

eBots Transforms Flexible PCB Manufacturing Through Next-Generation Adaptive Robotics

How AI-Driven Dual-Arm Automation Delivers the Complete Technology Blueprint

Previous papers throughout this series defined what flexible circuit manufacturing needs, including adaptive substrate handling, dual-arm coordination that replicates human dexterity, three-dimensional vision that provides comprehensive quality verification, a level of precision that exceeds human capability by 3X-5X, AI-driven continuous improvement, and 15-minute changeovers that enable high-mix economics.

These requirements emerged directly from specific limitations that have prevented conventional automation from solving flexible circuit challenges. This includes single-arm systems that fail at two-handed tasks, fixed-force placement that damages delicate substrates, prohibitive changeover economics, two-dimensional vision that misses critical quality information, and inadequate precision that creates yield failures.

eBots was designed from the ground up to implement this complete blueprint. Every architectural decision was made to address the specific limitations that have been documented throughout this series. The result is comprehensive automation that solves flexible circuit challenges rather than partial solutions that leave critical gaps, thereby forcing continued manual operations.

The eBots Technology Architecture

Synchronized Dual-Arm Coordination

eBots features synchronized dual arms that provide six degrees of freedom per arm working together as an integrated system, to deliver twelve axes of coordinated control. This coordination enables operations that single-arm systems can't perform, regardless of programming sophistication.

One arm secures delicate flexible substrates with minimal holding force while the other performs precision component placement. The forces dynamically balance, with the holding arm providing exactly enough resistance to prevent substrate movement without overpowering the placement operation or causing substrate damage.

Dual-arm capabilities become decisive for reformable component installation. Installing flexible cables requires one arm feeding the cable through assembly paths while the other maintains proper orientation. Similarly, shield installation requires precise positioning with one arm while the other applies progressive snap-fit force while monitoring feedback through force sensors. These operations are precisely what are forcing manufacturers to retain manual processes despite their overwhelming desire for comprehensive automation. eBots completely eliminates this compromise.

Adaptive Force Control

eBots employs closed-loop force feedback that senses substrate characteristics in real-time and dynamically adjusts placement pressure. Force sensors measure applied force with resolution of 10 to 50 mN at millisecond response times, which enables adjustments to be made before excessive force causes damage.

Control algorithms employ force signature analysis to distinguish proper component seating from substrate compression. Proper seating produces a characteristic profile as solder paste compresses and component leads make contact, while substrate compression produces an abnormal profile that triggers an immediate reduction in pressure. This real-time analysis maintains the narrow window between insufficient seating and substrate damage that manual processes and fixed-force automation both struggle to sustain.

Pre-placement substrate characterization maps surface topology using three-dimensional scanning, identifying actual positions and local stiffness variations. Then, environmental compensation automatically adjusts for temperature and humidity effects on substrate properties. This comprehensive adaptive capability handles ultra-thin substrates of 25 microns without tearing, accommodates rigid-flex combinations, and manages components from delicate 01005 passives to substantial connectors within a single integrated system.

Three-Dimensional Vision at 409 Frames Per Second

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and dynamic correction during placement rather than detecting problems later through after-the-fact inspection.

Vision resolution reaches sub-pixel accuracy with effective measurement capability in the five to ten micron range, enabling reliable identification of 0201 and 01005 components and detecting defects that are invisible to two-dimensional imaging, as well as human inspection.

Component height verification measures actual seating depth at multiple points to detect incomplete seating that creates electrical failures, in addition to compression that indicates substrate damage. Substrate topology mapping identifies actual surface positions prior to placement, with the placement program dynamically compensating for measured variations rather than assuming flatness.

Post-reflow solder joint analysis assesses defect categories that determine long-term reliability that two-dimensional inspection can't evaluate. These include fillet profiles, joint volumes, void presence, bridging between adjacent pads, and wetting quality.

Placement Precision: ± 22 Microns Sustained

eBots achieves placement accuracy of plus-or-minus twenty-two microns, which is 5X finer than human hair and 3X to 5X better than what even the most skilled human assemblers are capable of. It also delivers motion accuracy of ± 40 microns to provide the consistent repeatable movements required to enable the reliable assembly of 01005 components, dependable placement for three-tenths millimeter pitch or finer, and assembly yield rates that exceed 99.95% across complex multi-step processes.

Continuous calibration monitoring uses precision reference targets to detect drift and trigger correction before precision degrades beyond acceptable limits. Statistical process control data from eBots installations demonstrates placement accuracy distributions that remain within specifications over years of operation, thus providing evidence of a robust architecture rather than initial precision that degrades without intensive maintenance.

Genuine AI: Continuous Improvement Without Manual Intervention

eBots incorporates authentic machine learning that meets all three tests of genuine AI: autonomous improvement without reprogramming, knowledge transfer across product families, and real-time adaptation without engineer intervention.

Performance demonstrably improves from month one to month six on identical products, because the system discovers optimizations through systematic parameter analysis during normal operation and then implements improvements that accumulate over its operational life. Throughput improvements of 20% to 30% beyond initial operation develop through AI refinement rather than manual engineering effort.

Knowledge transfer measurably accelerates new product introduction, due to the system's ability to identify similar products across its accumulated experience and then apply their optimized parameters as starting points. Placement force optimization for specific

component types transfers across all products using those components and vision recognition strategies transfer across products using similar packages. As a result, eBots customers report 70% to 90% reductions in their new product introduction timeline compared to manual assembly or conventional automation.

Real-time adaptation maintains consistent performance without manual intervention despite material lot variations, environmental changes, and equipment state changes. Predictive quality management identifies patterns that precede quality issues, which enables preventive action to be taken before defects occur, rather than relying on reactive correction afterward.

15-Minute Changeover

eBots reduces product changeover from four to eight hours to approximately fifteen minutes through four integrated capabilities: vision-guided substrate location, software-defined processes, AI-driven parameter optimization, and universal component handling.

Vision-guided substrate location eliminates product-specific mechanical fixtures, because products are located optically using fiducial marks rather than mechanical constraints. Any product fitting within the fixture's size envelope runs without hardware changes, which eliminates setup costs of \$20,000 to \$50,000 per variant that have previously made traditional automation economically impossible for high-mix portfolios.

Software-defined processes enable product changes to be made through programming rather than physical reconfiguration. Similarly, AI-driven parameter optimization applies knowledge from similar products as starting points and converges on optimal settings through guided iteration that complete in hours rather than days. And universal component handling accommodates multiple package types without mechanical changes across the majority of typical flexible circuit component populations.

When changeover can be accomplished in as little as 15 minutes, batch size becomes economically irrelevant, so even lot-size-of-one production becomes viable. In addition, just-in-time manufacturing with minimal inventory becomes achievable and custom configurations become profitable rather than burdensome.

Real Customer Results

Medical Device Manufacturer: Quality and Market Access

A medical device manufacturer producing wearable continuous glucose monitors struggled with 87% first-pass yields, four to six week new product introduction timelines, and an inability to demonstrate the levels of process capability and traceability that ISO 13485 certification requires. External consultants estimated that achieving certification with manual processes would require investments in excess of \$500,000 and still might not provide adequate capability demonstration.

After implementing two eBots systems, results exceeded expectations. New product introduction dropped by 85%, from four to six weeks, to three to five days. Similarly, product changeover dropped to 15 to 18 minutes and first-pass yield improved from 87% to 99.7%.

Material waste reduction saved approximately \$2 million per year while rework elimination saved an additional \$300,000. Field failure rates dropped 80% reducing warranty costs by \$400,000 per year. And ISO 13485 certification was achieved in just eight months, which opened European markets that now represent 30% of company revenue. Return on investment was achieved in just 11 months, driven primarily by quality improvement rather than labor reduction.

Automotive Contract Manufacturer: Reshoring Success

A contract manufacturer that produces flexible circuits for automotive applications faced intense offshore price pressure. Previous conventional automation attempts were disappointing, with long changeover times that made high-mix production uneconomical, as well as equipment that struggled with flexible substrates.

After implementing three eBots systems that covered 70% of production volume, labor cost per unit dropped by 65% despite domestic wage rates. First-pass yield improved from 91% to 99.8%, saving approximately \$1.8 million per year. And changeover efficiency recovered more than 120 hours each month, enabling throughput to increase by 20% without additional capital investment.

They also achieved IATF 16949 certification within 14 months which enabled them to enter the automotive safety system business at margins that were double what they see in commercial electronics. Three major customers transitioned their production from Chinese suppliers to this domestic manufacturer, representing \$15 million in annual reshored revenue. Return on investment occurred in 14 months.

High-Mix Manufacturer: Business Model Transformation

A specialized contract manufacturer producing 50 to 70 active product variants each month relied entirely on manual assembly, because legacy automation economics made high-mix production automation impossible.

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After piloting one eBots system, the 12- to 15-minute changeover time made even 50-unit batches economically viable. As a result, production shifted from weekly batching to daily orders that are matched to actual demand. Inventory dropped by 60% which freed \$400,000 in working capital.

New product introduction accelerated from three weeks to four days, creating a premium-priced rapid prototyping service that generates \$1.2 million in new annual revenue and quality improved to 99.6% which reduced material waste by \$300,000 per year. As a result, return on investment occurred in nine months which led to three additional system orders that covered 70% of the company's production volume.

The Complete Economic Case

eBots delivers measurable value across multiple dimensions that compound into economic impact that typically far exceeds labor savings alone.

Labor elimination of \$75,000 or more per workstation per year provides the most visible benefit, because it translates to \$750,000 per year for 10 workstations. But material waste reduction from yield improvement frequently delivers \$3 million to \$4 million in annual savings on moderate production volumes, which is several times higher than labor savings. And hundreds of thousands to millions more per year can be saved through rework elimination, field failure cost reduction, and compliance administrative burden elimination.

Gaining market access to regulated segments with premium margins frequently creates the largest single value component. For example, entering medical device markets at margins that are double those of commercial electronics leads to profit improvements that manufacturing cost savings simply can't match. Manufacturers capturing this complete value demonstrate ROI payback periods of six to 18 months against 10-year operational lifespans, thereby creating cumulative returns that are many times the amount of the initial investment.

Implementation: The eBots Approach

Recommended Pilot Strategy

eBots recommends a staged deployment strategy that begins with pilot programs to validate technology and demonstrate measured value before making a full facility commitment. Pilots focus on product families that represent typical challenges with sufficient production volumes for meaningful data and strategic importance where success creates organizational momentum.

Success metrics must be explicitly defined before pilots begin. This includes specific yield targets, throughput levels, changeover times, and quality metrics as predetermined success criteria rather than subjective evaluation. Then, the evaluation phase following pilots need to employ the actual production data for business case development, so that capital approval is secured from evidence rather than vendor claims.

Many successful eBots customer relationships began with skeptical pilots that proved value and therefore expanded to multi-system deployments. The pilot approach transforms automation from investment leap-of-faith to validated strategic decision.

From Eight to Sixteen Weeks to Production

Typical eBots implementations require eight to 16 weeks from order to production. The process begins with pre-delivery preparation, which covers site readiness, utilities, product data gathering, and component library development. Then comes installation and commissioning, which includes mechanical installation, software configuration, and system checkout. Then, configuration and validation comprises vision calibration, process development, first article builds, capability studies, equipment integration, and training. And finally, production ramp proceeds with engineering support through gradual volume increase to full capacity.

Training and Support

eBots provides comprehensive training across operator, technician, and engineer levels to ensure successful operation and continuous improvement capabilities. Ongoing support includes technical support via multiple channels, as well as software updates, optional service contracts, on-site field service, and quarterly business reviews to identify optimization opportunities.

Conclusion — The Complete Solution

Every challenge documented in this white paper series has a proven solution, every requirement defined in the technology blueprint has been implemented, and every business case outlined in the economics analysis has been validated with actual customer results.

The complete capability set works together as an integrated system:

- Adaptive substrate handling replaces rigid-board fixturing that often damages delicate materials
- Dual-arm coordination enables complex operations that are impossible for single-arm systems
- Three-dimensional vision at 409 frames per second provides a level of quality verification that two-dimensional imaging can't deliver
- Precision of +/- 22 microns exceeds human capability by factors of 3X to 5X
- Genuine AI enables 15-minute changeovers and continuous performance improvement

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Real customers have proven that transformation is achievable. This includes medical device manufacturers that can suddenly access European markets, automotive manufacturers that reshore \$15 million in annual revenue, and high-mix manufacturers that transform from commodity producers to premium service providers. These aren't projections, they're measured results from production environments.

The question facing flexible PCB manufacturers isn't whether or not transformation is possible. Instead, it's whether manufacturers will proactively embrace it while competitive advantages remain available, or if they'll wait until competitive necessity forces a reactive response from a position of weakness.

eBots is ready to begin your transformation.

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