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ENGINEERING **RESEARCH REPORT · Engineering research report**

Modular Quick-Change and Error-Proofing Methods for Multi-Model Mixed-Production Handling Tooling

Public-source research, engineering derivation, and verification methods for assisted handling and custom tooling in the automotive industry

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Research and Verification Methods · Not Product Certification or Evidence of Customer Acceptance

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> Research Boundary Standards, papers, and vendor data in the main text are used to support the methodological framework; example calculations contain assumptions. Project applications must be supplemented with real workpiece, tooling, action curves, risk assessments and original test evidence.

> Research boundary — Document type: public-source research and engineering design methods. The interface, coding, and verification examples in this report do not indicate that any specific quick-change product or production line has passed safety certification or cycle-time acceptance.

00 Executive Summary

This report proposes a four-layer architecture: common load-bearing base, standardized interface, model-specific functional modules, and docking stations with recipe control.

Research on reconfigurable automotive assembly systems emphasizes responding to changes in products and volume through module selection, system integration, and reconfiguration strategies [1]. ISO 11593:2022 provides a terminology framework for automatic end-effector exchange systems [2]. Mechanical flanges may reference the dimensions and marking requirements of ISO 9409-1:2004, but that standard expressly does not specify other requirements or the load capacity of a quick-change device [3]. Use of a standardized flange therefore does not by itself establish the safety, stiffness, or load capacity of the quick-change system.

Core conclusion

- The modularity boundary should be determined by part families, functional differences, load envelopes and maintenance strategies, and should not be aimed at "the more modules, the more advanced".
- Quick-change interfaces must simultaneously verify positioning, locking, load, stiffness, media transfer, lock/unlock feedback and tool presence; a single "locked" signal is not sufficient to cover all errors.
- Error-proofing shall verify consistency among five items: planned vehicle model, actual workpiece, installed tool, control recipe, and storage location. It shall remain conservative under sensor faults and manual bypass attempts.
- Unlocking must be subject to the conditions that the tool has entered safely, the load has been removed, the movement has stopped, and the permissions are valid.
- The cycle time evaluation should simultaneously calculate the single-piece cycle time, changeover time, first-piece confirmation and abnormal recovery, and should not obtain a superficial quick change speed by canceling necessary confirmations.

01 Problem definition and modular boundaries

The study covers handling tooling for automotive components, including mechanical grippers, suction-cup beams, support arms, internal supports, and locating modules for workpieces such as door panels, headliners, instrument panels, seats, battery packs, and glass. The carrier may be a Pneumatic Industrial Manipulator, industrial robot, or purpose-built handling machine. This report focuses on end modules and the changeover process; it excludes production-sequence optimization for the complete mixed-model line.

Defining the part family is the first step in modular design. For each vehicle model/part, record mass, center of gravity, inertia, permitted contact zones, prohibited/restricted zones, pickup and placement orientations, path envelope, cycle time, quality requirements, and abnormal states. Then cluster parts by common load-bearing principle, similar interface, and shared verification envelope. If parts require fundamentally different load paths or safety functions, use different modules or separate equipment rather than forcing commonality.

Architecture layer	Main responsibilities	design freeze
Shared carrying body	Provides rated load, degrees of freedom, balance and base control	Maximum load/moment, interface location, envelope
Primary Quick-Change Interface	Repeatable positioning, locking, media and signal transmission	Mechanical datum, locking principle, capacity, and service life
Model-Specific Functional Module	Contact, locate, and clamp or grip the specific workpiece by suction	Contact area, clamping force, module ID, restricted area
storage station	Supports offline tools and allows safe coupling/decoupling	Guidance, presence detection, docking, cleanliness, and collision prevention
Recipes and Traceability	Vehicle model identification, tool authorization, parameters and records	Version, permissions, verification, changes and logs

02 Mechanical and load design of quick-change interface

The quick-change interface shall separate the locating and locking functions: locating elements establish the repeatable datum, while locking elements provide preload and carry load. Fastening screws shall not be assumed to provide precision location. Verify the interface for six-component loads, combined moments, impact, fatigue, and stiffness rather than only rated payload mass.

$$U = |F_x|/F_{x,allow} + |F_y|/F_{y,allow} + |F_z|/F_{z,allow} + |M_x|/M_{x,allow} + |M_y|/M_{y,allow} + |M_z|/M_{z,allow}$$

The primary interface connects the manipulator flange to the interchangeable functional module.

02.1 Positioning, Locking, and Loss-of-Pressure State

Public quick-change product information generally provides locking/unlocking position feedback, tool presence or locking preparation signals, and adopts mechanical self-maintaining or fail-safe locking structures [4][5]. These product features can only be used as an architectural reference, and actual integration still needs to be verified on a project basis. After losing the locking air pressure, even if the mechanical structure can prevent the tool from falling off, the positioning accuracy may no longer be maintained, so the system should usually stop movement and re-confirm locking after recovery rather than continue production [4].

Mechanical properties	design issues	Verification method

Mechanical properties	design issues	Verification method
Repeatable Positioning	Is TCP/baseline drift acceptable after multiple changeovers?	Coordinate measurement after repeated changeover cycles
Locking ability	Retention after worst-case eccentric loading, emergency stop, and service-life cycling	Static load, dynamic, durability and pressure loss tests
Resistant to misinstallation	Can the wrong direction/wrong module be physically inserted?	Reverse, offset and similar module trial assembly
Docking Support	Whether the tool is fully supported by the station before unlocking	Docking sensing, load removal, and unlocking test
contamination tolerance	Do welding slag, oil, and dust affect positioning/connection?	Cycle testing under specified contamination conditions

03 Media, signal and tool identification

pneumatic circuit, vacuum, power, communication and cooling media require standardized connections, but standardization does not mean that all modules open all media. Unused ports should be blocked or explicitly disabled in the recipe to avoid misconnections and leaks. Electrical contacts should be evaluated for coupling sequence, live insertion and removal, arc flash, pin damage, and contamination; pneumatic/vacuum interfaces should be evaluated for residual pressure, cross-connection, and seal life.

Tool identification can use mechanical coding, independent discrete codes, RFID, memory chips or network device identification. High-risk scenarios should not rely solely on a text label that can be easily copied. If n-bit discrete codes are used, the Hamming distance between legal codes must be at least 2 to detect any single-bit error; if you want to correct single-bit errors at the same time, the minimum distance must reach 3. The engineering should also include tool presence, locking and physical interface error-proofing.

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Run_Enable = Locked ∧ Tool_Present ∧ ID_Valid ∧ (Tool_ID = Target_ID) ∧ Utilities_OK ∧ Recipe_Valid
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A valid recipe not only means "number matching", but also includes version, approval status, integrity check and applicable workpiece version. When the network is unavailable or there is an identity conflict, the system should refuse to enter automatic/production actions and give diagnostic information.

04 error-proofing chain: from production planning to action permission

Error-proofing shall cover the entire changeover chain, not merely add a sensor to the quick changer. Compare five items for consistency: target vehicle model/part, actual on-site workpiece, tool retrieved from its storage location, tool detected at the quick-change interface, and recipe loaded by the control system. If any item is inconsistent, the system shall remain in a recoverable state.

04.1 error-proofing level

1. Physical error-proofing: Asymmetrical pins, keys, contours and connectors prevent the wrong module from being fully inserted.
2. Status error-proofing: Tool presence, lock preparation, locking, unlocking, media pressure/vacuum and station status can be measured.
3. Identity error-proofing: Module ID is consistent with the target model, workpiece identification and formula.
4. Unlocking is prohibited until the tool is docked, unloaded, and stationary; departure from the station is prohibited until locking is complete.
5. Administrative error-proofing: unique module identification, storage location, inspection, post-maintenance reverification, and software-version approval.

error scenario	How should the system block	evidence
Incorrect tool presented to the primary interface	Physical keys or identities are inconsistent	Misinstallation test, ID log
Tool unlocked before it is fully docked	Docking/load-removal interlock	Semi-inbound fault injection
Lock feedback false	Lock/unlock complementarity, tool presence, pressure/position rationality	Signal stuck test
Correct tool loads wrong recipe	Three-party verification of tool ID, target workpiece and recipe version	Recipe mismatch testing
Similar tools misplaced	Station ID and tool ID verification, physical outline	Misplaced storage test
Tool size drift after repair	Maintenance status lock, measuring tool or calibration confirmation	Maintenance release record

05 Changeover State Machine and Safety Control

The recommended state machine includes: production complete, load cleared, return to the safe changeover position, tool docked, load-removal confirmation, unlock permission, unlock, primary side withdrawal, target-station confirmation, approach to the target tool, preparation for locking, lock, lock verification, tool-ID/media/recipe verification, unloaded functional check, first-piece confirmation, and production release.

Unlocking permissions is a critical security feature. At least the following conditions should be met: the tool is in the correct storage station, the tool is fully supported by the station, the end load is zero or within the specified range, the carrier movement stops, it is in the allowed attitude, the personnel/area conditions are met, and the authorized command is valid. Any lock sensing discrepancy or communication interruption should stop the changeover and prohibit departure.

ISO 10218-2:2025 covers the integration, debugging, operation, maintenance and decommissioning of industrial robot applications and units [6]; as an integrated component, the end quick change should be included in the risk assessment of the entire machine. If used on Pneumatic Industrial Manipulator or other non-robotic carriers, the same system boundary ideas can also be used, but must be combined with applicable regulations and equipment standards.

06 Optimization of cycle time, availability rate and number of modules

Changeover performance should be evaluated using total lost time:

```
T_change,total = T_clear + T_return + T_dock + T_unlock + T_pick + T_lock + T_verify +
T_recipe + T_first-piece
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Only counting "locking action time" will underestimate the actual changeover loss. Too few modules will increase the risk of complex adjustments and misconfiguration, while too many modules will increase the burden of investment, storage and maintenance. Multi-objective trade-offs should be made based on vehicle model mix, changeover frequency, cycle time, reliability, end weight and maintenance inventory.

06.1 Example decision matrix

Plan	end weight	Changeover time	error-proofing complexity	Suitable Conditions
Single adjustable tooling	high or medium	Low	It is difficult to adjust the position error-proofing	Small parts differences and frequent model changes
Shared body + quick change module	in	Medium/Low	Interface and identity error-proofing clear	Functions are modularizable; many vehicle models

Plan	end weight	Changeover time	error-proofing complexity	Suitable Conditions
Multiple sets of complete tooling	low/medium	Medium	The main tool selection is error-proofing	Big difference, high value of single module
Standalone device	Optimize by workstation	No mixed-line changeover	System boundaries are clearest	Loads/risks/paths vary greatly

The decision shall also consider recovery time after a changeover fault and first-pass yield. A configuration with a nominally fast changeover but frequent remating, recalibration, or manual alarm bypass may have lower overall availability.

07 Verification Matrix and FMEA

Verification project	Test conditions	record	Acceptance Logic
Repeatable Positioning	Multiple changes of equipment, temperature and life nodes	TCP/benchmark deviation	Process tolerances are met and trends are stable
Load Retention by the Lock	Maximum six components and emergency stop	Displacement, lock state, structural strain	No unlocking, no exceeding structural limits
Loss of pressure / power	After locking and while in motion	Tool displacement, control status	Tool remains attached; motion stops safely and recovery is possible
Half lock/foreign object	Specify clearance and contamination	lock/unlock/presence signal	No off-site or production allowed
Wrong tools/wrong recipes	All invalid combinations	ID, interlock, alarm	All were rejected with clear prompts
Media connection	Maximum flow, vacuum, communication load	Leakage, pressure drop, messages, and temperature rise	Meet functionality and troubleshooting
Retest after durability	Representative changeover cycle	Positioning, locking force, sealing, contacts	Can be monitored before reaching the maintenance boundary
Safe Recovery	Network disconnection, lag, station damage	Steps, permissions, time	No dangerous bypass, status traceable

failure mode	Consequences	Prevention/Detection	Verify
Locking-mechanism wear	Tool gap or fall off	Life management, locking feedback, periodic measurement	Durability and load bearing retest
Tools are unlocked before entering the site	Tool drop	Station interlocking, load shedding, permissions	Semi-inbound unlock test
ID misidentification	Incorrect recipe or workpiece	Diversity identification, legal code checking	Broken wire/short circuit/conflict injection
Connector not fully connected	Air pressure/vacuum/signal abnormality	Media health check and locking stroke	Incomplete plug test
Storage station deformation	Positioning deviation and stuck	Station inspection, replaceable guide, protection	Post-collision inspection and recovery drill
Software version drift	Parameters do not match tool	Version signing, approval and rollback	Old version/broken recipe testing

Fault injection shall cover at least: lock/unlock sensors stuck ON or OFF, an incorrect tool-presence signal, a single-bit ID error, communication interruption, reduced locking pressure, a false docking signal, inadvertent triggering of the release command, and an incorrect storage location. The system shall not use manual confirmation of a failed sensor as a routine production mode.

08 Implementation route and conclusion

Implementation stages are: freeze part-family and process data; review functional decomposition and module boundaries; define interface loads and media standards; design error-proofing and the state machine; verify the prototype on a bench; verify all vehicle-model/tool/recipe combinations; verify on-site cycle time and abnormal recovery; and manage mass-production maintenance and change. Deliverables shall include the interface control document (ICD), tool-ID table, docking-station drawing, six-component load table, recipe versions, fault-state table, verification records, and spare-parts/maintenance plan.

The value of multi-model mixed-production tooling is not that one interface can accept many tools, but that every valid combination is identifiable, lockable, verifiable, and maintainable, while every invalid combination is blocked before hazardous motion. Modularity shall reduce propagation of system complexity rather than transfer unbounded complexity from the mechanical design to software recipes. This report provides a basis for design and verification methods; it is not a selection guarantee for a specific quick changer, complete-machine safety certification, or a customer cycle-time acceptance report.

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