Fall Test Plan

Flying Hand

Aerial Manipulator for Non-Destructive Testing



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1. Introduction

This document details the Fall 2026 Test Plan for Team C's Flying Hand project: an aerial manipulator designed to perform contact-based non-destructive testing (NDT) on hard-to-reach industrial assets.

At the SVD, the team demonstrated that the fully-actuated hexarotor platform could make and hold contact with a flat surface at the target 5 N force under wind disturbances up to 2 m/s with gusts of 5 m/s, and that near-wall position hold met the localization accuracy requirement. The end-to-end autonomous localize-and-contact pipeline (visual servoing, POI detection, and the position–wrench hybrid controller) was validated in Gazebo simulation.

Based on lessons learned since the SVD, the team has decided to de-risk the Fall Validation Demonstration by keeping UAV flight itself under manual pilot control — takeoff, transit to the Area of Interest, and the return flight are all manually flown — while concentrating fall-semester validation on the manipulator subsystem, where the team's new 6-DOF arm now provides substantially more capability and where the two operating modes central to the FVD (autonomous multi-point contact and leader-arm teleoperation) are demonstrated. This lets the team rigorously validate manipulator kinematics, force control, collision safety, and IBVS behavior in a controlled, incremental fashion before combining them at the FVD.

The fall semester's work is therefore organized around a bench-to-flight qualification sequence for the manipulator: bench teleoperation via a leader arm, mechanical integration onto the UAV, kinematics (FK/IK) accuracy, contact-force characterization, collision and path safety, robustness of IBVS control near singularities, force-controller consistency under a moving (hovering) base, and finally full autonomous end-to-end manipulation. These threads converge at the Fall Validation Demonstration (FVD) on November 16, where the team will manually fly the UAV to the Area of Interest, demonstrate autonomous multi-point contact-based manipulation on a planar target, switch to leader-arm teleoperation to reach additional target points, and manually fly the UAV back to the launch point.

The remainder of this document is organized as follows: Section 2 summarizes personnel roles, shared equipment, and testing sites common to most tests. Section 3 maps each remaining Progress Review and the FVD to its capability milestone(s), associated test(s), and associated system requirements. Section 4 describes each planned test in detail, culminating in the FVD. Appendix A reproduces the system requirements referenced throughout the plan.

2. Logistics

2.1 Personnel Roles

For bench tests, the team designates a test operator (commands the manipulator/leader arm and runs the test script) and a data logger (records measurements against the verification criteria). For flight tests, the team additionally designates: a pilot (manual takeoff, transit, and return — the UAV is not flown autonomously this semester), a manipulator operator (commands autonomous target selection and, later, the leader-arm teleoperation switch), and a safety officer (monitors the test area and holds authority to abort). Roles rotate among the five team members based on subsystem ownership, consistent with the round-robin Progress Review presenter schedule.

2.2 Shared Equipment

- Tarot X6 airframe with Cube Orange flight controller (PX4 v1.16), flown manually for all fall flight tests
- New 6-DOF manipulator (follower arm) , UAV-mounted for flight tests
- Leader arm / haptic teleoperation input device and teleoperation bridge computer
- NVIDIA Jetson Orin Nano (kinematics, IBVS, and force-controller compute)
- Camera (Intel RealSense / RGB) for IBVS and POI detection
- Web-based manipulator control panel for commanding end-effector pose/orientation
- Mock target surface(s)/panel with multiple marked contact points
- Futaba receiver/transmitter and telemetry radios
- Ground Control Station laptop

2.3 Testing Sites

MRSD Project Lab: Primary workspace for bench teleoperation, mechanical integration, kinematics, force characterization, and collision-safety testing (T14–T18, T20).

Scaife Drone Cage: Indoor facility used for lower-risk IBVS and end-to-end manipulation testing under direct supervision, with the UAV either base-fixed or manually piloted (T19, T21).

RIC Drone Cage: Primary site for end-to-end autonomous manipulation testing and the Fall Validation Demonstration. Required safety training has been completed and facility access is secured (T21, T22).

3. Schedule

The table below maps each remaining Progress Review and the FVD to its capability milestone, the associated test(s) from Section 4, and the associated system requirements (see Appendix A).

Date	Identifier	Capability Milestone(s)	Associated Test(s)	Associated System Requirements
9-Sep	**PR 7**	Manipulator teleoperation (leader–follower) validated on the bench, independent of the UAV platform.	T14	M.F.7
23-Sep	**PR 8**	Manipulator mechanically integrated on the UAV; workspace, joint ranges, and FK/IK kinematics accuracy validated.	T15, T16	M.F.6, M.F.7, M.P.5
7-Oct	**PR 9**	Contact-force capability characterized across the workspace; collision-free path planning and safety validated via the web control panel.	T17, T18	M.F.9, M.N.1, M.P.5

Date	Identifier	Capability Milestone(s)	Associated Test(s)	Associated System Requirements
28-Oct	**PR 10**	IBVS robustness near kinematic singularities and force-controller consistency under simulated base motion validated.	T19, T20	M.F.5, M.F.6, M.F.8, M.P.6
11-Nov	**PR 11**	Full autonomous end-to-end manipulation pipeline demonstrated on a multi-point target surface; serves as the FVD dress rehearsal.	T21	M.F.5, M.F.6, M.F.7, M.F.8, M.P.4, M.P.5
16-Nov	**FVD**	Manual flight to the Area of Interest, followed by autonomous multi-point manipulation and teleoperated multi-point manipulation via the leader arm, then a manual return flight.	T22	M.F.1–M.F.11, M.P.1–M.P.9

4. Tests

T14: Manipulator Leader–Follower Teleoperation Unit Test (Bench, Off-UAV)

Objective	Validate that the 6-DOF manipulator (follower) can be reliably teleoperated via a leader arm, with the manipulator mounted on a bench stand rather than the UAV, verifying joint-space command tracking, latency, and operator controllability before any flight integration.
Element(s)	Manipulator (Follower Arm), Leader-Arm Teleoperation Interface
Location	MRSD Project Lab
Equipment	6-DOF follower manipulator on a bench mount Leader arm / haptic input device Teleoperation bridge computer (Jetson Orin Nano or dev PC) Joint-angle logging tool / oscilloscope
Personnel	Chenyang / Shubham

Procedure

1. Mount the follower manipulator on a bench stand and connect it to the leader-arm teleoperation software stack.
2. Command each leader-arm joint through its full range of motion and verify correct (1:1 or scaled) joint-space mapping to the follower.
3. Measure end-to-end teleoperation latency from leader-arm motion to follower-arm response.
4. Have an operator perform a set of representative reach/point tasks with the leader arm and log the follower end-effector trajectory.
5. Verify that safety cutoffs (e-stop, joint-limit clamping) correctly halt or protect the follower arm when triggered.

Verification Criteria

1. The follower manipulator tracks leader-arm commands with joint-space error within the team's defined tolerance.
2. End-to-end teleoperation latency remains within an acceptable bound for smooth operator control.
3. E-stop and joint-limit safety cutoffs correctly halt or protect the follower arm in all trials.

T15: Mechanical Integration & Workspace Test

Objective	Verify that, after mounting the manipulator on the UAV, joint ranges, end-effector workspace, and mechanical limits match the design specifications, and that no interference occurs with the airframe, propellers, or wiring.
Element(s)	Manipulator, UAV Airframe
Location	MRSD Project Lab
Equipment	Full Flying Hand platform with manipulator mounted in flight configuration Calipers / protractor Workspace-mapping fixture (or motion capture, if available)
Personnel	Shubham / Shunxuan / Weerachai

Procedure

1. Mount the manipulator onto the UAV airframe in its flight configuration.
2. Command each joint through its full range of motion individually and verify there is no mechanical interference with the airframe, propellers, landing gear, or onboard wiring.
3. Sweep the end-effector through boundary poses of its designed reachable workspace and record the actual reachable envelope.
4. Compare the measured joint ranges and workspace envelope against the CAD/design specification.
5. Verify that mechanical hard-stops and/or software soft-limits engage at the expected joint angles.

Verification Criteria

1. No mechanical interference occurs across the full commanded joint range in the flight configuration.
2. Measured joint ranges and workspace envelope match the design specification within tolerance.
3. Hard-stops/soft-limits engage within the expected tolerance of the designed joint limits.

T16: Kinematics Accuracy Test (FK/IK)

Objective	Verify that forward kinematics (FK) and inverse kinematics (IK) correctly map between joint configurations and end-effector poses across nominal and boundary cases, while respecting joint limits and reachability.
Element(s)	Manipulator Kinematics Software
Location	MRSD Project Lab
Equipment	Manipulator (UAV-mounted) Ground-truth measurement tool (calipers, motion capture, or a checkerboard/fiducial target) Computer running the kinematics stack
Personnel	Tanaya / Chenyang

Procedure

1. Command a set of nominal joint configurations; compute the FK end-effector pose and compare it against the measured ground-truth pose.
2. Command a set of nominal target end-effector poses via IK and verify the resulting joint configuration reaches the commanded pose within tolerance.
3. Repeat for boundary-case poses near the edges of the reachable workspace and near joint limits.
4. Command deliberately unreachable target poses (outside the workspace) and verify IK correctly reports infeasibility rather than returning an invalid solution.
5. Verify that all returned IK solutions respect the manipulator's joint limits.

Verification Criteria

1. FK-predicted end-effector pose matches the measured ground truth within the defined position/orientation tolerance.
2. IK-commanded poses are reached within tolerance for all nominal and boundary test cases.
3. IK correctly rejects or flags unreachable target poses instead of returning an invalid solution.
4. No returned IK solution violates a joint limit.

T17: Contact Force Categorization & Maximum Reliable Force Test

Objective	Categorize the contact force the manipulator can generate at the end-effector across its workspace, and calibrate a motor-current-based force estimator so the maximum force it can reliably and repeatably apply at the contact point can be determined without a dedicated F/T sensor.
Element(s)	Manipulator, Motor-Current-Based Force Estimation
Location	MRSD Project Lab
Equipment	Manipulator (base rigidly fixed, representing a stationary/hovering platform) Motor drivers/ESCs with per-joint current-sensing telemetry (basis for the force estimator) Rigid test contact surface Calibrated reference load cell (ground truth used only to calibrate and validate the current-to-force model; not used onboard the flight platform)
Personnel	Shubham / Shunxuan

Procedure

1. Rigidly fix the manipulator base and position the end-effector against the rigid test surface.
2. Command increasing contact force in small increments (e.g., 1 N steps); at each step, record the per-joint motor current draw together with the ground-truth force measured by the reference load cell.
3. Repeat at multiple points across the reachable workspace (near-base, mid-reach, full extension) to fit a per-configuration current-to-force calibration, since the same end-effector force requires different joint torques (and therefore different motor currents) depending on arm configuration.
4. Continue increasing commanded force until the arm can no longer reliably maintain it (e.g., due to motor current reaching its rated/thermal limit, actuator saturation, or arm deflection); record this as the maximum reliable force for that configuration.
5. Repeat each configuration three times to assess repeatability, then fit the current-to-force calibration model (e.g., a per-configuration linear or lookup-table mapping) and validate it against a held-out set of load-cell measurements not used for fitting.

Verification Criteria

1. The motor-current-based force estimate tracks the load-cell-measured commanded force within tolerance up to the identified maximum reliable force at each tested configuration.
2. The maximum reliable contact force is documented for near-base, mid-reach, and full-extension configurations.
3. Force-output repeatability across the three trials is within tolerance at each tested configuration, and the fitted current-to-force model matches held-out load-cell measurements within tolerance.

T18: Collision & Path Safety Test

Objective	Verify that self-collisions are correctly detected and that planned trajectories remain collision-free and satisfy all joint constraints, using a web control panel to command end-effector pose and orientation (kept perpendicular to the contact surface).
Element(s)	Manipulator Motion Planning & Safety Software
Location	MRSD Project Lab
Equipment	Manipulator (UAV-mounted) Web-based control panel for commanding end-effector pose/orientation Computer running the motion planner
Personnel	Tanaya / Weerachai

Procedure

1. Using the web control panel, command a series of end-effector target poses, with orientation constrained to remain perpendicular to a representative contact surface.
2. For each target, verify the planner checks for self-collision (arm-to-arm and arm-to-airframe) before executing the motion.
3. Deliberately command targets that would require a self-colliding configuration and verify the planner rejects or re-plans around them.
4. Execute a sequence of collision-free targets and verify the resulting trajectory remains collision-free and within joint limits throughout the motion, not only at the start/end poses.
5. Log planning time for each commanded target.

Verification Criteria

1. All commanded trajectories remain collision-free throughout motion, not only at the start/end poses.
2. Self-colliding target configurations are correctly detected and rejected or re-planned.
3. All executed trajectories satisfy joint-limit constraints throughout.
4. End-effector orientation remains perpendicular to the contact surface, within tolerance, for all commanded targets.

T19: Singularity & IBVS Robustness Test

Objective	Verify that image-based visual servoing (IBVS) control remains stable near kinematic singularities and does not generate excessively large or divergent joint commands.
Element(s)	Manipulator, IBVS Control
Location	MRSD Project Lab / Scaife Drone Cage
Equipment	Manipulator (UAV-mounted) Camera Target markers / POI Computer running the IBVS controller
Personnel	Tanaya / Chenyang

Procedure

1. Identify joint configurations near known kinematic singularities of the manipulator (e.g., near full extension or wrist alignment).
2. Command an IBVS-guided approach toward a target POI positioned so the arm is driven near a singular configuration.
3. Monitor commanded joint velocities/torques for spikes or divergence as the arm approaches the singularity.
4. Verify that singularity-avoidance or damping logic (e.g., damped least-squares IK) limits joint-command magnitude near singularities.
5. Repeat for multiple approach directions/target placements that stress different singular configurations.

Verification Criteria

1. Commanded joint velocities/torques remain within safe operating bounds near all tested singular configurations.
2. IBVS control converges to the target, or safely aborts, without divergent or oscillatory behavior near singularities.
3. No joint-limit violations or unsafe motions occur during any trial.

T20: Force Controller Consistency Under Moving-Base Test

Objective	Ensure the force controller, using motor-current-based force feedback in place of a dedicated F/T sensor, maintains consistent end-effector contact force when the manipulator's base (representing the hovering UAV) undergoes small positional and attitude disturbances, by simulating base motion of 5–10 cm in all axes and ±10° in roll, pitch, and yaw.
Element(s)	Manipulator Force Controller (Motor-Current-Based Feedback), Base-Disturbance Fixture
Location	MRSD Project Lab
Equipment	Manipulator mounted on a fixture capable of simulated base displacement/rotation Rigid contact surface
Personnel	Chenyang / Shunxuan / Tanaya

Procedure

1. Mount the manipulator on a base fixture that can be manually or mechanically displaced/rotated to simulate UAV hover disturbances.
2. Command the end-effector to make contact with a rigid surface at the target 5 N force.
3. While maintaining contact, perturb the base by 5–10 cm along each translational axis (x, y, z) individually, then in combination.
4. Perturb the base attitude by ±10° in roll, pitch, and yaw individually, then in combination, while maintaining contact.
5. Continuously log the motor-current-based force estimate throughout all perturbations.

Verification Criteria

1. The motor-current-based force estimate remains within 5 N ± 1 N throughout all translational base disturbances (5–10 cm, all axes).
2. The motor-current-based force estimate remains within 5 N ± 1 N throughout all rotational base disturbances (±10°, roll/pitch/yaw).
3. No loss of contact (estimated force dropping to zero) or excessive estimated-force spikes occur during any disturbance trial.

T21: End-to-End Autonomous Manipulation Test

Objective	Verify the full autonomous manipulation pipeline — from visual input through IBVS, kinematics, safety/planning, and actuator commands — to ensure the manipulator can reliably reach and make contact with target points on a real surface.
Element(s)	Full Manipulator Pipeline (Perception, IBVS, Kinematics, Planning, Actuation)
Location	Scaife / RIC Drone Cage
Equipment	Full Flying Hand platform (manipulator mounted, base fixed or UAV hovering) Camera Mock target surface with multiple marked contact points Ground Control Station / laptop
Personnel	Shunxuan / Chenyang / Weerachai / Shubham / Tanaya

Procedure

1. Present the camera with a target surface containing multiple marked contact points.
2. Command the system to autonomously detect a target point, plan a collision-free path via IK, and drive the end-effector to make contact using IBVS-guided visual feedback.
3. Verify the force controller, using motor-current-based force feedback, establishes and holds the target contact force upon arrival at each point.
4. Repeat the full pipeline for multiple target points on the same planar surface within a single session.
5. Log end-to-end latency, contact accuracy, and force-tracking performance for each target.

Verification Criteria

1. The manipulator autonomously and reliably reaches each commanded target point within the designated positioning tolerance.
2. Contact force (motor-current-based estimate) is established and held at 5 N ± 1 N at each target.
3. No collisions, joint-limit violations, or IBVS divergence occur during full-pipeline execution across all tested targets.

T22: Fall Validation Demonstration (FVD)

Objective	Demonstrate end-to-end readiness of the Flying Hand system: the UAV is manually flown to an Area of Interest, the manipulator autonomously contacts multiple points on a planar target surface, control is then switched to teleoperation via the leader arm to contact additional points, and the UAV is manually flown back to the launch point. This is the final test of the Fall Test Plan.
Element(s)	Flying Hand (Full System)
Location	RIC Drone Cage
Equipment	Full Flying Hand platform (manipulator, camera, IBVS stack) Leader-arm teleoperation station Ground Control Station / laptop Mock industrial asset/panel with multiple marked target points Radio transmitter
Personnel	Weerachai / Tanaya / Shubham / Chenyang / Shunxuan

Procedure

1. Pilot performs pre-flight checks and manually pilots the UAV to a stable hover position near the target panel (Area of Interest).
2. With the UAV holding position, the system autonomously detects and sequentially contacts multiple marked target points on the panel using the IBVS-guided manipulator pipeline, holding the target contact force at each point.
3. Operator switches the manipulator to teleoperation mode via the leader arm.
4. Operator teleoperates the manipulator to sequentially reach and contact additional marked target points on the panel.
5. Once both the autonomous and teleoperated manipulation phases are complete, the pilot manually flies the UAV back to the launch point and lands.

Verification Criteria

1. The manipulator autonomously contacts at least 3 target points on the panel, each within the designated positioning tolerance and holding 5 N ± 1 N contact force.
2. The mode switch from autonomous to teleoperated control is executed cleanly, without loss of contact-force control or unsafe motion.
3. The operator successfully teleoperates the manipulator to contact at least 2 additional target points via the leader arm, meeting the same force/positioning criteria.
4. No collisions, joint-limit violations, or safety failsafe triggers occur throughout the demonstration.
5. The UAV is safely manually flown back to the launch point and lands without incident.

Appendix A: Associated System Requirements

A.1 Mandatory Functional Requirements

ID	Description
M.F.1	The system shall sense the surrounding environment.
M.F.2	The system shall localize its own pose relative to the environment.
M.F.3	The system shall allow an operator to manually pilot the Flying Hand to an Area of Interest (AOI).
M.F.4	The system shall provide real-time visual feedback to the operator.
M.F.5	The system shall allow the operator to define a Point of Interest (POI) from the video feed.
M.F.6	The system shall autonomously plan arm motion to reach a selected POI.
M.F.7	The system shall manipulate the end-effector to establish contact with the POI.
M.F.8	The system shall maintain stable end-effector contact during NDT execution.
M.F.9	The system shall perform contact-based non-destructive testing.
M.F.10	The system shall store and relay NDT data to the ground station.
M.F.11	The system shall execute a fail-safe response upon loss of communication.

A.2 Mandatory Performance Requirements

ID	Metric
M.P.1	The system shall sense the environment within the range of 0.5–4 m from the Flying Hand.
M.P.2	The system shall localize its position with an error of at most 5 cm under nominal conditions.
M.P.3	The Flying Hand shall navigate at speeds up to 1 m/s during manual flight.
M.P.4	The system shall detect a POI from a distance of at least 0.6 m.
M.P.5	The system shall maintain end-effector positioning accuracy within ±50 cm during contact-based NDT.
M.P.6	The system shall maintain stable contact under wind disturbances up to 3 m/s.
M.P.7	The system shall complete at least 5 NDT measurements in a single flight.
M.P.8	The system shall relay data to the ground station with latency not exceeding 100 ms.
M.P.9	The system shall execute a fail-safe response within 1 s of communication loss.

A.3 Mandatory Non-Functional Requirements

ID	Description
M.N.1	The system shall be modular to allow rapid probe or end-effector replacement.
M.N.2	The total take-off mass shall not exceed 15 kg.
M.N.3	The system shall be operable by a trained operator with minimal setup time.
M.N.4	The system shall store NDT data in standard reusable formats.
M.N.5	The system shall operate in temperatures from −5°C to 40°C and humidity up to 95%.

A.4 Desirable Functional Requirements

ID	Description
D.F.1	The system may employ deep learning to identify points of interest.
D.F.2	The system may adapt manipulation strategies based on surface characteristics.
D.F.3	The system may have autonomous capability in controlling Flying Hand to the area of interest instead of manual teleoperation.

A.5 Desirable Performance Requirements

ID	Metric
D.P.1	The system may perform more than 5 NDT measurements in a single flight.
D.P.2	The system may maintain contact stability under wind disturbances exceeding 3 m/s.