Multi-Agent Geometric Inspection and Classification (MAGIC)

Spring Project Test Plan

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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 Spring Validation Demo (SVD). 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 SVD; the rest of the requirements are going to be met by the time of the Fall Validation Demo (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 (Ex: laundry basket, custom 3D-printed parts).

Schedule

Date	Identifier	Capability Milestone(s)	Tests	Requirements
13-Feb	Progress Review 1	- Set up simulation and start impedance control in MuJoCo for one arm - Annotate and label 6D poses of test object 1 across frames in the video - Train a 6D pose estimation using Gen6D - Camera Calibration, initial automation - Perform SAM-based turntable 3D reconstruction on target demo object - Motion planning for one arm in MoveIt	1, 2	M.F.1, M.F.2, M.F.5 M.P.1
27-Feb	Progress Review 2	- Integrate basic MAPF algorithms in MoveIt (collision-free planner) - Integrate tracking with a 6D pose estimation model - Determine primitive object manipulation policy for 3D reconstruction. - Arms simultaneously reach given grasp point and lift object in simulation	3, 4, 5, 6	M.F.1, M.F.2, M.F.4, M.F.5 M.P.1, M.P.2.1, M.P.2.2, M.P.4, M.P.5.1
20-Mar	Progress Review 3	- Both arms plan and execute paths to the target item upon receiving position in the simulation - Work on rotating object mid-air in simulation	7, 8	M.F.2, M.F.3 M.P.3.1
8-Apr	Progress Review 4	- Both arms plan path/trajectory to their target position/pose within 10 seconds. - Start sim2real work - Demonstrate reconstruction of the object (except the handle faces)	9, 10	M.F.2, M.F.5 M.P.5.1
17-Apr	SVD	- Arms should accurately reach grasp points IRL (no manipulation in real life) - Demonstrate manipulation of a simple object fully in simulation - Demonstrate 3D reconstruction (without optimization)	11	M.F.1, M.F.2, M.F.3, M.F.4, M.F.5
24-Apr	SVD Encore	- Optimized 3D reconstruction - Improve sim manipulation - Sim2real progress	11	M.F.5 M.P.5.2

Tests

Test 1: Camera Pre-Calibration Verification	
Objective	To confirm the accuracy of the pre-calibrated intrinsic and stereo extrinsic parameters of a stereo 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: Robot Localization and Calibration	
Objective	To localize and calibrate the robot in the workspace
Element	Control Subsystem
Location	Wean Hall 1302
Equipment	Kinova Arms, Control PCs, position measurement tools
Personnel	Kailash and Megan
Procedure	
1. The home position of the robots in the workspace is measured and noted down. 2. The configuration limits are defined and verified by programming the robot to move to the desired points. 3. Configuration space boundary and workspace boundary are mapped and recorded.	
Verification Criteria	
1. The robots should be able to access the boundaries of the workspace (except the singular configurations).	

Test 3: Object-Eye Calibration (Camera-to-Object 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	Shreya
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 $\leq 1°$	

Test 4: Impedance Control	
Objective	To verify the tuning and performance of the impedance controller in the simulation environment.
Location	Wean Hall 1302
Element	Control Subsystem
Equipment	MuJoCo (Virtual Simulation)
Personnel	Megan and Kailash

Procedure

1. Set the test sample at a known location in the simulation workspace.
2. Set the position and velocity parameters for the robotic arm to reach and apply force on the test sample.
3. Once the end effector of the arm applies the force on the test sample, induce motion in opposing direction (manually) using an obstacle.
4. Record the opposing force applied on the robotic arm.
5. Observe the response of the robotic arm and the deviation (if any) from the end-effector's position.
6. Observe the joint torques and joint velocities.

Verification Criteria

1. The robotic arm is able to resist the opposing force to a maximum of 400N.

Test 5: Object 6D pose estimation inference Test	
Objective	To validate the inference time of the pose estimation model to infer the current frame through the model.
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. Pass the captured image through the model at a timestep 3. Move the object through a known set of transformations while capturing frames. 4. Compute the expected object pose using the trained model and record timestamp. 5. Compute inference time. 6. Repeat for 5 different transformations.	
Verification Criteria	
1. Constant inference time.	

Test 6: Object 6D pose estimation Test	
Objective	To validate the accuracy of the pose estimation model to accurately detect the 6D 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. 6.	
Verification Criteria	
1. Translation error ≤ 5 cm 2. Rotation error $\leq 5°$	

Test 7: MAPF Robot Simulation in MoveIt & MuJoCo	
Objective	Verify that both robots successfully execute motion planning, reach planned locations, and avoid collisions in simulation.
Element	Simulation Subsystem
Location	MuJoCo (Virtual Simulation)
Equipment	PC, Monitor
Personnel	Emma and Kartik
Procedure	
1. Initialize the simulation by launching MuJoCo, loading the MAPF robots, and starting ROS2 with MoveIt. 2. Assign 100 target locations by defining waypoints for the robots to reach. 3. Plan and execute paths by generating trajectories and running them in MuJoCo. 4. Log the position of each robot as they move toward their assigned waypoints. 5. Verify that all robots reach their assigned destinations and record completion rates.	
Verification Criteria	
1. Robots reach at least 95% of planned locations within tolerance 2. No collision occurs, and MoveIt successfully replans when obstacles appear 3. The system remains stable, with planning times within 5 seconds. 4. Logged data confirms trajectory accuracy and successful execution	

Test 8: Robot Position Control	
Objective	To test the accuracy of the robot’s position control
Element	Control Subsystem
Location	Wean Hall 1302
Equipment	Kinova Arms, Control PCs, position measurement tools
Personnel	Megan and Kailash
Procedure	
1. The robotic arm is given a known point in the world frame. 2. The position control moves the arm to the designated point. 3. The error between the end effector position and the known point is measured. 4. The steps are repeated for 5 sample points and the variance is measured.	
Verification Criteria	
1. The average error should be less than 2cm.	

Test 9: 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 $\leq$ 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 10: Trajectory Tracking	
Objective	To verify the accuracy and latency of the tracking controller for the robotic arm.
Element	Control Subsystem
Location	Wean Hall 1302
Equipment	Kinova Arms, Control PCs, position measurement tools
Personnel	Kailash and Megan
Procedure	
1. The planning sub-system generates a trajectory for the robotic arm which is first simulated in the physics engine to verify the trajectory. 2. The verified trajectory is then fed to the tracking controller and we record the live end effector position data from the Kinova API. 3. The observed trajectory is compared with the input trajectory.	
Verification Criteria	
1. The robotic arm's end effector needs to follow the trajectory with RMSE less than 10 cm.	

Test 11: Spring Validation Demo

Objective	Demonstrate manipulation in simulation and validate real-world reachability to a test object. Verify repeatability and perception integration, and independently demonstrate 3D reconstruction.
Element	Perception, Planning, Controls
Location	Wean Hall 1302
Equipment	Simulation Environment: MoveIt, MuJoCo, ROS2 Physical Setup: Robot arm with end-effector, Desktop Test Object: Basket, 3D printed object Perception System: ZED 1 Stereo/ Intel RealSense D435i
Personnel	Kartik, Emma, Megan, Shreya, Kailash

Procedure

1. Launch simulation environment in MuJoCo and MoveIt, and initialize arms.
2. Run a simulation where the robotic arms pick up and manipulate objects.
3. Log planned vs. executed trajectories to analyze accuracy and performance.
4. Independently perform and validate 3D reconstruction of a known object with 3 cm precision.
5. Ensure the 3D reconstruction process outputs usable data within 10 minutes.
6. Set up the physical robotic arm in the real-world test environment.
7. Command the robotic arm to move and reach grasp points while staying within valid movement constraints.
8. Verify that the robotic arm reaches the intended position within tolerance ±2 cm with a tape measure.
9. Record the motion execution and verify smooth movement without errors.
10. Measure the time taken for the arm to reach the basket.
11. Validate localization accuracy and confirm that planned vs. actual movement remains within acceptable error margins.
12. Repeat the verification at least three times with varying initial object poses.
13. Review data to verify system performance and identify potential improvements.

Verification Criteria

1. The arms in the simulation must successfully pick and manipulate objects.
2. The physical arm must successfully reach the grasp points in all trials while staying within movement constraints and pathfinding tolerance ±2 cm.
3. MAPF should take within 4.4 ± 3.4 seconds to calculate arm trajectories.
4. The 3D reconstruction process should be completed within 10 minutes, and post-estimation should validate localization and positioning accuracy.
5. 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 4.4 ∓ 3.4 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 irregular shape objects	D.P.2 Successfully grasp object 80% of the time
D.F.3 Optimize 3D Reconstruction	D.P.3 Target millimeter level accuracy