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Systematization of Approaches to Transferring Integration and Calibration Procedures for Electro-Optical Systems from Prototype Development to Serial Production

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Abstract

Electro-optical and laser systems reach their specified performance only after assembly, alignment, and calibration, and the knowledge behind these operations accumulates in the prototype laboratory long before serial production begins. Drawings and specifications travel to the factory with the product, while the integration know-how stays with developers and integrators, leading to rework, unit failures, long test and calibration cycles, and a lasting dependence of production on the development team. This review systematizes approaches to transferring integration and calibration procedures from prototype development to serial production. An integrative review of recent research on optical packaging, alignment automation, production ramp-up, tacit knowledge transfer, work instructions, design for assembly, and multistage inspection supported a classification built on four criteria: the lifecycle stage at which transfer begins, the carrier of integration knowledge, the division of labor, and the control strategy during calibration. The analysis yields five classes, namely documentation handover, expert accompaniment, procedure codification, design anticipation, and equipment embedding, together with a mechanism that decouples mechanical assembly from integration. Firsthand integration practice illustrates the codification and design anticipation classes, as well as the decoupling mechanism. Transfer can become more predictable once integration requirements enter design reviews and calibration procedures include staged checkpoints that localize deviations, thereby opening a path toward shorter test and calibration cycles.

Keywords: *Electro-Optical Systems, Design Transfer, Production Ramp-Up, Optical Alignment, Calibration Procedure, Tacit Knowledge, Design For Assembly*

INTRODUCTION

Electro-optical and laser systems integrate optics, precision mechanics, electronics, and control software into a single assembly whose performance depends on the relative positions of its elements. Packaging and assembly have become recognized barriers to scaling optoelectronic technologies, as these steps account for a large share of product cost and limit throughput (Ranno et al., 2022). The alignment of laser optics remains skilled and time-consuming work, and automated or learning-based methods still handle a small part of it (Rakhmatulin et al., 2024).

The prototype stage yields two results: a working unit and the knowledge of how to build it. Developers and integrators assemble the first systems by hand, form hypotheses about the causes of deviations, take measurements, and test corrective actions together with optical engineers and physicists. Each iteration adds to this knowledge, which includes the order of adjustments, the intermediate readings that signal convergence, and the symptoms that indicate a faulty element. Fifteen years of first-hand work on the assembly, alignment, calibration, and testing of prototype electro-optical and laser systems reveal a recurring pattern: this knowledge stays with the people who built the prototype and leaves no trace in drawings. The factory then receives a complete design package and lacks the integration knowledge that made the prototype work.

Production ramp-up is the phase in which this gap becomes costly. Decisions during ramp-up rest on limited reliable data, and the methods addressing this shortage remain scattered (Haller et al., 2026). Research on safety-critical domains treats the transfer of tacit knowledge as a deliberate process with dedicated mechanisms (Eklund & Osvalder, 2026). Structured on-the-job training, mentoring, and job rotation

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support such transfer (Al-Zoubi et al., 2025), yet each of these channels is contingent on the availability of experts.

The relevant literature is distributed across separate fields, which include photonic packaging, alignment automation, ramp-up management, knowledge management, design for assembly, and multistage inspection. Each field covers a part of the transfer problem. In the reviewed literature, no systematization of approaches to transferring integration and calibration procedures for electro-optical systems from prototype development to serial production is seen from the position of the system integrator.

The aim of this review is to systematize such approaches. The objectives are, first, to identify approaches described in recent research, second, to define classification criteria, third, to classify and compare the approaches, fourth, to position the practices developed during a first-hand transfer of a laser system within the classification, and fifth, to derive recommendations that connect procedure transfer with shorter test and calibration cycles.

MATERIALS AND METHODS

The study follows the design of an integrative review, which suits a problem whose literature spans optical engineering, manufacturing management, human factors, and knowledge management. The sources differ in method and type of evidence and cannot be pooled in a quantitative synthesis, so the review merges them into a single classification and uses first-hand cases to illustrate how selected classes operate in practice.

The search covered Scopus, Web of Science, Crossref, Google Scholar, and publisher platforms. Search strings combined terms for the technical object, such as optical alignment and photonic packaging, with terms for the transfer process, such as production ramp-up, work instructions, tacit knowledge transfer, and multistage inspection. The time window spanned the years 2021 to 2026. Inclusion required a peer-reviewed publication with a registered DOI and a contribution to at least one element of procedure transfer, namely knowledge capture, delivery of knowledge to production staff, design-stage anticipation, in-process control, or automation of alignment. Trade publications, patents, and vendor materials were excluded, and eleven sources formed the analytical corpus.

The classification emerged through inductive coding. Each source received codes for the stage of transfer, the knowledge carrier, the roles involved, and the form of quality control, and recurring combinations of codes formed classes, which were refined until each class rested on at least one source, and the first-hand cases fit the classes without overlap. Individual sources then served as support for one or more classes or for the cross-cutting mechanism. The first-hand cases come from the transfer of a laser system to serial production and from earlier prototype integration work.

The method has three boundaries. The review relies on published sources and first-hand cases and involves no dedicated sample or experiment. The first-hand illustrations are generalized and omit system parameters, product names, and organizational identifiers. The quantitative observations drawn from first-hand practice are practitioner estimates without primary datasets.

RESULTS

Characteristics of the Corpus

The eleven sources fall into five groups. Three sources address optical assembly, covering the packaging bottleneck in integrated photonics (Ranno et al., 2022), the automation of laser optics alignment (Rakhmatulin et al., 2024), and the automated batching of optical elements for the selective assembly of camera lenses (Levin & Kachurin, 2021). One source reviews sixty-four studies on Industry 4.0 methods in production ramp-up (Haller et al., 2026). Three sources examine tacit knowledge, covering its transfer in safety-critical systems (Eklund & Osvalder, 2026), its capture into rules for shop-floor assistance (Hoerner et al., 2023), and its link with training, mentoring, and job rotation (Al-Zoubi et al., 2025). Two studies examine how instructions reach operators: through digitized information presentation in five industrial cases (Li et al., 2022) and through an experiment comparing paper and digital assembly instructions (Ivan et al., 2026). The last two sources contribute a framework that brings design for assembly into early product architecture (Monetti et al., 2025) and a sequential inspection procedure for multistage manufacturing (Moliner-Heredia et al., 2021). None of the three optical sources describes how integration knowledge reaches production staff, and the sources on knowledge transfer leave alignment and calibration outside their scope, so the classification has to connect technical and organizational findings.

Classification Criteria

Four criteria structure the classification. The first criterion is the lifecycle stage at which transfer begins: design, prototype integration, pilot batch, or serial production. The earlier the stage, the larger the share of transfer cost that moves from production rework to design effort. The second criterion is the carrier of integration knowledge, which can be drawings, people, procedures, design requirements, or equipment. The third criterion is the division of labor among developers, integrators, and assemblers. The fourth criterion is the control strategy during calibration, which ranges from a single acceptance test to staged checkpoints and automated in-process measurement. Recurring combinations of these values form five classes of transfer approaches, which Section 3.5 then evaluates by a separate set of practical criteria.

Classes of Transfer Approaches

Fig. 1 places the five classes on the product lifecycle. The letters A to E mark documentation handover, expert

accompaniment, procedure codification, design anticipation, and equipment embedding, and the solid green bars mark the classes that first-hand practice illustrates. Equipment embedding covers fixtures, automated alignment stations, and calibration software and rests on the literature alone.

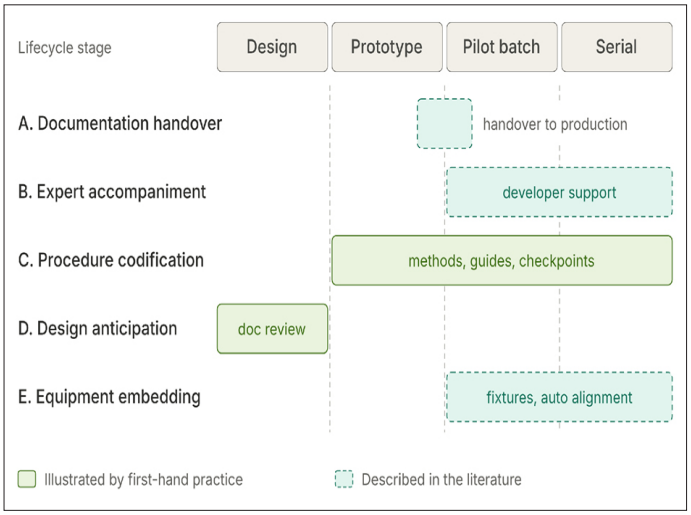


Fig. 1. Classes of approaches to transferring integration and calibration procedures across the product lifecycle

The first class is a documentation handover. Responsibility passes to production once, at the boundary between the prototype and the pilot batch, and its carrier is the design package. The package keeps receiving revisions through serial production, yet these revisions record design changes and leave the integration sequence aside. Integration knowledge remains implicit, and deviations surface at the final test, where their cause is hard to trace to a specific step. Ramp-up research describes this phase as one in which decisions are based on scarce, unstructured data (Haller et al., 2026). For electro-optical systems, the scarcity becomes more pronounced because the acceptance test measures the combined result of dozens of adjustments and reveals little about which of them failed.

The second class is expert accompaniment. Developers or prototype integrators follow the product into the pilot batch, resolve on-site deviations, and train production staff by working alongside them. Mentoring and structured on-the-job training act as recognized channels of tacit knowledge transfer (Al-Zoubi et al., 2025), and research on safety-critical systems links such transfer to guided practice (Eklund & Osvalder, 2026). The cost of this class lies in its scaling limits, since each additional line or shift raises the demand for developers who the next development project also needs.

The third class is procedure codification. Transfer begins during prototype integration, and its carrier is a set of documents for production specialists, which comprises an integration methodology, assembly guides, and calibration guides with checkpoints. Tacit expert knowledge can be elicited through interviews, observation, and protocol analysis, and converted into explicit rules, as in the 261 anomaly-resolution rule sets of one shop-floor assistance system (Hoerner et al., 2023). The form of delivery matters as much as the content. Information presentation adapted to operators' cognitive situation helps them cope with complex production (Li et al., 2022), and step-by-step digital instructions cut assembly time by about 45% and reduce errors from 56 to 9 compared with paper instructions (Ivan et al., 2026).

Direct transfer practice for a laser system belongs to this class. The integration methodology and the assembly and calibration guides carried the knowledge accumulated during development to the production floor, and the checkpoints built into the calibration procedure enabled detection of a deviation at the point of origin. The documentation reduced production's dependence on developers and lowered the number of breakdowns and failures; the same procedures were applied in subsequent projects.

The fourth class is design anticipation. Transfer begins before any hardware exists, and its carrier is a set of integration and calibration requirements checked during design reviews. Work on design for assembly identifies the barriers that keep assembly considerations out of architecture decisions and proposes guidance for the early design stage (Monetti et al., 2025). A first-hand documentation review during the initial design stage extended this logic to calibration access and revealed that the planned mechanical structure blocked access to an optical element requiring calibration. Detecting the conflict before parts were manufactured prevented rework of fabricated parts, the system structure, and the documentation.

The fifth class is equipment embedding. Transfer begins with the pilot batch and expands during serial production; its carrier is production equipment, including alignment fixtures, automated stations, test benches, and calibration software. Automation and machine learning can take over mirror positioning, beam triangulation, and the selection of control settings, and the setup of industrial laser systems remains a field where such methods are underused (Rakhmatulin et al., 2024). Automation also reaches the logistics of optical assembly, as in the sequential batching of optical elements for selective lens assembly (Levin & Kachurin, 2021). This class removes the largest share of human judgment from production, though it requires a stable design and an investment that grows with the degree of automation, so full automation pays off at high volumes and stage-wise automation at medium ones.

Decoupling of Mechanical Assembly from Integration

Alongside the five classes, the analysis identifies an organizational mechanism that cuts across them. In the initial arrangement, the integrator performed the mechanical assembly of each unit in the integration laboratory before alignment, calibration, and acceptance. Integrator time included work that required no integration knowledge, and faults found at acceptance restarted the sequence

and led to escalation toward the developers. This initial arrangement combined features of documentation handover and expert accompaniment. The first-hand transfer moved the mechanical assembly to an earlier stage and assigned it to an assembler working from an assembly guide, with an assembly check closing that stage. The integrator received the assembled unit and could begin alignment and verification simultaneously. According to a first-hand estimate, this change reduced integrator time per unit by about 30%. In parallel, the calibration procedure was divided into stages, each closed by a checkpoint, as part of the codified procedures of the third class. Fig. 2 contrasts the initial and the decoupled arrangements, including the document flow, the handover of the assembled unit, and the staged calibration.

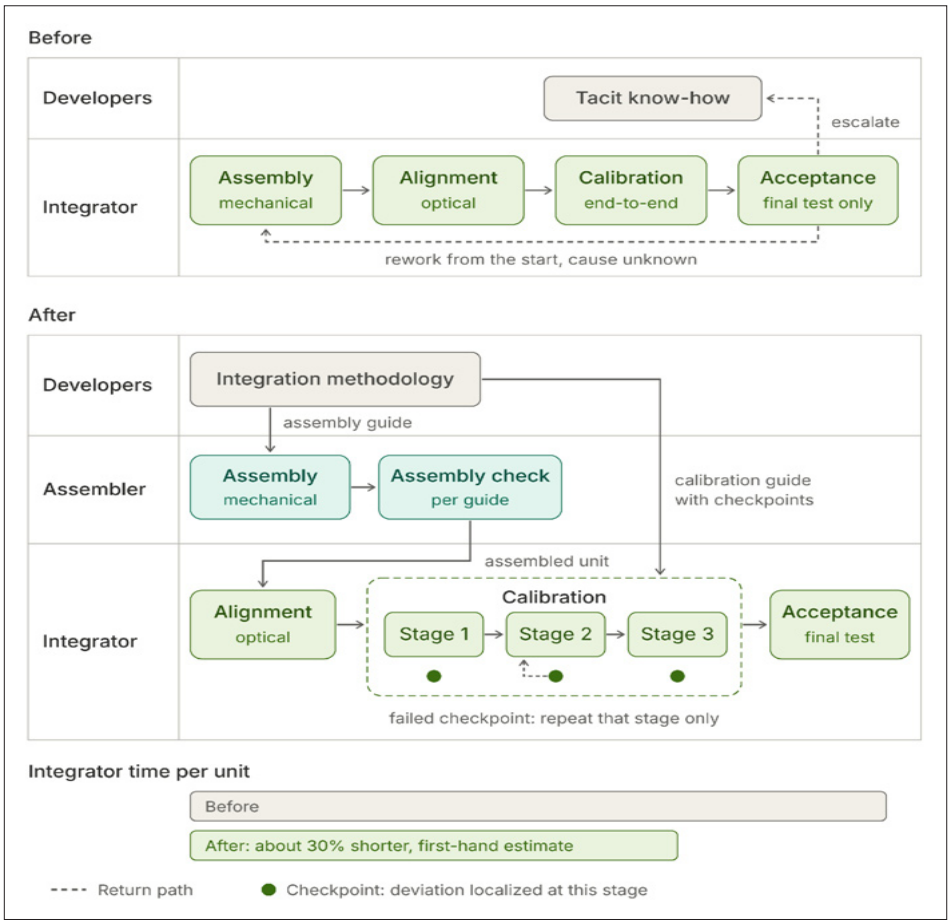


Fig. 2. Decoupling of mechanical assembly from integration with staged calibration checkpoints

The mechanism finds support in research on multistage manufacturing, where a sequential inspection procedure that selects inspection points based on expected information gain located faults with an average of 4.2 inspections, compared with 6 for a fixed scheme (Moliner-Heredia et al., 2021). Calibration checkpoints apply the same principle to integration. They confine the search for the cause of a deviation to a single stage and reduce the number of complete calibration runs per unit.

Comparative Assessment

Table 1 compares the five classes across criteria that matter for production, from the start of transfer to the production context in which each class fits. These evaluation criteria describe production consequences and differ from the classification criteria. The assessment is qualitative and combines the findings of the corpus with first-hand observations.

Table 1. Comparative assessment of approaches to transferring integration and calibration procedures

Criterion	Documentation handover	Expert accompaniment	Procedure codification	Design anticipation	Equipment embedding
Start of transfer	Handover after the prototype	Pilot batch	Prototype integration	Design	Pilot batch, expanding in series
Knowledge carrier	Drawings and specifications	Developers and integrators	Methodology, guides, checkpoints	Design requirements and reviews	Fixtures, stations, software
Dependence on developers	High, hidden	Highest	Low	Indirect, through simpler procedures	Low

Localization of deviations	Final test	Depends on the expert	Calibration stage	Design conflicts, before fabrication	Automated, by stage
Required staff qualification	High	Medium	Medium	Unaffected	Low
Implementation cost	Low	Medium, developer time	Medium	Low to medium	High
Effect on test and calibration cycle	Long, unstable	Limited by expert availability	Shorter, predictable	Fewer rework loops	Shortest
Typical fit	Simple, tolerant designs	Early pilot, low volume	Low to medium volume, complex alignment	New designs	Medium to high volume, stable design

No single class leads on every criterion. Procedure codification reduces dependence on developers at moderate cost; design anticipation reduces it through simpler procedures; and equipment embedding achieves the shortest cycles at the cost of high investment and a frozen design. Documentation handover is the cheapest class to introduce and the most expensive to operate, because its costs arrive later as rework and failures.

DISCUSSION

The classification places the integrator at the junction where development knowledge is either lost or converted into procedures. Developers know why the design looks the way it does, production staff know how to execute defined operations, and the integrator knows which adjustment to make when a measured value drifts. Procedure codification externalizes this tacit knowledge, and both the assistance system built from expert rules (Hoerner et al., 2023) and the review of transfer in safety-critical systems (Eklund & Osvalder, 2026) show that externalization depends on a dedicated elicitation effort. The direct practice summarized in Section 3.4 further states that the integrator holds this knowledge in a form that already follows the production sequence, thereby making the integrator the natural owner of transfer procedures.

The classes describe positions, and real transfer moves between them as the carrier of knowledge changes from people to documents and then to equipment. Expert accompaniment carries knowledge through the first units of the pilot batch, procedures drafted during prototype integration take over as these units verify them, and equipment embedding grows as serial volume and design stability justify fixtures and automated stations. Design anticipation is a precondition for this trajectory and lowers the cost of subsequent steps, since a design with calibration access leads to simpler procedures and fixtures. Ramp-up research identifies the shortage of dedicated data models as a barrier to Industry 4.0 solutions (Haller et al., 2026), and codified checkpoints provide the structured data on which such models can be built, because each produces a recorded value tied to a known stage of a known unit.

Long test and calibration cycles stem from late detection of deviations, repetition of entire procedures after a failure, and integrator time spent on operations that require no integration knowledge. Staged checkpoints address the first two causes, and the decoupling of assembly from integration addresses the third. Equipment embedding yields further gains when checkpoints serve as measurement points for a test station, so the stage structure that guides a human integrator can also guide an automated alignment loop (Rakhmatulin et al., 2024). The checkpoint structure of a codified procedure can then serve as the specification for fixtures and measurement modules, each automating one stage. This hybrid of procedure codification and equipment embedding allows stage-wise automation at volumes that would not justify an end-to-end automated line.

Organizations preparing a transfer can act on four points. First, design reviews can include checks of calibration access and assembly sequence. Second, the transfer package can consist of an integration methodology, assembly guides, and calibration guides prepared by the integrator who completed the prototype. Third, checkpoints can sit at the boundaries between calibration stages where a measurable quantity confirms convergence. Fourth, mechanical assembly can move to an earlier stage with its own closing check.

The review rests on eleven sources and first-hand cases and includes no dedicated sample or experiment. The first-hand illustrations exclude system parameters, product names, and organizational identifiers. The reported reductions in integrator time and failures are practitioner estimates, not based on primary datasets. Further research can test the classification on first-pass yield and integrator time per unit and can treat checkpoint placement as an optimization problem.

CONCLUSION

The transfer of an electro-optical system from prototype development to serial production depends on integration knowledge, which defines how the system is assembled, aligned, and calibrated. This review systematized approaches to the transfer of such knowledge using four criteria and identified five classes, complemented by decoupling mechanical assembly from integration. Procedure codification converts the integrator's tacit knowledge into documents that production specialists can use; design anticipation moves the start of transfer to the design stage; and decoupling frees

the integrator's time for operations that require integration knowledge. Staged checkpoints, early design checks, and a clear division of labor together form a basis for shorter test and calibration cycles and for test equipment that automates calibration stage by stage.

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