



CASE STUDY · AEROSPACE & DEFENSE

Unstructured Connector Manipulation & Insertion

One Control Model, Two Connector Families

Autonomous unstructured connector manipulation and mating for F100 Aerospace and Defense Prime RJ45 Ethernet and 15-pin D-sub.

97%

FZERO SHOT COMPLETION OF RJ45
INSERTION

93%

ZERO SHOT COMPLETION OF D-SUB
INSERTION

±1 mm

ALIGNMENT, 6-14 S CYCLE TIME

1 SUMMARY

A single control model picked, aligned, and mated two dissimilar connector families with zero per-connector programming and zero reconfiguration to switch between connector types. Our zero-shot completion accuracy in 6 to 14 seconds, with alignment held within ± 1 mm was 97% for the RJ45 ethernet cable and 93% in . Connectors were placed randomly within a defined tray area rather than fixed, and the robot located, grasped, and inserted them without operator intervention.

The result that matters commercially is not the success rate on two connectors. It is that one model covered both. Conventional control treats every new connector as a new programming task against a fixed frame of reference. Active inference treats it as a new set of priors over the same high-level behavior, which makes onboarding further geometries a tuning exercise rather than a rewrite.

2 PROBLEM

Connector mating in aerospace harness assembly is manual, repetitive and error prone, and it resists conventional automation for four compounding reasons.

- **Rigid control assumes a rigid world.** Classical control solves inverse kinematics against a fixed reference and replays stored positions, which depends on a highly structured, sensitively calibrated environment. If a component shifts slightly, the system stops for recalibration or the environment is adjusted back to match expectations.
- **Cables are deformable linear objects.** With effectively infinite degrees of freedom, a cable bends, twists, folds or coils under its own weight, so small perturbations invalidate planned motion. Published sim-to-real work on deformable objects reports ~77% success for well-scoped tasks, and lower on real hardware.
- **Reprogramming does not scale.** A harness bill of materials can carry hundreds of connector geometries, and per-connector scripting turns every variant into an engineering ticket.
- **Every harness behaves differently.** Stiffness, sheath friction and bundle structure vary from thin signal wire to semi-rigid power cable, and a controller tuned for one may buckle or jam on another.

3 REQUIREMENTS

ACCEPTANCE CRITERIA	TARGET
Task	Identify, pick, manipulate, align or re-align, and insert connectors in the correct orientation into the correct rack slot
Connectors	RJ45 Ethernet and PCD15M98S0T2s-1193.18 or similar 15-pin D-sub
Accuracy required	≥ 90% wire and slot identification; alignment within ≤ ±1 mm
Gentle handling	No damage to connectors, wire insulation or rack slots

4 APPROACH

System

A Universal Robots UR5e provides the reach and repeatability across tray, part and insertion targets, with a force-torque sensor built into the tool flange so the controller senses contact directly at the wrist. A Weiss Robotics WSG32-068 gripper holds connectors and presents them in a repeatable orientation. An Intel RealSense D405 depth camera gives a wide view of the tray during picking and a focused view of the mating area during alignment. Camera and robot frames share a calibrated reference so vision hands off cleanly to motion control.

Control

One active inference model spans both connector families. It adapts to the different handling each requires while following the same high-level approach, so switching connector type costs no reconfiguration or reprogramming. Vision brings the part into the alignment window; the wrist sensor takes over for fine alignment as contact is made.

Perception

Initial pipeline estimated 6D pose markerlessly: YOLO segmentation, K-means refinement to handle the connectors' uniform colour, deprojection to a partial point cloud, then multi-scale ICP against the CAD model. We utilized AprilTag fiducials, which gave consistent localisation for this task.

Force

The force layer is a fixed safety envelope, set once for the gripper and connector class and unchanged across parts and scenarios. Inside it, the controller adapts. Force and torque feed the control loop at 500 Hz. Multi-scale admittance control runs with directional selectivity: low sensitivity in free space to ignore disturbance, rising sensitivity as the connector nears the mating interface. Admittance is disabled along the insertion axis to maintain positive insertion force, while lateral compliance stays active in X-Y at a 3 N threshold with ±2 mm maximum correction. Above 10 N lateral force the controller runs an adaptive search at 0.25 mm pitch; above 15 N it backs off in 0.2 mm increments to protect pins and housings.

WHY THIS TRANSFERS : ADAPTIVE ONBOARDING INSTEAD OF REPROGRAMMING

Because behaviour lives in one adaptive model rather than in per-connector scripts, onboarding a new connector family is two small jobs rather than a programming project. The model learns from **less than 10 real insertions**, which is all it needs to refine its priors. A person supplies the rest: maximum force threshold, insertion location, and the other part-specific limits that should be set deliberately rather than discovered. The production platform targets onboarding a **new connector family in under one hour** of connector-specific tuning, reaching >90% first-pass success after that session.

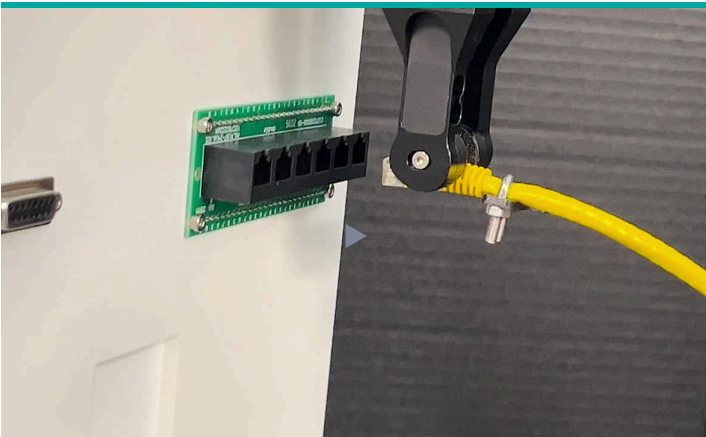
5 RESULTS

Demonstrated. Measured across randomised connector poses within the tray area:

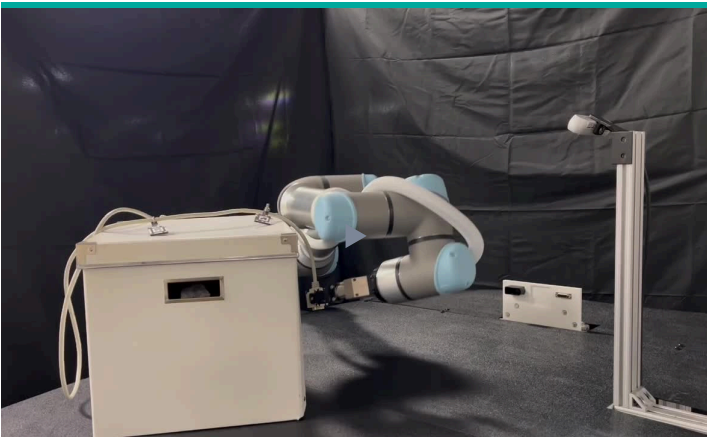
MEASURE	RJ45 ETHERNET	15-PIN D-SUB
First-pass insertion success	97%	93%
Cycle time (pick 2–4 s, align 2–4 s, insert 2–6 s)	5 to 11 s	6 to 14 s
Success where grasp stayed stable throughout motion	near 100%	near 100%

Failures were almost exclusively due to minor errors in localization or minor shifts of the connector within the robot fingertips. Success came down to two variables:

- Grasp quality: determined by fingertip material against the connector surface
- Grasp accuracy: determined by how well vision localized the part before the grasp.



RJ45 Ethernet: same model, no reconfiguration
Pick from random position to insertion



V15-pin D-sub: same model, no reconfiguration
Pick from random position to insertion

<div>≥ 93–97%</div> <div>First-pass success across randomised positions in an unstructured environment</div>	<div>6 –14 s</div> <div>Cycle time, RJ45 / D-sub</div>	<div>> 99%</div> <div>After automated pass to detect and retry</div>
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WHAT THIS MEANS FOR THE INDUSTRY AND OUR CUSTOMERS

<div>Onboarding replaces reprogramming.</div> <div>A harness bill of materials with hundreds of geometries stops being hundreds of engineering tickets and becomes an hour of tuning per family.</div>	<div>Fixturing budget drops.</div> <div>Connectors placed randomly in a tray, located by vision and finished by force, remove the precision jigs that conventional mating lines depend on.</div>	<div>Manual work becomes automatable.</div> <div>Wrist-level force at 500 Hz, adaptive search and back-off protect pins and housings, so fine-pitch connectors are in scope rather than reserved for hand assembly.</div>
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ABOUT
THOUGHTFORGE

ThoughtForge is a robot control system for both simple and complex tasks. Using our patented AI, ThoughtForge-powered robots easily adapts in real time to new parts, dynamic changes, and varying environments, planning motion and paths on-the-fly with unmatched accuracy and robustness.