Multi-Agent Geometric Inspection and Classification (MAGIC)

Fall Project Test Plan

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Table of Contents

Introduction

This document serves as a plan for how this team will demonstrate the progress of the MAGIC system and the completion of the milestones. One or more of these tests will be demonstrated during the Progress Reviews, and the final test will be executed for the Fall Validation Demo (FVD). The schedule for these tests is outlined in the Schedule section of this document. The purpose of these tests is to demonstrate that we have met the requirements for this system, which are defined in the Appendix section. We intend to show that we have met some of the requirements by the time of FVD.

Logistics

Location

Most of the tests will occur in the ARCS Lab (Wean Hall 1302) because that is where the robot arms are located.

Equipment

The equipment for these tests includes 2 Kinova Gen3 Arms, Intel Realsense D453i, Zed Stereo Camera (Gen 2), and several objects to manipulate (e.g. custom 3D-printed parts).

Schedule

Date	Identifier	Capability Milestone(s)	Tests	Requirements
10-Sep	Progress Review 7	Recreate Sprint Validation Demo Print small-scale testing object Order a large-scale test object Unify the environment for manipulation and perception Research motion planning method Update simulation environment in Riviz	1, 3, 6	M.F.1, M.F.2, M.N.3
24-Sep	Progress Review 8	Train model for object detection- object localization Lift test object and spin 360 degrees Solidify test object 3D reconstruction of test object	2, 3, 4, 8, 9	M.F.1, M.F.2, M.F.3, M.F.5; M.P.1, M.P.2, M.P.3.1, M.P.5; M.N.3
8-Oct	Progress Review 9	Complete FSM on RViz Finish manipulation policy Deploy the reconstruction pipeline during manipulation 4D pose estimation Finish integration of pose estimation and manipulation Finalize stretch goal object	4, 5, 7, 9, 10	M.F.1, M.F.2, M.F.3; M.P.1, M.P.2.1–2.2, M.P.3.1; M.N.2–M.N.3
29-Oct	Progress Review 10	Full integration Try to manipulate the stretch goal object in parallel (Stretch Goal)	2, 5, 7, 8, 10	M.F.1, M.F.3, M.F.5, M.F.7; M.P.2, M.P.3.1
12-Nov	Progress review 11	End-to-end dress rehearsal Lock demo scripts, safety roles, and E-stop drills	All	M.F.1–M.F.7; M.P.*; M.N.1–M.N.3
17-Nov	FVD	Public demo: integrated perception + manipulation + reconstruction on a regular-shaped object Show repeatability and error recovery	11	All mandatory acceptance targets
26-Nov	FVD Encore	Stretch goal: irregular/obscure-shape handling and recon quality optimization	7, 8, 11	D.F.2, D.P.2; D.F.3, D.P.3

Tests

Test 1: Camera Pre-Calibration Verification

Objective	To confirm the accuracy of the pre-calibrated intrinsic and stereo extrinsic parameters of the new ZED 2i camera and rerun calibration if deviations exceed acceptable limits.
Element	Perception subsystem
Location	On the computer and test environment
Equipment	1. Stereo Camera 2. Calibration board (checkerboard or ArUco marker board) 3. Computing system
Personnel	Shreya

Procedure

1. Retrieve the intrinsic parameters from the camera's SDK (focal length, principal point, distortion coefficients).
2. Retrieve the stereo extrinsic parameters (rotation & translation between left and right cameras).
3. Capture images of the calibration board at multiple angles and distances.
4. Compute the reprojection error for intrinsic parameters.
5. Compute the depth map using the disparity map.
6. If errors exceed acceptable thresholds, rerun the camera's SDK calibration pipeline.

Verification Criteria

1. Reprojection error ≤ 1 pixels
2. Disparity error should be ≤ 2% of object depth

Test 2: 3D Printed Object Grasp Optimization

Objective	Validate grasp planning for new 3D Printed test object on real hardware
Element	Manipulation Subsystem
Location	Wean Hall 1302
Equipment	Kinova Arms, Control PCs, 3D Printed Part
Personnel	Megan

Procedure

1. Place the object in the center of the workspace with arms in home position.
2. Attempt grasp on 8 different object orientations and locations within workspace boundaries. Plan and execute trajectory to the grasp points.
3. Lift up and ensure the object doesn't slip.
4. Place back down.
5. Measure success rate.

Verification Criteria

1. The robots should be able to plan and execute a trajectory to the grasp points with an 80% or higher success rate.
2. No damage is done to the part after being grasped and placed down.

Test 3: Constraint Handling for Planning

Objective	Validate joint locks and end-effector orientation constraints during a 360° spin trajectory.
Element	Planning & Control subsystem (MoveIt/OMPL + low-level controller).
Location	MoveIt first, then bench on a single Kinova arm with no payload
Equipment	Kinova Gen3 arm, control PC;
Personnel	Emma

Procedure

1. Define constraints: lock selected joints (e.g., shoulder/elbow) within ±0.2°, set End Effector target position in camera's field of view, and enforce orientation alignment to world Z.
2. Move to show-to-camera pose while satisfying the locked joint constraints.
3. Plan a trajectory where the EE spins 360° in place about its tool axis, keeping position fixed and orientation aligned.
4. Execute the spin at reduced speed on the Kinova arm.
5. Log joint states, EE pose, orientation error, and positional drift for later analysis.

Verification Criteria

1. Orientation axis error ≤ 0.5° throughout spin
2. EE positional drift ≤ 10 mm
3. Locked joint deviation ≤ 0.2°
4. No planner constraint violations or unexpected collisions
5. Motion completes smoothly without controller faults

Test 4: Object 4D pose estimation Test

Objective	To validate the accuracy of the pose estimation model to accurately detect the 4D pose of the test object on the workbench.
Element	Perception subsystem
Location	On the computer and test environment with the test object
Equipment	1. Stereo camera 2. Test Object 3. Computing system
Personnel	Kartik

Procedure

1. Capture the object in a known static pose to estimate the initial transformation.
2. Move the object through a known set of transformations while capturing frames.
3. Compute the expected object pose using the trained model.
4. Compare the expected pose to the measured pose from the model.
5. Compute the pose error in translation and rotation.

Verification Criteria

1. Translation error ≤ 5 cm
2. Rotation error ≤ 5°

Test 5: Extrinsic Calibration

Objective	To validate the accuracy of the object-to-camera calibration and ensure proper alignment between the object's known motion and its perceived position in the camera frame.
Element	Perception subsystem
Location	On the computer and test environment with the test object
Equipment	1. Stereo camera 2. Test Object with a calibration marker 3. Computing system
Personnel	Kartik

Procedure

1. Capture the object in a known static pose to estimate the initial transformation.
2. Move the object through a known set of transformations while capturing frames.
3. Compute the expected object pose using the known transformations.
4. Compare the expected pose to the measured pose from the camera.
5. Compute the pose error in translation and rotation.
6. If errors exceed thresholds, recalibrate the object-to-camera transformation.

Verification Criteria

1. Translation error ≤ 1 cm
2. Rotation error ≤ 1°

Test 6: Transformation Verification

Objective	To verify the transformations of the test object from the robotic manipulators.
Element	Manipulation subsystem
Location	On the robot in lab environment with calibration markers and measurement setup
Equipment	1. Robot manipulators
Personnel	Kailash Jagadeesh

Procedure

1. Set the robot to a known reference configuration (home position with known joint angles).
2. Move the robots to the position to pick up the object and record the joint angles.
3. Record the initial pose of the test object with a known reference frame.
4. Move the test object using the 2 robotic arms to some standard movements (movement in X, movement in Y, movement in Z and movement in orientation) and record the joint angles and the actual positions of the object in the workspace.
5. Compare the measured pose of the test object against the pose calculated based on the DH table.

Verification Criteria

1. The position error needs to be within 1 cm.
2. The orientation error should be less than 1 degree.
3. Consistent results across repeated trials (Variance should be <= 5mm / 0.5 degree)

Test 7: Full Manipulation Policy Robustness Test

Objective	Demonstrate manipulation to show the remaining faces of the test object. Full FSM sequence should be completed and tested for robustness.
Element	Manipulation subsystem
Location	Wean Hall 1302
Equipment	Kinova Arms, Control PCs, 3D Printed Part
Personnel	Megan and Emma

Procedure

1. Place the object in the center of the workspace with arms in home position.
2. Execute full manipulation policy: Lift -> Rotate 360 -> Place down -> Grasp other handles -> Rotate to show remaining sides
3. Make sure remaining 2 sides are exposed to perception system to correct transforms
4. Ensure the object doesn't slip during the whole sequence.
5. Place back down.
6. Repeat this 10 times with different initial positions of the object.
7. Measure success rate.

Verification Criteria

1. The robots should be able to execute full FSM with an 80% or higher success rate.
2. No damage is done to the part after being grasped and placed down.

Test 8: 3D Reconstruction Accuracy

Objective	To measure the accuracy of the reconstructed 3D model compared to the real object using an undeformed reference object. The assumption is that accuracy in reconstructing the undeformed object will translate to accurate reconstruction of the deformed version.
Element	Perception subsystem
Location	On the computer
Equipment	1. Camera sensor 2. Turntable 3. Object with known dimensions (undeformed) 4. Computing system
Personnel	Shreya

Procedure

1. Capture a complete 360-degree image set of the undeformed object.
2. Run the 3D reconstruction pipeline to generate a point cloud.
3. Compare the reconstructed model with ground truth measurements (CAD).
4. Analyze deviations in shape and scale.

Verification Criteria

1. Dimensional Accuracy: The average deviation in reconstructed dimensions should be ≤ 5% of the object's real-world dimensions.
    1.1. Example: If an object is 20 cm wide, the reconstructed width should be within ±1 cm.
2. Surface Completeness: The reconstructed model should have at least 95% coverage of the object’s surface.
3. Point Cloud Density: The mean point cloud density should be greater than 1000 points per m^2 to ensure fine details are captured.

Test 9: Manipulation Camera Sync

Objective	To verify that the transformations from the robot's Inverse Kinematics (IK), published as ROS messages, are accurately synchronized and paired with each manipulation camera frame, ensuring the capture rate matches the robot's transformation update rate.
Element	Perception and manipulation subsystem
Location	On the computer and test environment
Equipment	Kinova Arms, Control PCs, 3D Printed Part
Personnel	Kartik

Procedure

1. Measure and confirm the publishing rate of robot IK transforms and camera frame capture rate.
2. Verify timestamps and system clock synchronization.
3. Collect synchronized data from both IK transforms and camera frames.
4. Pair each camera frame with the closest IK transform based on timestamps.
5. Check time differences between pairs against acceptable thresholds.
6. Validate consistent rate matching and look for drift or missing pairs.
7. Perform tests under varying speeds and conditions to confirm robustness.
8. Investigate and resolve any synchronization errors found.

Verification Criteria

1. Publishing Rate Match: IK transform and camera frame rates should be within ±5% of each other.
2. Timestamp Accuracy: Timestamp differences between paired IK transform and camera frame should be ≤ 10 ms.
3. Synchronization Consistency: At least 95% of camera frames must have a corresponding IK transform within the acceptable time threshold.
4. No Significant Drift: Time offset between transforms and frames should remain stable throughout the test (no growing drift).
5. Robustness: Synchronization holds true under different robot speeds and camera capture rates without dropped or mismatched pairs.
6. Error Handling: Any synchronization failures are logged and addressed with corrective actions.

Test 10: Integration of Pose Estimation with Manipulation System

Objective	To validate that the pose estimation system accurately provides 4D object poses and grasp points, which are correctly received and utilized by the manipulation system to execute grasps or actions
Element	Perception, Manipulation
Location	Wean Hall 1302
Equipment	Stereo camera, Test object, Robot manipulation system, Computing system running both pose estimation and manipulation nodes
Personnel	Kartik

Procedure

1. Capture the test object at a known static pose; pose estimation system outputs the 4D pose and grasp points.
2. Pass the estimated pose and grasp points to the manipulation system through the integration interface (e.g., ROS topics/services).
3. Manipulation system plans and executes the grasp based on the received data.
4. Move the object through a predefined set of transformations; repeat pose estimation and manipulation execution.
5. Log timestamps and data flow to verify synchronization between pose estimation outputs and manipulation commands.
6. After each grasp attempt, record success/failure and measure any deviation between expected and actual grasp positions.
7. Perform multiple trials to assess consistency and robustness.

Verification Criteria

1. Pose estimation data (4D pose and grasp points) is successfully transmitted to the manipulation system with ≤10 ms latency.
2. Manipulation system executes grasp within 2 cm translation and 2° rotation error of the pose estimation input.
3. At least 80% successful grasps over multiple trials based on pose estimation data.

Test 11: Fall Validation Demo

Objective	Demonstrate full integration of perception and manipulation systems on real hardware with reliable object pose estimation, 3D reconstruction, and successful manipulation of regular-shaped objects. Validate system repeatability and error recovery capabilities, with stretch goal of handling irregular-shaped objects.
Element	Perception, Manipulation
Location	Wean Hall 1302
Equipment	Physical Setup: 2 Kinova Arms, Desktop Test Object: 3D printed object, stretch goal object Perception System: ZED 2 Stereo
Personnel	Kartik, Emma, Megan, Shreya, Kailash

Procedure

1. Initialize the integrated perception-manipulation system on physical robotic arms.
2. Validate workspace boundaries and safety constraints. Ensure people are on E-stops.
3. Place the 3D-printed test object in the workspace within boundaries.
4. Use pose estimation to move and reach grasp points and lift up the object.
5. Start capturing for 3D reconstruction.
6. Rotate end effectors to show the faces of the object. Place back down.
7. Use pose estimation again to reach the other two grasp points to lift and show the remaining faces of the object.
8. Process data for 3D reconstruction
9. In parallel, repeat the manipulation policy at least three times with varying initial object poses.
10. Review data to verify system performance and identify potential improvements.
11. Stretch Goal: Perform manipulation on an additional object that is irregular in shape.

Verification Criteria

1. The arms must successfully pick and manipulate objects without causing damage.
2. The arms must successfully reach the grasp points in all trials while staying within movement constraints and pathfinding tolerance ±2 cm.
3. Plan should take within 4 ± 3 seconds to calculate arm trajectories.
4. The 3D reconstruction process should be completed within 10 minutes to 3cm precision.
5. Pose-estimation should detect grasp points.
6. No unexpected errors, delays, or hardware failures should occur during execution.

Appendix

Mandatory functional requirements

Functional Requirement	Performance Requirements
M.F.1 Sense and estimate part pose	M.P.1 Detect given grasp points with 90% of the time
M.F.2 Plan arm trajectory and move to desired point	M.P.2.1 Plan movement inside valid zones 100% of the time M.P.2.2 Plan desired paths for both arms within 4 ∓ 3 seconds
M.F.3 Pick Up and Manipulate Part	M.P.3.1 Pick up and manipulate 90% of the parts successfully M.P.3.2 Pick up objects up to 2kg
M.F.4 Avoid Collision	M.P.4 Avoid 85% collision
M.F.5 Perform 3D Reconstruction	M.P.5.1 3 cm precision M.P.5.2 Construct within 10 minutes
M.F.6 Compare to ground truth and calculate differences in surface contours	M.P.6.1 Robust to outliers 95% of the time
M.F.7 Avoid causing surface damage to samples	M.P.7 No surface change to part after manipulation 80% of the time

Mandatory non-functional requirements

Non-Functional Requirement
M.N.1 Robust to environmental changes
M.N.2 Incorporate safety measures
M.N.3 Be reliable
M.N.4 Robust to sensor and behavior failures

Desired functional requirements

Functional Requirement	Performance Requirement
D.F.1 Render 3D reconstruction in real time	D.P.1 Display 30 frames per second
D.F.2 Handle irregularly shaped objects	D.P.2 Successfully grasp object 80% of the time
D.F.3 Optimize 3D Reconstruction	D.P.3 Target millimeter level accuracy