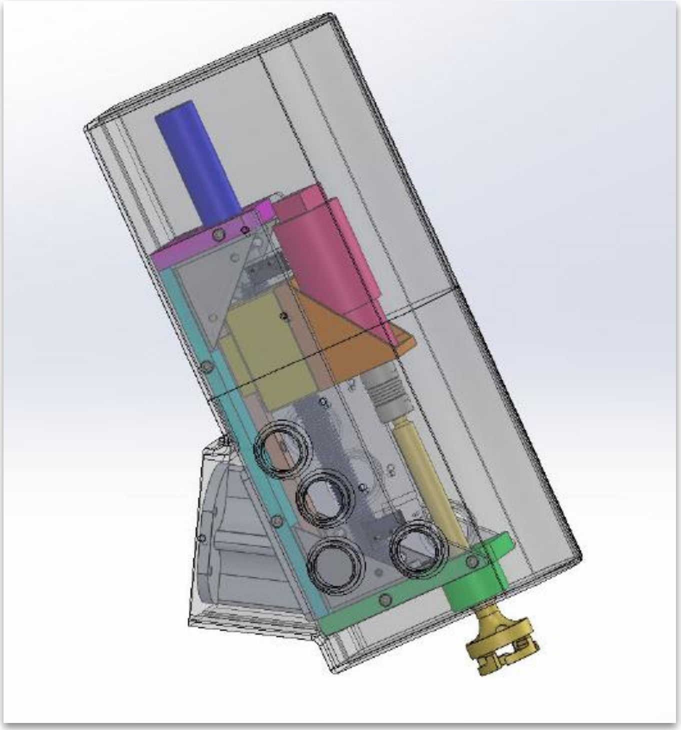
Next Steps

1. Test watchdog functionality with the controls subsystem on the real arm by simulating edge cases.
2. Integrate watchdog with the User Interface and display all critical parameters.
3. Log critical parameters on to a text file for future reference.

Hardware & Actuation

New End-Effector Design!

- Previous design led to vibrations, loss of degrees of freedom, and awkward planning
- New design is linearly actuated, held at an angle, and allows for more robust controls to be integrated
- New Components:
  - ServoCity 116 rpm Planetary Gear Motor
  - Ball Screw Linear Actuator
  - Limit Switches
  - Vibration Isolation Bearings and Couplings



CAD Depiction

Hardware & Actuation

Current Functionality

Finished Tests	Results	Outcome
Test 1 3D Printed Prototype Assembled	Prototype capable of > 50 mm actuation, minimal vibrations, remains attached	Success
Test 4 Integration with Electrical System	Able to control motors via ROS, limit switches integrated, information transmitted to ROS	Success

Upcoming Tests	Description
Test 11	Fully manufactured end effector prototype integrated with electrical system and ROS

Hardware & Actuation

Challenges:

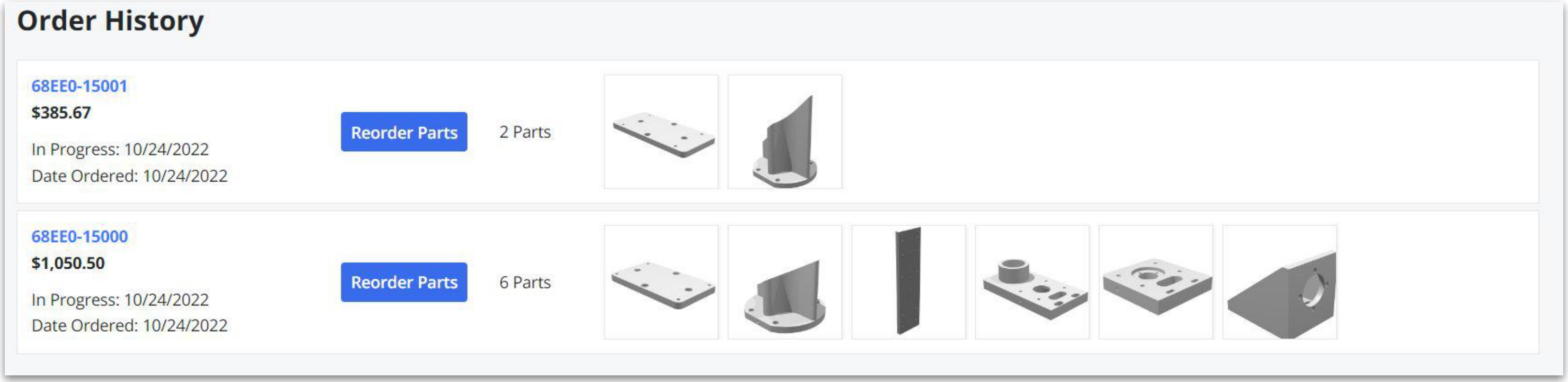
- Typical 3D printing issues
- Had issues with Cytron MD10C
  - Some had terminal blocks and didn't work, some had no terminal blocks and did work
- Delays in receiving our current sensors
  - No current sensors meant a delay in being able to measure force
- Wiring :(
  - Could not find any connectors in inventory that worked for us, leading us to rely on soldering wires together

Moving Forward:

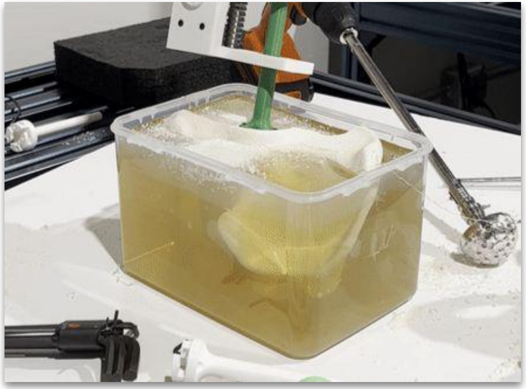
- Redesigning end-effector parts for aluminum manufacturing
  - One more round of 3D printing to validate
- Get quotes and manufacture parts
- Integrate current sensors into our electrical system
  - Will allow for force sensing
- Develop more robust microcontroller control code for system
  - Want to turn on reaming motor when contacting pelvis and use PID force control

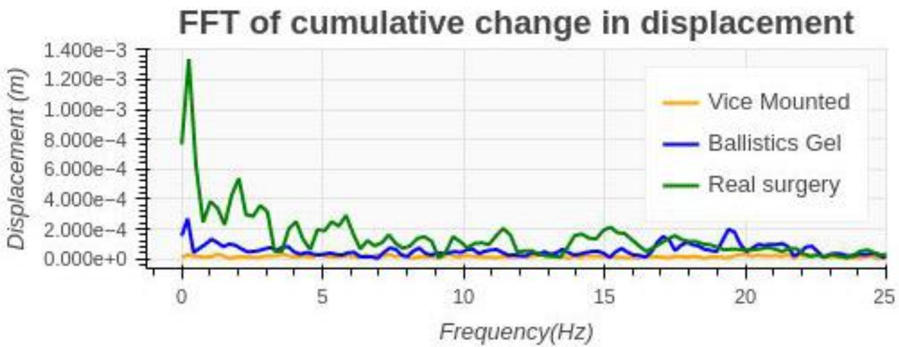
Update as of 10/24

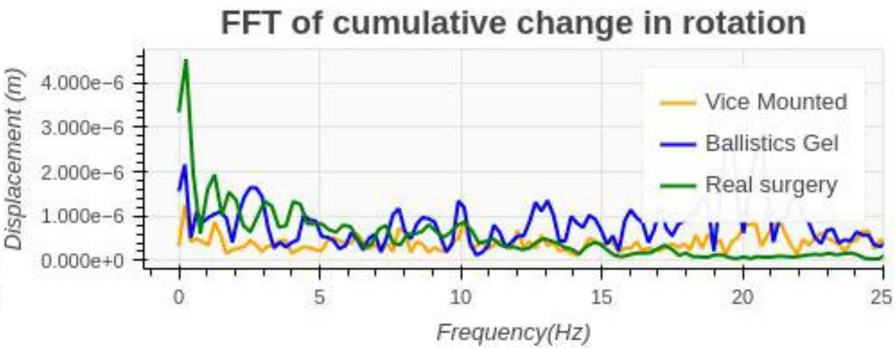
- Xometry order placed
- Parts should arrive by November 10th and 11th
- Parts made of Aluminum 6061
- Ordered two different end-effector adapter components (with two different angles)



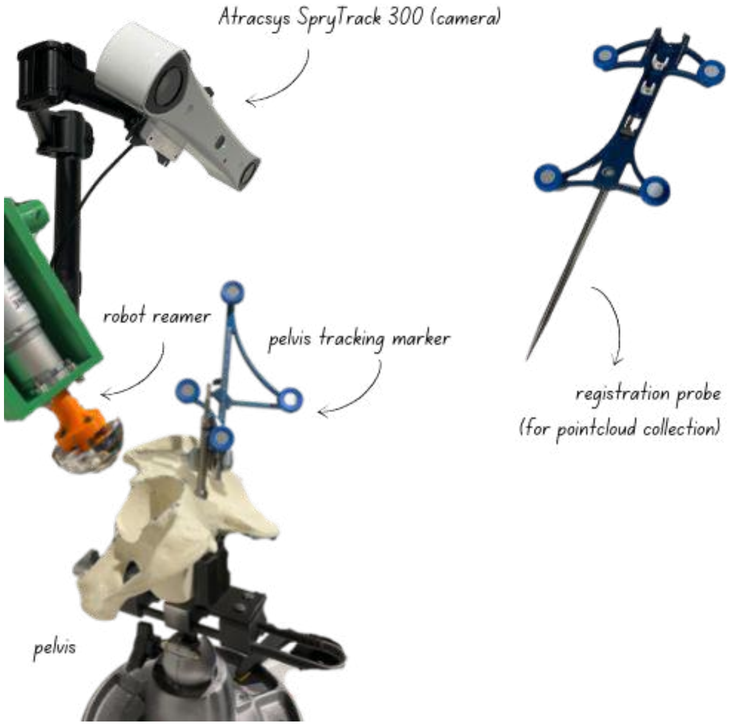
Ballistics Gel Experimentation



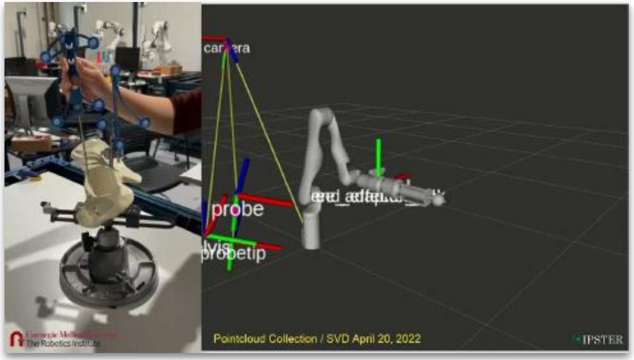




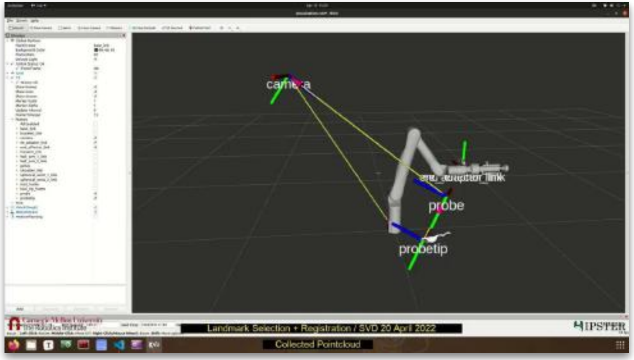
Perception & Sensing



Perception Subsystem Overview



Pointcloud Collection



Registration

Perception & Sensing

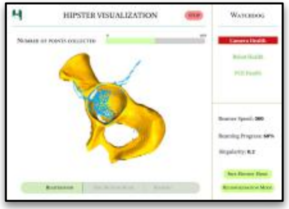
Challenges

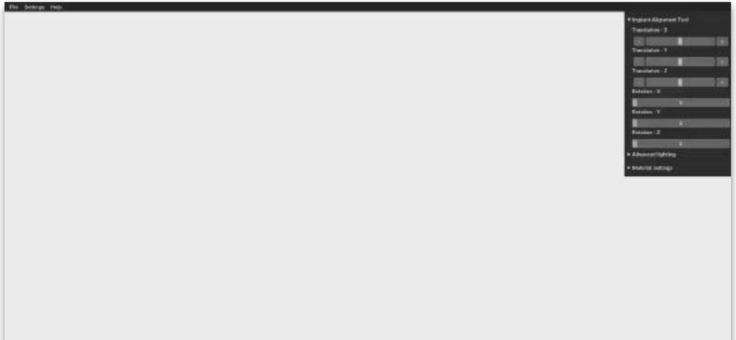
1. Interfacing Atracsys camera with ROS
2. Multiple frame handling
3. High-fidelity data acquisition
4. Validation criteria for registration and tracking performance

Next Steps

1. Integrating perception with UI
2. Online hand-eye calibration
3. FVD final error validation

UI





Implant Alignment Tool

[Internal] Tests	Results	Outcome
Loading multiple pointclouds + Displaying custom layouts	Loaded pelvis and cup models; Created custom implant alignment layout	Success
Viewing/manipulating multiple pointclouds	Applied transformations through UI widgets onto pointclouds	Success
Communicate with watchdog via ROS	Create simple subscriber to obtain watchdog data	TODO

Upcoming Tests	Description
Test 6	End-point pose communicated through UI to system
Test 10	UI Integration with WatchDog + Subsystems

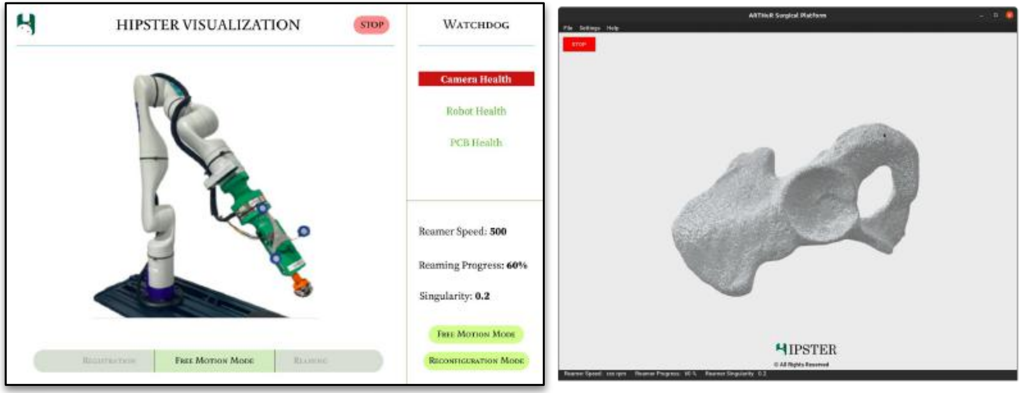
UI

Challenges

1. Selecting base framework for development
2. Matching UI wireframes due to limitations in software
3. Structuring large codebase for maintainability and debugging
4. System integration challenges

Upcoming Tasks

1. Embed registration task into UI
2. Test complete system integration



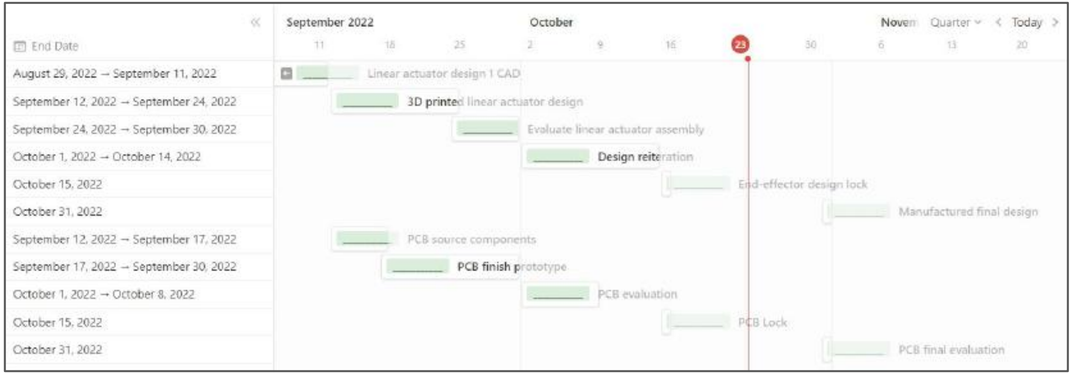
[Left] Wireframe [Right] Current UI

Project Management

- Schedule Status
- Test Plan
- Budget Status
- Risk Management

Schedule Status

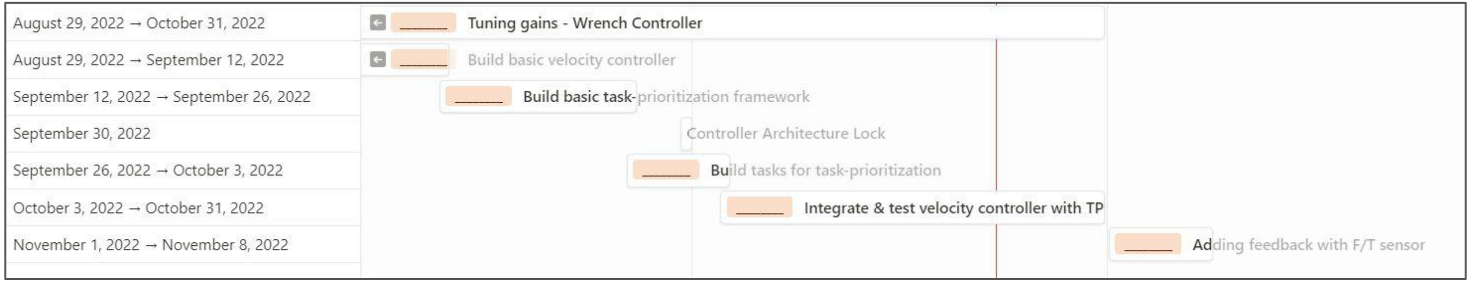
Hardware Subsystem



Milestones	Date	Status
3D Printed Linear Actuator Design	September 25	Completed
End-effector Design Lock	October 15	Completed
Electrical Subsystem Working Prototype	October 15	Completed
Manufactured End-Effector	November 6	Ongoing
Electrical Subsystem Final Tests	November 6	Ongoing

Schedule Status

Controls Subsystem



Milestones	Date	Status
Basic Joint Velocity Controller Implemented	September 12	Completed
Controller framework lock	September 30	Completed
Task Prioritization Controller Implemented	October 31	Ongoing (Working in Sim, Needs testing in real)
Reamer Force Feedback	November 8	To Do

Schedule Status

Watchdog & User Interface

Milestones	Date	Status
Watchdog version 1- Terminal Logger	October 2	Completed
User Interface Version 1	October 2	Completed
Watchdog & UI integration	November 1	In-Progress

Test Plan - Capability Milestones

Progress Review 10:

- Task-prioritization working with the real arm
- End-effector control integrated with ROS
- Finalized user interface and watchdog
- Use user interface to communicate surgical plan to the system

Progress Review 11:

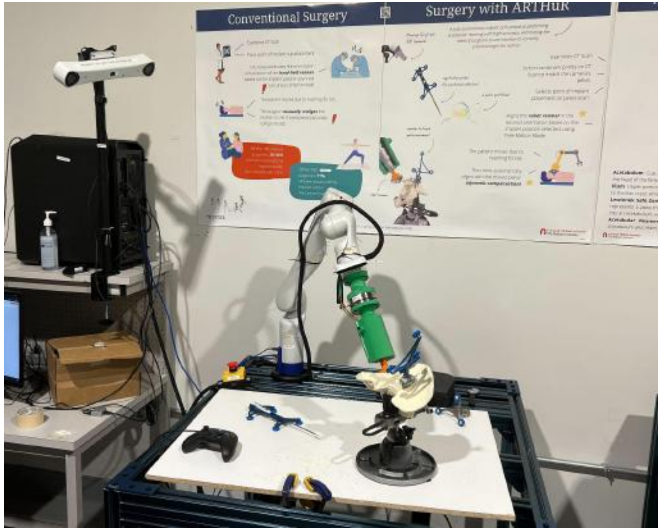
- Fully manufactured end-effector control integrated with system
- Demonstrate full system capabilities prior to our fall validation demonstration

Schedule			
Identifier	**Capability Milestone(s)**	**Associated Tests**	**System Requirements**
Progress Review 7 (09/07)	- Re-assemble system - Run SVD again - Assess dynamic compensation with wrench controller	N/A	N/A
Progress Review 8 (09/28)	- Assemble 3D-printed end-effector design - Implement basic velocity control on arm	Test 1 Test 2	M.F.1 M.F.2 M.F.4 M.F.5
Progress Review 9 (10/12)	- Develop first version of user interface - Develop functioning logger in watchdog - Integrate end-effector with electrical subsystem - Evaluate use of ballistics gel as a proxy for soft tissue around the pelvis	Test 3 Test 4 Test 5	M.F.4 M.F.5 M.F.7 M.F.8 M.N.2 M.N.3
Progress Review 10 (11/02)	- Task-prioritization working with the real arm - End-effector control integrated with ROS - Finalized user interface and watchdog - Use user interface to communicate surgical plan to the system	Test 2 Test 6 Test 7 Test 8 Test 9 Test 10 Test 11	M.F.1 M.F.2 M.F.5 M.F.7 M.F.8 M.N.1 M.N.2 M.N.3
Progress Review 11 (11/16)	- Fully manufactured end-effector control integrated with system - Demonstrate full system capabilities prior to our fall validation demonstration	Test 4 Test 11 FVD	All
Fall Validation Demo (11/21)	- Demonstrate full system capabilities	FVD	All

Fall Validation Demonstration

Location: NSH B512

Equipment: Kinova Gen-3 Arm, Atracsys Camera, PC, Sawbone Pelvis in Ballistics Gel, Fiducial Markers



Approximate Test Setup

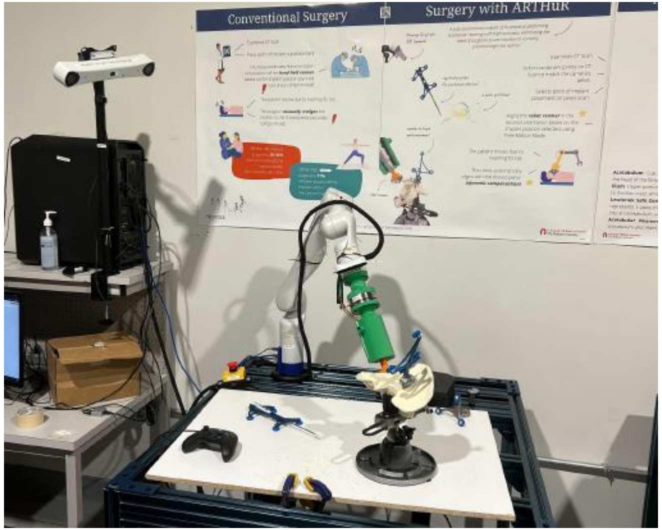
Quantitative Performance Metrics:

- The camera is able to localize the registration probe, end-effector marker, and pelvis marker within a latency of < 25 ms.
- The system is able to detect pelvis position error greater than 1.5 mm, and an orientation error greater than 1.5 degrees within a latency of 25 ms.
- Personnel should be able to move robot arm freely with the free motion mode.
- Once the e-stop is pressed the motor turns off and the arm stops moving within 500 ms .
- The axial force applied to the pelvis must not exceed 100 Newtons.
- When the pelvis error is more than 2 mm or 1.5 degrees, the end-effector will retract and the arm will realign with the pelvis pose before reaming again.
- While reaming, the pelvis alignment error is less than 2 mm and less than 1.5 degrees.
- User interface allows for control and visualization of the procedure with a latency no greater than 150 ms.

Fall Validation Demonstration

Location: NSH B512

Equipment: Kinova Gen-3 Arm, Atracsys Camera, PC, Sawbone Pelvis in Ballistics Gel, Fiducial Markers



Approximate Test Setup

What you will see:

- A surgical plan will be chosen using the UI
- Arm autonomously aligns to the desired pelvis pose
- End effector actuates until it makes contact with bone
- Reamer turns on to start reaming bone
- Dynamic compensation occurs throughout
- End effector retracts if pelvis moves > 2 mm or 1.5 degrees
- Reaming stops when end-point is reached

Improved Validation

Improved Validation Necessary:

- Better validation necessary to truly verify the performance of the system
- Need to be able to compare the surgical plan directly to the surgical result

Procedure:

1. Scan pelvis prior to procedure
2. Ream acetabulum using ARTHuR
3. Scan pelvis after the procedure
4. Subtract both meshes from one another
5. Compare resulting reamed bone to surgical plan

Faro Arm

Autodesk Meshmixer

Budget Status

Budget	Expenditure	Balance
$5000	$4226.23	$773.77

Percentage Spent: 85%

Expenses Left:

Backup parts — $250

Swag — $250

Emergencies — $250

Balance at the end of project — $23.77

Risk Management

Risk #	Risk	Type	Likelihood #	Consequence #	Risk Mitigation Action
1	**End effector development delays**	Technical	4	3	• Start early and lock design by October 15th • Brainstorm multiple solutions • 3D print to test before final manufacturing • Make system simple enough to get it manufactured in-house • Use 3D printed design as a fallback
2	Electrical sub-system failure & delays	Technical	2	4	• Test breadboard prototype • Seek feedback from Luis • Use off-the-shelf boards to reduce PCB complexity of PCB • Order spares
3	Dynamic compensation not achievable	Technical	3	3	• Iterate with multiple control architectures • Utilize earlier compensation solution as a fallback • Evaluate need for isolating controller from ROS • Benchmark latencies in system • Use pub/sub communication instead of server/client communication
4	UI does not integrate with system	Technical	4	2	• Start working on the UI early • Plan architecture and consult each stakeholder • Start testing by Oct 31st
5	**Performance requirements not met**	Programmatic	4	4	• Track & evaluate quantification of performance requirements • Revisit performance requirements every sprint meeting • Have a risk-manager to track key risks
6	**Integration issues between subsystems**	Technical	5	4	• Define clear inputs and outputs of each subsystem • Host frequent meetings & retrospectives • Create documentation at the end of every milestone

Risk Management

Risk ID	Risk	Type	Likelihood	Consequence
2	Robot arm failure	Technical	2	5
5	Performance requirements not met	Programmatic	4	4
6	Integration issues between subsystems	Technical	5	4
7	Camera hardware fails	Technical	2	4
9	Team member has difficulties working on their part of the project	Programmatic	5	2
12	End effector development delays	Technical	4	3
13	Electrical subsystem failure & delays	Technical	3	4
14	Dynamic compensation not achievable	Technical	2	3
15	System robustness issues	Technical	4	3
17	UI does not integrate with system	Technical	4	2

Ongoing Risks Summary

Risk Management

Likelihood	5	#10	#9			
	4		#3, #17	#14	#5, #12, #13	#6
	3		#16	#4	#15	
	2				#7	#2
	1	#1, #8				#11
		1	2	3	4	5
		Consequence				

Project Management Review Risks

Likelihood	5	#10	#9			
	4		#3, #17	**#12**	#5	#6
	3		#16	#4	#15, **#13**	
	2			**#14**	#7	#2
	1	#1, #8		#4		#11
		1	2	3	4	5
		Consequence				

Current Risks

We got to see the surgery :)

($10 if you want to see pictures)

Thank You!
Any Questions?

HIPSTER

Autonomous Reaming for Total Hip Replacement (ARTHuR)