Team C Fall 2022 Test Plan

Autonomous Reaming for Total Hip Replacement

HIPSTER | ARTHuR

Team C:

Anthony Kyu | Gunjan Sethi | Kaushik Balasundar

Parker Hill | Sundaram Seivur

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Carnegie Mellon University

The Robotics Institute

Contents

1 Introduction

This document describes the various tests to be performed on the Hipster system (and subsystems in simulation/reality) throughout the fall semester in order to validate and verify that the system and subsystems are meeting stated functional and performance requirements. The tests are designed such that there is an incremental increase in the complexity of the test and the necessary state of the system in order to properly perform the task, which will provide a good deadline for finishing functionalities. The results of these tests will be reported during the progress reviews. Each test has a name/number, an objective, elements, a location, equipment, personnel, procedure, and verification criteria. Our goal is to have our entire system operational by the fall validation experiment and robust to any errors or issues that may arise during a procedure.

2 Logistics

All of these tests as well as the Fall Validation Demonstration will take place in Newell-Simon Hall in room B512. The Fall Validation Demonstration will be presented via a live demo, while the rest of the plans will be demonstrated via videos or reports on the results of the tests during progress reviews. All team members will be present for the Fall Validation Demonstration, and while it would be ideal for all members of the team to be present for all tests, it is only necessary for the system lead and one other person to be present during the testing. The following equipment would be necessary for the majority of our tests:

- **Desktop Workstation**: necessary for interfacing with the robot manipulating
- **Monitor**: necessary for displaying GUI information and camera output
- **Robot arm**: manipulator arm coupled with a custom reaming end-effector
- **Atracsys camera**: the camera which can detect the location of marker arrays and computer their location into transformations
- **IR markers**: markers which can be detected by the Atracsys camera
- **Marker arrays**: arrays which hold the IR markers in unique orientations such that they can be detected by the Atracsys camera
- **Vention table**: rigid table for the robot arm and all tasks to be performed upon
- **Sawbone pelvis**: foam replica of a pelvis to be used with physical validations of the system
- **Panavise mount**: vise to hold pelvis during testing

Further equipment for specific tests will be specified in the testing plans. Some of these performance requirements and tests are subject to hardware we plan on receiving, and given the uncertain nature of our hardware acquisition currently, some of these requirements and tests may change.

3 Schedule

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

4 Tests

4.1 Test 1

Objective	
Verify that the 3D-printed linearly actuating end-effector is firmly assembled and can actuate as necessary for the system	
Equipment	Desktop workstation, Robot arm, 3D-printed end-effector, Dial calipers
Elements	Hardware unit: reaming end-effector
Personnel	2 people necessary, one to monitor and evaluate the end-effector, and one to control the motion of the robot arm from ROS
Location	NSH B512
Procedure	
1. Assemble 3D-printed linearly actuated end-effector and verify that all parts are firmly connected 2. Using a dial caliper, measure the distance the reaming motor and reaming handle can travel while actuating the ballscrew by hand 3. Attach the end-effector to the end of the Kinova Gen-3 arm 4. Using admittance mode, move the robot arm through the work area and verify performance and attachment of the end-effector when the arm is at singularity, at joint limits, and when inverted 5. Using dynamic compensation mode, move the pelvis throughout space and verify the end-effector remains rigidly attached and does not exhibit excessive vibrations	
Validation	
1. Ballscrew is capable of actuating reamer motor and reaming handle > 50 millimeters 2. The end-effector remains attached to the arm and is capable of actuating in any position/orientation 3. The end-effector's vibrations are minimal during dynamic compensation	

4.2 Test 2

Objective	
Test the ability of the velocity controller to track a moving frame	
Equipment	Desktop workstation, Robot arm with reaming end effector
Elements	Controls sub-system
Personnel	Two people needed - one to operate and monitor the system, and another to move the pelvis frame.
Location	NSH B512
Procedure	
1. Mount a tracking marker to the Illiac Crest of the pelvis and ensure it is visible to the camera. 2. Perform extrinsic calibration to determine the transformation between the camera and the robot frame. 3. Move the robot arm to its home position. 4. Run the controller script to track the pelvis marker frame with a predetermined offset. 5. Translate and rotate the pelvis within the workspace of the robot to allow the robot arm to track it.	
Validation	
1. The robot arm's velocity controller is able to consistently track the position and orientation of the pelvis marker frame at 40 Hz. 2. The robot arm is able to achieve a position error of < 2mm and an orientation error of <=1.5 degrees when the frame remains stationary.	

4.3 Test 3

Objective	
Test functioning of the first version of the watchdog, the terminal logger.	
Equipment	Desktop workstation, robot arm
Elements	Software
Personnel	2 people necessary; 1 person checking all the logs on the workstation and another person to manipulate the arm, hit e-stop etc.
Location	NSH B512
Procedure	
1. Turn on the Gen3 arm, the Atracsys camera, and the electrical subsystem for the end-effector. 2. Launch the watchdog node on the workstation to start logging the critical features of the system on the terminal. 3. Launch the perception node and check if the watchdog is recieving data from the camera about the pose of the end-effector marker, pelvis marker, and registration probe. 4. If perception subsystem health is ok, watchdog will send a signal to controller node to initiate reaming alignment. 5. Send command to end-effector from watchdog to start reaming process after reaming alignment is completed. 6. Check if reamer speed and load cell force is logged on the terminal during reaming.	
Validation	
1. Watchdog is able to communicate with all the subsystems. 2. Watchdog acts as a filter between subsystems to monitor communication and identify any malfunctions. 3. Watchdog is able to log all the critical information on the terminal for user/surgeon to evaluate.	

4.4 Test 4

Objective	
Verify that the end-effector is properly integrated with the electrical system and capable of reporting the axial force applied to the pelvis and the rotational velocity of the reamer to a ROS topic	
Equipment	Desktop workstation, robot arm, end-effector, electrical subsystem
Elements	Hardware subsystem: need all elements that allow end-effector to properly function
Personnel	2 people necessary, one person at the workstation to observe the data being received by certain ROS topics, and one person to manipulate the arm and end-effector
Location	NSH B512
Procedure	
1. Attach the end-effector to the end of the Kinova Gen-3 arm 2. Connect all wires from the end-effector to the electrical subsystem 3. Using admittance mode, move the arm so that the reamer head is within 50 millimeters of a foam pelvis when the end-effector is fully retracted 4. Echo the ROS topics which report axial pelvis force and reamer velocity 5. Send a command via a ROS topic to the arduino to start the reamer motor spinning at 300 rpm and verify that it starts and that the reported reamer velocity measured via encoders remains consistent 6. Send a command via a ROS topic to the arduino to begin rotating the ballscrew motor and verify that it starts to move the reamer head 7. Once the reamer head makes contact with the pelvis, verify that a force is recorded in ROS and that the reamer velocity remainds consistent at 300 rpm	
Validation	
1. Reaming motor is capable of being turned on and off 2. Ballscrew motor is capable of being turned on and off 3. Reamer velocity can be monitored via a ROS topic and remains controlled to a set velocity via PID control 4. The axial force applied to the pelvis can be monitored via a ROS topic either by indirect current sensing or load cells 5. Electrical subsystem and end-effector report no errors during test	

4.5 Test 5

Objective	
Validate the efficacy of the ballistics gell in simulating the real dynamics of pelvis motion during reaming.	
Equipment	Desktop workstation, Robot arm with reaming end-effector, pelvis foam bone encased in ballistic gel
Elements	Surgical setup test
Personnel	Two people are needed - one to operate the system, and another for manual intervention in-case test setup becomes unstable and requires manual intervention.
Location	NSH B512
Procedure	
1. Encase the pelvis foam bone in a container filled with Ballistics gel, while ensuring that the acetabulum is visible and accessible to the robot arm. 2. Use mounting screws to screw in the pelvis tracking marker on the Illiac Crest of the pelvis. 3. A few seconds before collecting the reaming data, start a rosbag file to record the pelvis marker pose topic 3. Perform the reaming operation on the pelvis. Continuously monitor the setup to carry out any manual intervention and stop the system if the setup becomes unstable. 4. Post-process the data and obtain the frequency spectrum of the collected data.	
Validation	
1. The marker's frequency spectrum of velocity and acceleration during reaming should be comparable to the data obtained during the Cadaver Lab. 2. The maximum range of motion of the pelvis should be comparable to the data obtained during the Cadaver lab.	

4.6 Test 6

Objective	
Validate communication of cup implant pose via UI to controls subsystem.	
Equipment	Desktop workstation
Elements	Hardware subsystem: need all elements that allow end-effector to properly function
Personnel	1 personnel
Location	NSH B512
Procedure	
1. Use the UI to align cup implant to desired pose. Hit "Confirm" once completed. 2. Check watchdog logger to verify the timestamp of new cup implant pose. Match with current time.	
Validation	
1. Cup implant pose received by controls subsystem to begin surgery. 2. Cup implant pose logged on watchdog logger and saved in local directory as text file.	

4.7 Test 7

Objective	
Verify the stability of the inverse kinematic controller near or at singularities during task execution	
Equipment	Desktop workstation, Robot arm with reaming end effector
Elements	Controls sub-system
Personnel	One person needed to start and monitor the system.
Location	NSH B512
Procedure	
1. Move the robot arm to its home position. 2. Run dummy pelvis script that broadcasts a dummy pelvis frame that moves the robot arm through a singularity. The dummy pelvis script will move no faster than 2 mm and 1.5 degrees per second. 3. Run the controller script to track the dummy pelvis frame.	
Validation	
1. The robot arm's velocity controller is able to consistently track the position and orientation of the dummy pelvis frame at 40 Hz. 2. The robot arm is able to achieve a position error of < 2mm and an orientation error of <=1.5 degrees during the scripted dummy pelvis movement. If singularity damping does not function, the arm will move unexpectedly fast at singularity, failing the position error test.	

4.8 Test 8

Objective	
Verify that joint limit avoidance is properly implemented in the inverse kinematic controller	
Equipment	Desktop workstation, Robot arm with reaming end effector
Elements	Controls sub-system
Personnel	One person needed to start and monitor the system.
Location	NSH B512
Procedure	
1. Move the robot arm to its home position. 2. Run dummy pelvis script that broadcasts a dummy pelvis frame that moves the robot arm through one joint limit, followed by a second joint limit. 3. Run the controller script to track the dummy pelvis frame.	
Validation	
1. The robot arm's velocity controller is able to consistently track the position and orientation of the dummy pelvis frame at 40 Hz. 2. The inverse kinematic controller should stop sending joint velocity commands to joints at joint limits. 3. The inverse kinematic controller should send joint velocity commands to joints previously at joint limits when the dummy pelvis frame moves back into joint range. 4. When at two joint limits, the robot should stop tracking the dummy pelvis frame.	

4.9 Test 9

Objective	
Verify the end-effector to camera alignment task tracks and aligns the end-effector marker frame to the camera frame, and that it still works during task prioritization	
Equipment	Desktop workstation, Robot arm with reaming end effector
Elements	Controls sub-system
Personnel	One person needed to start and monitor the system.
Location	NSH B512
Procedure	
1. Move the robot arm to its home position. 2. Run dummy pelvis script that broadcasts a dummy camera frame. 3. Run the controller to track and align the end-effector marker frame to the dummy camera frame. 4. Run the controller to track and align the end-effector marker frame to the dummy camera frame while holding the end-effector aligned to a static dummy pelvis frame	
Validation	
1. The robot arm's velocity controller is able to consistently track the position and orientation of the dummy pelvis frame at 40 Hz. 2. During step 3, the robot arm should align the end-effector marker frame to the dummy camera, with a orientation error of <= 10 degrees. 3. During step 4, the robot arm should remain aligned with the static dummy pelvis frame, with a position error of < 2 mm, and orientation error of <= 1.5 degrees. 4. During step 4, the robot arm should be using the redundant joints to move and track the dummy camera frame.	

4.10 Test 10

Objective	
Evaluate watchdog functionality and display all the subsystem health parameters on the User Interface.	
Equipment	Desktop workstation, robot arm
Elements	Software
Personnel	2 people necessary; 1 person checking all the logs on the workstation and another person to manipulate the arm, hit e-stop etc.
Location	NSH B512
Procedure	
1. Turn on the Gen3 arm, the Atracsys camera, and the electrical subsystem of the end-effector. 2. Launch the watchdog node and the User Interface (UI) on the workstation to start logging the critical features of the system on the UI. 3. Follow the instructions on the UI to complete registration, free motion mode, and begin reaming. 4. Monitor the system health as displayed by the watchdog on the UI. 5. Press the e-stop button on the UI to stop the process in case of emergency.	
Validation	
1. Validate proper functionality of the watchdog and ensure if the watchdog module is able to dectect system malfunctions. 2. Validate if all the critical information is visible on the UI while the robot is reaming. 3. Ensure if the watchdog initiates an emergency stop during malfunction or if the user/surgeon presses e-stop on the UI. 4. Validate the latency added to the system by the watchdog module is less than 25ms.	

4.11 Test 11

Objective	
Verify that the fully-manufactured end-effector is capable of receiving a command to start reaming to a specified end-point, reams to that end-point while maintaining a consistent RPM and not exceeding force thresholds, and reports important values to a ROS topic throughout the procedure	
Equipment	Desktop workstation, robot arm, end-effector, electrical subsystem
Elements	Entire hardware subsystem
Personnel	2 people necessary, one person at the workstation to observe the data being received by certain ROS topics, and one person to observe the arm
Location	NSH B512
Procedure	
1. Verify that the end-effector is connected firmly to the Kinova Gen-3 arm, and that all wires connecting the electrical subsystem to the end-effector are properly connected 2. Following the typical procedure for the fall validation demonstration, set up the arm to track the pelvis dynamically and ream to a specified end-point 3. Click to begin reaming on the user interface and verify that the ballscrew motor begins actuating 4. Once the reaming head makes contact, verify that an axial force is reported in the user interface 5. After contact is made, verify that the reaming motor turns on and maintains a consistent rpm 6. Verify that the reaming operation is not impeded when the arm dynamically compensates for motion 7. Using the stop built into the user interface, verify that the reaming motor and ballscrew motor both stop actuating as soon as the stop is pressed 8. Restarting the procedure from the beginning, verify the stability of the end-effector as the reamer head moves along the axis of the pelvis and that the force threshold is not exceeded 9. Verify that the end-effector reams to the endpoint and the resulting pelvis matches the surgical plan	
Validation	
1. Reaming motor is capable of being turned on and off by ROS autonomously 2. Ballscrew motor is capable of being turned on and off by ROS autonomously 3. Reamer velocity can be monitored via the user interface and remains controlled to a set velocity 4. The axial force applied to the pelvis can be monitored via the user interface and does not exceed the set force threshold 5. Motors stop in the end-effector in less than 500 ms from when a stop command is sent 6. Dynamic compensation does not effect the end-effectors ability to ream the pelvis	

4.12 Fall Validation Experiment

The objective of our fall validation demonstration is to demonstrate that the system is capable of autonomously localizing, planning, and executing an acetabular reaming operation as it would be performed in an operating room. We would be demonstrating this in NSH B512, utilizing all the hardware that we summarized in the full system depiction section. Our demo would consist of one team member interacting with the robot arm and work environment, one member controlling the robot arm and monitoring the Surgeon I/O, and the rest presenting and answering questions.

Procedure:

1. Begin by setting up the work environment by clamping the Sawbone pelvis which is encased in ballistics gels in a new position in a vise, fixing a fiducial marker screw mount on the pelvis, and placing the fiducial marker onto the end-effector of the robot arm.

2. The system will then be turned on and a user interface will appear on the screen to take surgeons through the procedure step by step. The surgeon will start by determining the surgical plan by choosing the acetabular implant's pose on a pelvis mesh obtained pre-operatively.

3. Utilizing a registration probe, the surgeon collects a set of points on the acetabulum to register the pelvis to a known pelvis mesh obtained preoperatively. Using the computed transformation, the endpoint of the reaming operation will be determined using the surgical plan with respect to the robot's frame of reference.

4. Utilizing free motion mode, the robot arm will be placed near the center of the acetabulum. The surgeon will then examine the user interface to ensure there are no joint singularities.

5. Control will then be given over to the arm and it will then navigate to a position where the reamer head is less than 50 mm away from the acetabulum axially and begin to actuate the reamer head towards the pelvis.

6. Once the reaming head contacts the pelvis and turns on, the e-stop is hit to demonstrate the safety of the system.

7. The robot arm will then be reset with free motion mode and the reaming operation would then be allowed to progress freely.

8. As the robot arm begins to ream the acetabulum, the pelvis would experience motion as a result of the ballistics gel, causing the pelvis to move as would occur in a normal procedure, forcing the arm to have to dynamically compensate for the motion during the reaming operation. For further demonstration of dynamic compensation, a team member will manually move the pelvis to mimic a jerking motion that could be seen during a procedure.

9. When the robot arm has completed the reaming operation, it will remove itself from the pelvis, and the resulting acetabulum can be analyzed.

10. During this procedure, all processes can be seen on the user interface and all issues would be reported to the watchdog.

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.

5 Appendix

5.1 Functional and Performance Requirements

Functional Requirement	Performance Requirement	Justification
M.F.1 The system shall use the Atracsys camera to track the pelvis, registration probe, and robot arm markers.	**M.P.1.1** The system shall 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 and latency less than or equal to 25 milliseconds.	From Atracsys Sprytrack 300 camera's specifications sheet.
	M.P.1.2 The system shall 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.	State-of-the-art, FDA-approved medical tracking systems are able to track fiducial pose with a position accuracy of 0.5 mm.
M.F.2 The system shall continuously calculate the error in pelvis movement.	**M.P.2.1** The system shall continuously calculate the error in pelvis movement with a frame rate greater than or equal to 40 Hz or latency less than or equal to 25 milliseconds.	Values are derived from the specified tracking performance and performance of using Eigen to calculate simple Euclidean distance.
	M.P.2.2 The system shall use the Atracsys camera to track the pelvis, registration probe, and robot arm markers with a positional accuracy less than or equal to 1.5 mm, and orientation accuracy less than or equal to 1.5 degrees.	
M.F.3 The system shall perform registration between the collected point cloud and the given 3D pelvis scan.	**M.P.3.1** The system shall perform registration between the collected pointcloud and the given 3D pelvis scan with a root mean square (RMS) error of 1 mm.	Time constraints on gathering points with a probe and the inaccuracies in the camera's detection of probe location combine to make it difficult to register a point cloud to a 3D pelvis scan with greater precision.
M.F.4 The system shall dynamically compensate for the movement of the pelvis.	**M.P.4.1** The system shall start dynamically compensating for the movement of the pelvis by commanding the end-effector to retract and/or power off the reamer with a latency of less than or equal to 25 ms when the error thresholds exceed 2 mm and 1.5 degrees.	Based on M.F.2 and M.F.5 the system must not ream while the error is greater than the acceptable thresholds, and must therefore turn off the reamer while realigning with the pelvis.
	M.P.4.2 The system shall dynamically compensate for the movement of the pelvis by beginning to realign the reamer with a latency of less than or equal to 50 ms.	Based on the current controller frequency with improved PID. Kinova Controller API is capped at 40 hz, so it can't be faster than 25 ms.
M.F.5 The system shall ream the pelvis based on the provided surgical plan.	**M.P.5.1** The system shall ream the pelvis based on the provided surgical plan with a positional accuracy of 2 mm.	Based on the extensive literature survey conducted and getting feedback from surgeons and our sponsors, these accuracy values are acceptable within the Lewinnek Safe Zone.
	M.P.5.2 The system shall ream the pelvis based on the provided surgical plan with an orientation accuracy of 1.5 degrees.	
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 and prevent the arm from making large motions around the patient and surgeons.
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 the 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

5.2 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.