

Supplementary Table S2. Study-level evidence characterisation and indicative maturity mapping

Optimising Automotive Wiring Harness Production Through Collaborative Robotics, Artificial Intelligence, and Digital Twins: A Structured Narrative Review

Ratings are conservative author assessments using the operational criteria defined in Table 4 of the revised manuscript. TRL values characterise the reported validation maturity of the empirical enabling work, not the importance of the study and not the maturity of the unresolved research gap. Review articles, normative and regulatory sources, and the three contextual references [18,72,80] are not assigned TRLs (see Supplementary Table S1, Part B). “NR” denotes not rated as a technology-validation study.

Ref.	Validation environment	Evidence level	Harness / automotive hardware	Experimental scale / comparator	Indicative TRL	Key reported outcome	Interpretation / limitation
[7]	Laboratory dataset; real harness RGB-D images	L1	Yes—real harness RGB-D images	Dataset scale/comparator not extracted (not required for TRL assignment)	3	Branch classification; RGB-D fusion evaluated	Algorithm-level evidence; no physical assembly task.
[8]	Physical centre-console connector-mating experiments	L2	Yes—automotive connector hardware	Physical connector experiments; comparator not extracted (not required for TRL assignment)	4	Robust model/AI-based mating with force/visuotactile input	Physical automotive connector task, laboratory validation.
[9]	Physical dual-robot assembly test	L1–L2	Yes—real wire harness	Dual-robot physical test; comparator not extracted (not required for TRL assignment)	4	3-D harness profile reconstruction and feasible grasp support	Real harness used in a practical robotic assembly test.
[10]	Synthetic point clouds + limited real data	L1	Partial—real harness data used in evaluation	Synthetic-data training compared with limited real-data training	3	Harness segmentation using synthetic-data-supported learning	Dataset/algorithm validation; no integrated physical task.
[11]	Synthetic RGB + small real dataset	L1	Partial—real harness images used in evaluation	Synthetic + small-real training compared with real-data training	3	Component detection with reduced real-data requirement	Algorithm validation; no integrated physical task.
[13]	Laboratory HRC/DT framework	L1–L2	No—generic HRC/DT	Laboratory framework; scale/comparator not extracted (not required for TRL assignment)	4	DT-supported action recognition and safety response	Implemented generic HRC framework; not harness-specific.
[29]	Laboratory user study; 10 participants	L3	No—generic HRC	10 participants; comparison condition not extracted (not required for TRL assignment)	4	Reduced joint overload during cobot-assisted power-tool task	Physical HRC with human participants; generic task.
[31]	Automotive-type HRC use case; experimental trials	L3	Automotive HRC use case; not harness-specific	Experimental trials; sample size/comparator not extracted (not required for TRL assignment)	4	VR + wearable sensing for real-time ergonomic evaluation	Prototype validation for pre-deployment assessment.
[35]	Industrial supplier case; physical harness workstation	L2–L3	Yes—automotive harness workstation	Manual vs collaborative taping; 40 s vs 35 s per harness	6	35 s/harness vs 40 s manual; RULA improvement; payback <1.5 years	Integrated harness workstation in an industrially relevant setting; sustained series production not reported.
[36]	Prototype harness board; emulated cable-tie task	L3	Yes—harness board/cable-tie task	Manual-risk baseline vs assisted concept: RULA 7 to 4; JSI 12 to 4.5	3	RULA 7 to 4; JSI 12 to 4.5	Physical concept but dedicated tie-placement end effector/cycle-time validation incomplete.
[37]	Harness-specific analytical task-allocation study	L2	Harness-specific analytical model; no physical cell	Analytical case; no physical experimental scale reported	3	Human/robot task-allocation specification	Method applied to harness assembly; integrated physical cell not established.
[38]	System-level simulation across harness/cobot configurations	L4 (simulated)	Yes—harness scenarios in simulation	Multiple simulated cobot/harness configurations; scenario comparison	3	Cycle-time improvement 12.30–22.27%; investment/ROI scenarios	System evidence is simulation-based, not post-deployment production evidence.

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[39]	Laboratory + industrially relevant automotive final assembly	L2–L3	Yes—automotive final assembly	Two-phase physical validation; comparator details not extracted	6	Reduced local physical discomfort; maintained quality; higher mental demand/time	Two-phase physical validation reported across TRL 4–6.
[40]	Harness-specific optimisation-oriented HRC study	L2	Harness-specific analytical study	Analytical/optimisation study; no physical experimental scale reported	3	Ergonomic/process/component criteria for allocation	Relevant-environment deployment not established.
[41]	Manufacturing-company case; simulation-linked DT	L2–L4	No—generic HRC/DT	Industrial case; scale/comparator not extracted (not required for TRL assignment)	4	DT framework for HRC design/build/control	Industrial case supports framework; sustained closed-loop production not established.
[42]	DT-based model + laboratory collaborative-workplace experiment	L2	No—generic HRC	Laboratory parameter-variation study	4	DT-based parameter changes evaluated via operation time	Physical laboratory HRC experiment; generic assembly.
[43]	Computational/simulation HRC validation	L2	No—generic HRC	Computational/simulation study; no physical sample	3	RL task allocation for assembly	No harness-specific physical-cell validation.
[44]	Computational HRC validation	L2	No—generic HRC	Computational study; no physical sample	3	RLHF task allocation incorporating human preference	Production-relevant physical validation not established.
[45]	Smart-factory computational/simulation setting	L4 (simulated)	No—generic smart-factory scheduling	Computational/simulation study; no physical sample	3	Multi-agent RL online scheduling	System-level scheduling evidence is computational and not harness-specific.
[46]	Physical aerospace wire-harness assembly task	L2	Analogous—aerospace wire harness	Physical harnessing task; sample size/comparator not extracted (not required for TRL assignment)	4	LLM-agent tool use and task execution validated	Physical analogous harness task; automotive production deployment not shown.
[47]	Physical automotive car-door connector trials; 60 insertions	L2	Yes—automotive car-door connector	60 connector insertions; no separate baseline reported	4	76.7% success; tolerates positional uncertainty up to 15 mm	Real automotive hardware; laboratory/prototype validation.
[48]	Synthetic-trained perception with experimental evaluation	L1	No—generic DLO perception	Algorithm evaluation; dataset scale not extracted (not required for TRL assignment)	3	FASTDLO real-time instance segmentation (>20 fps)	Perception evidence only; no physical harness operation by itself.
[52]	Stereo-camera laboratory configurations	L1	Yes—branched wire-harness configurations	Laboratory configurations; number not extracted (not required for TRL assignment)	3	Topology matching for branched DLOs/wire harnesses	Harness-specific perception; no integrated manipulation task.
[53]	Synthetic + annotated real harness data	L1	Yes—real harness data included	Synthetic + annotated real data; dataset scale not extracted (not required for TRL assignment)	3	Topology prediction; mAP@50–95 = 89.8%	Algorithm-level validation.
[54]	Image-based laboratory benchmark	L1	Yes—harness connectors/clips/branch points	Benchmark study; dataset scale not extracted (not required for TRL assignment)	3	Feature segmentation of connectors/clips/branch points	Perception benchmark; no integrated physical task.
[55]	Physical cable/fixtures experiments	L2	No—generic cable/DLO	Physical experiments; scale/comparator not extracted (not required for TRL assignment)	4	Force/torque-regulated cable manipulation	Physical generic cable task; not automotive harness-specific.
[56]	Simulation + real robot experiments	L2	No—generic DLO	Simulation + real-robot experiments; scale not extracted (not required for TRL assignment)	4	Model-based flexible-object shape manipulation	Physical generic DLO validation.
[57]	Physical cable-plugging experiment	L2	No—generic cable	Physical cable-plugging experiment; scale/comparator not reported	4	Visual curvature feedback; task execution demonstrated	Physical generic cable task.

Ref.	Validation environment	Evidence level	Harness / automotive hardware	Experimental scale / comparator	Indicative TRL	Key reported outcome	Interpretation / limitation
[58]	Physical rope/DLO experiments	L2	No—generic DLO	Multiple DLO/rope types; exact scale not extracted (not required for TRL assignment)	4	Online parameter estimation during shape control	Adaptive physical DLO validation; not a complete harness.
[59]	Physical robot; 50 random harness bin configurations	L2	Yes—wire harness	50 random bin configurations	4	82% overall successful harness grasps	Real harness bin-picking prototype; laboratory task.
[60]	Physical dual-arm experiments; two harness types	L2	Yes—wire harness	Two harness types; 91.2% average success	4	91.2% average entangled-harness picking success	Real-world laboratory experiment; no sustained line validation.
[61]	Harness-localisation case study	L1–L2	Yes—wire-harness localisation	Case study; scale/comparator not extracted (not required for TRL assignment)	3	Shape estimation + component localisation concept	Supports subsequent manipulation; integrated installation remains limited.
[62]	Simulation/model validation; preprint	L1	No—generic branched-DLO model	Model/simulation study; no physical comparator	3	Real-time differentiable branched-DLO model	Preliminary evidence; not used independently to raise maturity.
[63]	Laboratory cable-routing experiments	L2	Analogous—generic cable routing	Laboratory routing experiments; scale not extracted (not required for TRL assignment)	4	Hierarchical imitation learning for multistage routing	Physical analogous cable task; not automotive harness-specific.
[64]	Laboratory DLO routing manipulation	L2	No—generic DLO routing	Laboratory routing experiments; scale not extracted (not required for TRL assignment)	4	RL + diffusion policy for contact-rich routing	Physical generic DLO evidence.
[65]	Laboratory manipulation/tracking experiments	L1–L2	No—generic DLO	Laboratory tracking/manipulation experiments; scale not extracted (not required for TRL assignment)	4	Multiview model-based tracking during DLO manipulation	Physical generic DLO evidence.
[69]	Industrial collaborative-robot case; implemented DT safety framework	L2–L4	No—generic industrial HRC case	Industrial case study; no harness-specific comparator	5	Formal safety-controller evidence and virtual safety assessment	Relevant industrial case; harness-specific validation absent.
[70]	Physical HRC assembly demonstrator	L1–L2	No—generic HRC demonstrator	Physical demonstrator; scale not extracted (not required for TRL assignment)	4	Vision-based human localisation/collision warning in DT	Generic HRC demonstrator.
[71]	Two physical robot experiments	L2	No—generic manufacturing DT/HRC	Two physical experimental studies	4	AR-assisted DT with human-in-the-loop and multi-robot synchronisation	Implemented generic manufacturing DT/HRC prototype.
[74]	Conceptual/modular HDT–RDT framework	—	No—generic HDT/RDT framework	Conceptual framework; no empirical scale	NR	Framework for shared task-level HDT/RDT collaboration	No implemented technology validation used for TRL assignment.
[75]	Cyber-physical model-factory experiments	L2	No—generic model-factory DT	Model-factory experiments; scale not extracted (not required for TRL assignment)	4	Intelligent DT for self-improving situation awareness	Implemented generic HRC/DT experiment.
[77]	Collective case study; three automotive manufacturers	L3 / case-study	Automotive manufacturing cases; not harness-specific	Collective case study involving three automotive manufacturers	NR	Four ergonomic-DT maturity models identified	Empirical taxonomy; no single implemented HDT technology validated.
[78]	Discrete-event simulation with automotive case data	L4 (simulate d)	Yes—wire-harness line simulation	Discrete-event simulation scenarios; no physical implementation	3	Wire-harness production-line design scenarios	Harness-specific system simulation; no physical implementation.
[79]	Simulation/mathematical model using operating-line data	L4 (simulate d)	Yes—engine-harness line data	Operating-line data; baseline/redesign comparison in simulation	3	Projected logistics/output improvement	No post-implementation validation; investment/OPEX/payback not reported.

Ref.	Validation environment	Evidence level	Harness / automotive hardware	Experimental scale / comparator	Indicative TRL	Key reported outcome	Interpretation / limitation
[81]	Physical dual-arm experiments; two realistic harness scenarios	L2	Yes—automotive wire harness	Two realistic assembly scenarios; 55% and 73% success	4	55% and 73% success in complex multi-branch assembly	Real harness task; sustained production-representative operation not established.
[92]	Methodological manufacturing small-data study	L1	No—generic manufacturing method	Methodological study; harness-specific comparator not reported	3	Data-augmentation/adaptation methods	Not harness-specific; no closed-loop changeover validation.

Evidence-level key. L1, algorithm/component; L2, physical robotic or human–robot task; L3, operator/human outcomes; L4, workstation/cell/line system outcomes. “L4 (simulated)” denotes system-level metrics obtained from simulation rather than sustained physical production.

Interpretation note. Where a publication did not report enough information to verify a higher operational criterion, the lower level was retained. A high task-performance metric does not, by itself, increase the TRL above the demonstrated validation environment. “Not extracted” means that the item was not required for the TRL assignment and was therefore not relied upon. For Figure 3 of the manuscript, entries marked “Yes”, “Partial”, or “Harness-specific” in the hardware column are counted as automotive harness-specific; all other rated entries are counted as generic or analogous, and the two entries marked “NR” are excluded.