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Enhancing PCBA Using AI Techniques: Tiny ML, Computer Vision, and Reinforcement Learning for Precision Assembly and Repair

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Abstract
The rapid growth in electronics manufacturing has created an increasing demand for its basic unit, the PCB. To increase the production of PCB, many techniques were adopted, leading to advancements in technologies like Printed Circuit Board Assembly (PCBA). The main challenges faced during PCBA are the misplacement of Surface Mounted Devices (SMDs), and cutting errors. This leads to wastage of huge number of PCBs, producing a lot of E-waste causing the company lose money. Also, traditional Automated Optical Inspection (AOI) and machine vision systems often rely on centralized computing, leading to high operational costs and latency. This paper proposes an AI-driven autonomous PCBA system that integrates TinyML, deep learning-based defect detection, reinforcement learning based robotic repair, and other Computer Vision algorithms to identify faults and solve the problem. This approach aims to solve the issues related to misplacements, and prevention of usage of the defected PCBs in PCBA. The model helps in real-time component verification before placement, AI-guided SMD placement correction, predictive maintenance and anomaly detection for pick-and-place robots, and error prevention by indicating what error the system has encountered and it also suggests the next steps to be done and by which methods. These help in preventing the usage of defected PCBs, identifying the faults in placement of SMDs, and robotic failures before they impact production. By embedding optimized machine learning models directly into pick-and-place robots and PCBA systems, this approach eliminates the need for cloud-dependent processing. The proposed system eliminates scrape rates and increases placement accuracy. These advancements can benefit other sectors that rely on accurate electronic components, such as aerospace, automobile, and medical industry.
Keywords*: Printed Circuit Board, Artificial Intelligence, TinyML, Computer Vision, Deep Learning, Reinforcement Learning, Pick-and-Place Robotics, Predictive Maintenance, Automated Optical Inspection*

INTRODUCTION

In this rapid tech development era, the consumption of electronics has grown a lot, leading to the production of PCBs in large amount. Due to the increasing demand and advancements in technology, the PCBs' manufacturing rate and innovations are increasing every day. PCBs are becoming more and more compact, containing many tiny high performing components. Due to their compact size, it is necessary to carefully monitor and design the PCBs, as if there are any errors, the company will lose money. Also, customers will have to face issues due to misalignment of certain components. Surface Mount Technology (SMT) is being used to manufacture small PCBs, as they don't need holes to be drilled on the PCB, making the process easier. It only includes soldering the Surface Mount Devices (SMDs) to the PCB with the help of solder paste. Since the size of the PCB is being shrunk according to their roles and functions, many errors may arise, such as misalignment of the components, overflow of the solder paste, mistakes in cutting the PCB board to its precise length, etc. Conventional Automated Optical Inspection (AOI) and other traditional inspection and defect correction methods lack adaptability and predictive intelligence. Manual inspection methods take a lot of time and mostly are not a reliable method, as human error might occur.

In this paper, we've come across an enhanced way of PCB assembly, which can improve the existing PCB assembly methods, increasing the reliability and overcoming the drawbacks of the existing methodologies. The idea proposed uses technical stacks such as Tiny Machine Learning (TinyML), Computer Vision (CV), and Reinforcement Learning (RL) to enhance PCBA precision, reduce defects, and to analyze the error to find the apt solution for the problem. Usage of these tech stacks primarily focuses on combatting the drawbacks in the current methodologies.

The PCB is analyzed for errors before it undergoes further process. This saves the PCB from being wasted.

IMPORTANCE OF AI IN PCBA

AI is playing a crucial role in almost all sectors. The advent of AI has transformed the way how each process is done in every sectors. One such main impact made by AI is the precision in PCBA. It helps in carrying out PCBA efficiently, enhancing accuracy, improving defect detection, enabling predictive maintenance, etc. AI has brought lots of innovation in this field. As the size of PCBs are shrinking, it is important to focus on giving higher performance even in such a small area.

A. Precision in Component Placement

AI helps in providing precision in all areas. This is crucial in areas such as components placement, as even a small misalignment may cause huge loss to the company. Minute errors may cause the component to malfunction and there might be a chance of not being able to reuse them. To avoid all these inconveniences which are a great hinderance for a company, AI is used to reduce the errors, thereby increasing precision in component placement. The algorithms developed are used to place the components precisely.

B. Advanced Defect Detection & Quality Control

Traditional Automated Optical Inspection (AOI) helps us in identifying various minute errors with the help of 3D imaging, which won't be visible from the top camera view. It is also useful in new batch setup. But AI implemented AOI helps the company upload few images of the defected PCB, and train the machine learning model such as classification, regression, YOLO, etc. to identify the defects in the PCB. This helps us in providing good quality of PCBs to companies manufacturing electrical components [1].

Implementing AI in AOI not only increases the ease of identifying defects faster, but also allows us to detect errors which are more complex to identify by the traditional AOI. It can identify complex errors such as solder bridges (excess solders creating short circuits), cold solder joints (poor electrical connections), tombstoning (one side of a component lifting off the PCB), etc. AI models improve over time by learning from past inspection data, which leads to higher defect detection accuracy.

C. Predictive Maintenance and Process Optimization

AI implementation helps in predicting the future errors by analyzing the PCB before it undergoes any process, reducing the cost spent and wastage of the PCB. Prediction of defects helps in taking steps accordingly. This leads to the optimization of the whole PCBA, reducing errors, time spent, and increasing the production and profit. AI also helps in suggesting improved ways of PCBA process, to increase the efficiency and to reduce time taken to assemble. By analyzing historical data and identifying patterns in defects, AI can predict potential issues during the PCB assembly process.

D. Automated PCB Repair using AI

- AI can guide us in correcting the defected PCBs with the use of Computer Vision (CV) and Deep Learning.
- High-Resolution Cameras and Thermal Imaging Sensors capture images of the PCB, which are then fed to the model containing AI algorithms, such as CNNs, YOLO, etc. These help in detecting defects such as solder defect, burnt traces or short circuits, misplaced or missing components, PCB warpage due to heat stress, etc. AI classifies these identified defects by severity and suggests the best repair method.
- Once a defect is identified, AI powered robotic arms can perform precision repairs. They perform repairs such as applying optimal soldering techniques, guiding pick-and-place robots to replace faulty components, etc. Reinforcement Learning (RL) improves the repair process over time, reducing error rates.
- AI can help automate trace repairing using conductive ink printing or micro-laser welding, as damaged PCB traces can break electrical connections. AI analyses the PCB layout first, and identifies broken traces. Then a micro robot or conductive ink printer redraws damaged traces automatically. AI then verifies conductivity using electrical testing.

E. Reduction of Human Errors and Manual Effort

AI is playing a crucial role in mitigating the human errors occurring in places where those errors could make a huge destruction. AI-powered robotic arms can handle tasks precisely, reducing the errors caused by humans.

F. Real-Time Process Monitoring and Big Data Analytics

AI-driven Industrial Internet of Things (IIoT) sensors can monitor PCBA process in real-time. ML models can analyze big data to detect trends, optimize production cycles, and minimizing defects. Using TinyML in all the AI powered machineries, it is easier to and faster to process the data collected by the machines and process them without saving them to the cloud. TinyML helps in processing the real-time data collected by the AI-powered machineries, which can improve the model and help in predictive insights.

PCBA PROCESS

PCBA process varies from company to company, depending on their budget. While most of the budget-focused companies have workers inspecting the process manually, high-budget companies focus on the quality of the PCB, thereby making use of many high-tech machineries to identify defects and perform precise placements of SMDs. This is how a well maintained PCBA is done:

A. Bare Boards and Laser Markings

Bare boards used to mount SMDs are sent into the laser marking machine. The machine then marks the unique serial number, which comes from the Enterprise Resource Planning (ERP) and reports to the output file that the suite of software tools, designed to optimize the PCBA, can then collect the data. The serial number will allow us to track a specific board and know exactly what happened to it.

At the company, the serial numbers are generated by the ERP and are unique to each PCB.

B. Screen Printing

The screen printer applies the paste through the stencil. Each job has a different stencil, which is planned with a manufacturing process engineering tool, that enables manufacturers to efficiently program SMT manufacturing [2]. It must be precise per product and per revision. At this station, we can expect a relatively high rate of defects. It is very sensitive to environment condition, temperature, and humidity. This is the reason for many tests and inspection after this stage.

With a solution focused on optimizing material flow and efficiency in PCB assembly, we can conduct stencil verification, by scanning the stencil barcode and reporting the exact stencil and paste we have used.

C. Solder Paste Inspection (SPI)

The SPI machine tests the quality of the printer to verify that everything was printed according to the plan and there is paste, only where it should be. The SPI will run the test program and report the findings in a file including pass, fail, as well as measurements. This data is later on collected by a manufacturing solution that gathers live information from every process or machine.

D. Pick and Place

Commonly, there are 3 types of pick and place machines- a fast pick and place machine, a machine with a camera for small and subtle components when accuracy is highly important, and a very strong machine with high pressure for boards that require force in implementing its components. Having different pick and place machines is typical to many manufacturers. It allows for high accuracy and flexibility. A manufacturing process engineering tool can help in generating the assembly programs. IoT manufacturing solutions connects to the pick and place machine and can collect data regarding machine utilization. A solution that optimizes material flow in PCB assembly helps manage the material on the machine and replacement of material when it's consumed.

E. Visual Inspection

At the visual inspection station, operators can validate that the correct components were placed on the board before continuing in the manufacturing process. Tools are also used to create the documentation which will define for the operator what should be inspected at this stage.

F. Reflow Oven

Here, the soldering is done. The plant for the oven is referred to as an oven profile. The reflow oven is divided into several chambers. The speed through each chamber can be different and each chamber can have a different temperature. IoT manufacturing solutions helps connect the reflow oven and receives information regarding the actual temperature and speed of the oven.

G. Automated Optical Inspection (AOI)

At this station, we wish to ensure that each component was placed correctly in the right angle and that the soldering is good. PCBA software tools can help us prepare a test program so that the exact location where the pins contact the pads will be examined. At this point, the SMT process is complete.

H. Through Hole and Manual Assembly

Following the SMT process, some companies also have additional placement technologies, such as through-hole and manual assembly. At the through-hole station, the through hole components are placed manually on the PCB, but they are then soldered in a selective soldering oven.

I. Electrical Testing

There are two methods which are used to perform electrical tests on the PCB. Bed of nails for high volume which allows for shorter time of testing but requires expensive development of fixtures or flying probe test for high mix small volume. It takes longer to program the flying probe and run the test, but it is much easier to handle new products. A good manufacturing process engineering tool can help plan the fixture of the bed of nail as well as generate a program for the flying probe machine. In addition, IoT manufacturing solution will collect data from the different testers, including the different electrical measurement as well as the pass fail. The entire process is managed by the software a company uses to handle.

J. X ray

For large Ball Grid Array (BGA) components, we need to check that the pins reach the right layer. These pins are usually behind the component and therefore cannot be tested with AOI machines. In this case, we use an X-ray image of the PCB and make sure that the connectivity and the soldering is adequate.

K. Functional Test

Now we can actually test the functionality of the completed product. The preference is always to find issues through the different processes and avoid finding defects at the last stage of the functional test.

L. Final Manual Assembly

Here, mechanical parts are assembled manually or by a robot. At this point, the product assembly is complete.

M. Packaging and Delivery

The product is ready to be delivered, and can be packaged to send it to the end customer.

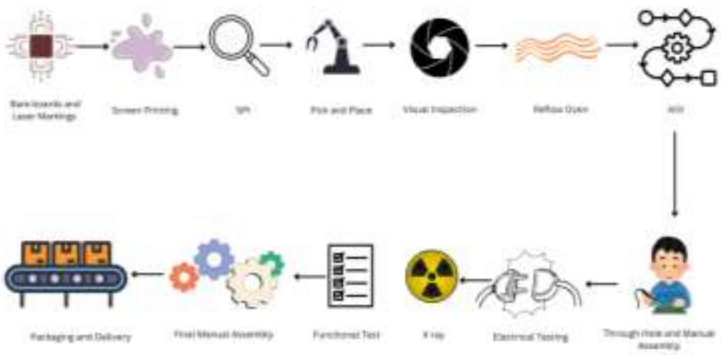

Figure 1 Typical PCBA Process

EXISTING USAGE OF AI IN PCBA

In this AI-driven era, where everything we do is dependent on AI, AI has also entered in fields like electronics, medicine, finance, manufacturing, and many more. Some of the companies are using analytical tools which are powered by AI, to increase their productivity.

A. AI and AR in Visual Inspecion

Some companies have come up with including Augmented Reality (AR) in guiding the workers to fix the defects in PCB. AI algorithms are used to identify the errors and using AR technology, it is easier to identity and spot the defect in the display and seeing it, the worker can fix the defect. If the defect is corrected, then it is displayed as corrected.

B. Pin Swapping

AI algorithms are used to ease the work of pin swapping. Pin swapping is the exchanging of the connections of pins within a component or between components to improve routing or address specific design issues, while ensuring the electrical functionality remains the same.

C. PCB Design Reuse

AI-powered PCB design tools are revolutionizing the way circuit boards are created and optimized. Modern software use ML and Reinforcement Learning (RL) to automate component placement, optimize routing, and predict design flaws before fabrication. AI-driven schematic recognition allows engineers to reuse and adapt existing circuit designs, reducing development time. Also, AI-assisted Bill of Materials (BOM) management helps prevent component obsolescence by suggesting replacements, while intelligent Design Rule Checking (DRC) ensures compliance with industry standards. They also enable suggesting the best design for the requested format. These advancements enhance the reusability of the designs, enabling innovation and increasing the productivity of the company.

ERRORS ENCOUNTERED IN PCBA

In spite of the current technical advancements, there are errors and defects that occur during PCB assembly. Poor planning during the design stage often results in assembly defects that compromise board functionality and reliability. Below are some key errors encountered in PCB assembly, stemming from common design mistakes, along with their implications.

A. Incomplete or Inaccurate Design Data

Design intent is a crucial aspect, which should be communicated to the manufacturers. Errors in design can produce inaccurate PCBs and thereby, they don't work. Errors include, Gerber file defects, centroid file errors, solder paste stencil file issues, inaccurate assembly drawings, inefficient CAD file conversion, etc. All these aspects should be flawless to provide the best outcome.

B. Improper Component Placement

Improper positioning of the components may lead to misfunction of the PCB. Even a slightest variation in measurements and placements may lead to defects. For example, placing components too close to each other or the board edge can interfere with soldering equipment, while misoriented polarized components (e.g., diodes or capacitors) can disrupt circuit functionality.

C. Insufficient Clearances and Spacing

Inadequate spacing between pads, traces, and components is a common design flaw that translates into assembly errors such as solder bridges or short circuits. If the spaces are not left correctly, the solders of the adjacent components may unintentionally connect with each other, creating electrical faults.

D. Poor Thermal Management

Thermal-related errors during assembly often result from designs that overlook heat dissipation. Components placed without regard for thermal relief or airflow can overheat during soldering, leading to issues like pad lifting, solder joint weakening, or component damage. For instance, high-power components grouped too closely without heat sinks or thermal vias can cause uneven heating, compromising solder quality. These thermal management failures not only affect assembly but can also degrade long-term board performance.

E. Ambiguous or Missing Assembly Instructions

Mistakes such as improper orientation of components or incorrect placement of parts usually stem from ambiguous or incomplete assembly procedures in design manuals. Omission of polarity symbols on components like diodes, inconsistent designators between drawings and the board, or ambiguous annotations may mislead assembly technicians or automated systems. This results in faults such as incorrect soldering or inverted operation, necessitating labor-intensive correction after assembly.

F. BOM and Component Sourcing Issues

BOM discrepancies often lead to assembly mistakes, including the installation of incorrect or non-existent parts. When the BOM does not contain correct part numbers, quantities, or vendor information, assemblers can install incompatible components, resulting in footprint mismatches or soldering defects. Outdated components specified without substitutes can bring assembly to a complete stop, while unvalidated component specs can lead to fit or performance problems during soldering.

Figure 2 A PCB without any defects

CONSEQUENCES OF ERRORS

The errors caused in PCB assembly causes various faults in the whole manufacturing process, leading to loss of the company and failure in many electronics. Here are some of the consequences faced:

A. Solder Bridges and Shorts

This is caused by insufficient spacing or excess solder mask, leading to electrical faults.

B. Pad Lifting

It is resulted from thermal stress or poor adhesion, weakening connections.

C. Component Misalignment

It occurs due to inaccurate placement or drill errors, affecting functionality.

D. Increased Costs and Delay

Due to the rework, redesigns, or sourcing issues, it extends production timelines.

E. Reduced Product Quality

Faulty boards fail prematurely, damaging reliability and reputation.

F. Generation of E-Waste

In the current generation of technological development, a huge amount of demand for electronics is prevailing. According to the demand, the production is also huge. If a small error occurs in the PCB, the whole electronic component would not work or will be of less quality, leading to not using the electronic component, and thereby, contributing to e-waste. Globally, a record 62 million tonnes of e-waste was generated in 2022, with only 22.3% formally collected and recycled, while the rest is either landfilled, stored, or recycled informally, highlighting a significant gap in e-waste management. This is gradually leading to pollution, emitting toxic substances, damaging the Earth.

MITIGATING ASSEMBLY ERRORS

In Some of the companies are using analytical tools which are powered by AI, to increase their productivity. Here are some solutions to the commonly occurred errors:

A. Solder Bridging

Description: Solder bridging occurs when excess solder connects adjacent pads or leads, creating unintended electrical shorts that impair circuit operation.

Causes: This issue often raises from flaws in the solder paste printing process, such as excessive paste application or paste slumping due to poor viscosity. Misaligned PCB pad designs or stencil inaccuracies can also contribute.

Solutions: Use a solder paste with an optimal metal-to-flux ratio to prevent collapse. Fine-tune the reflow profile, ensure precise component placement pressure, and verify placement accuracy.

B. Insufficient Solder Joints or Open Circuits

Description: An open circuit happens when solder fails to connect two points, breaking the electrical pathway due to inadequate solder joints.

Causes: This can result from too little solder on connectors, clogged stencil apertures blocking paste flow, or poor contact between leads and pads during reflow.

Solutions: Adjust the stencil's aspect ratio to prevent paste blockages (to avoid overly small openings). Maintain controlled environmental conditions to minimize solder paste contamination.

C. Solder Balls

Description: Solder balls are small, stray solder spheres that can bridge nearby leads, leading to functional circuit issues.

Causes: Moisture contamination in the solder paste is a primary culprit, alongside excessive oxide buildup in the solder powder.

Solutions: Opting for a coarser solder powder size reduces balling tendencies and ensures paste purity.

D. Tombstoning

Description: Tombstoning refers to a component lifting off one pad and standing upright, resembling a tombstone, due to uneven soldering.

Causes: This effect is triggered by unequal forces during reflow soldering, often from uneven heating across component terminals.

Solutions: We should ensure that the component spans at least 50% of both pads to balance soldering forces. We should also increase preheat temperatures to minimize thermal gradients during reflow.

E. Non-Wetting or De-Wetting

Description: Non-wetting occurs when molten solder fails to bond with the base metal, leaving pads or leads unsoldered. De-wetting involves solder retracting from pads, resulting in weak or incomplete joints.

Causes: Factors include subpar PCB surface finishes, prolonged soaking times in reflow, or inadequate heating.

Solutions: Upgrading to robust surface finishes like OSP or ENIG with better heat resistance. Shortening the pre-reflow soak duration to enhance wetting.

F. Solder Beads

Description: Unlike scattered solder balls, solder beads are distinct clumps of excess solder near components.

Causes: Overapplication of solder paste or flux outgassing that overcomes paste cohesion during preheating can lead to bead formation.

Solutions: Lowering stencil thickness or reducing aperture size to limit paste volume. Adjusting placement pressure to avoid excess pickup.

G. Insufficient Solder Paste or Filling

Description: This defect occurs when too little solder paste is applied, resulting in incomplete joints or flat, non-rounded fillets after reflow.

Causes: Low metal content in the paste, overly rapid squeegee speeds, or clogged stencils from dried paste are typical triggers.

Solutions: Regularly cleaning the stencils to ensure unobstructed paste flow. Slowing down the squeegee speed for consistent deposition.

H. Cold Soldering or Granular Joints

Description: Cold soldering refers to joints where solder doesn’t fully melt, appearing rough, grainy, or irregular due to incomplete fusion.

Causes: Inadequate reflow temperatures, short reflow durations, or dirty PCB pads can prevent proper solder melting.

Solutions: Raising the peak reflow temperature for sufficient heat transfer. Avoiding disturbing components during or post-reflow. Analyzing alloys to detect contaminants.

TINYML IN PCBA

All the above solutions are widely being followed by industries to cope up with the defects in PCBA. But most of the solutions are not that effective in reducing the loss to the company. To mitigate the defects from the early stages, a Machine Learning concept, which is specifically designed for working in embedded systems, can be used to amplify the process of error detection and preventing wastage of costly SMDs. Earlier detection and elimination of faults is crucial, as it reduces the cost spent by the company, and cuts down the e-waste generated.

A. TinyML

Machine Learning algorithms are used to predict the upcoming trends. It allows machines to learn patterns and trends from the data which is fed to the algorithm. These algorithms include random forest, decision tree, k-means, k-nearest neighbour, etc. TinyML is a growing field which involves implementing ML models in the microprocessors. This gives a huge power to the microprocessors, as they can collect real- time data and simultaneously predict the trends using ML algorithms. It focuses on the development of models to microcontrollers and other low-power edge devices, providing instantaneous output.

B. Benefits of TinyML

Edge Computing and Reduced Latency: TinyML enables machine learning models to run directly on devices, eliminating the need for constant data transfers to remote servers. This supports smooth, efficient, and offline operation of applications. By processing data locally, it significantly reduces response times, making it ideal for real-time use cases such as sensors and wearable devices in fields like IoT management.

Energy Efficiency: Devices with limited power often face operational challenges due to high energy demands. TinyML models are designed to be lightweight and compact, requiring far less power than traditional machine learning systems deployed on large clusters or cloud platforms. This allows TinyML to be implemented on low-power devices, extending battery life and enhancing usability in resource-constrained environments.

Privacy and Security: Since data processing and analyzing is done locally, privacy and security of the data is more compared to the cloud-ran ML models. Similar to privacy-focused tools that keep user data local, TinyML processes information directly on the device, reducing the risk of exposure to external entities. By keeping sensitive data onboard, it enhances security and minimizes the chances of breaches or unauthorized access. This is particularly valuable in applications where safeguarding privacy and adhering to data protection standards are critical.

Cost-Effectiveness and Scalability: TinyML makes machine learning accessible on low-resource devices, removing the need for costly high-end hardware. This approach lowers operational costs by reducing reliance on cloud infrastructure. Furthermore, it enables the deployment of intelligent applications across a wide range of devices, boosting scalability and efficiency without significant financial investment.

Real-time Processing: TinyML facilitates rapid inference of machine learning models without depending on internet connectivity. This capability is essential in today's fast-paced digital landscape, where delays due to network issues can hinder decision-making. It proves especially useful in scenarios requiring immediate responses, such as managing dynamic systems, and enhances the user experience by delivering seamless, responsive technology.

C. Types of ML Algorithms

They are categorized into supervised, unsupervised, semi-supervised, and reinforcement learning types, each with distinct approaches and applications.

Supervised Machine Learning: It is a type of Machine Learning, where the algorithms learn from labeled data. The data provided to the model is given with the correct answers, and model predicts the output to an unseen data.

Unsupervised Learning: It is a type of machine learning, where algorithms learn patterns and structures from unlabeled data, without explicit guidance or predefined outcomes. It aims to discover hidden insights and relationships.

Reinforcement Learning: This type of ML aims in predicting the outcome based on reward-punishment. If the model predicts the output wrong, a feedback is sent to the model that the outcome is wrong. If the output was predicted correctly, then it is awarded with reward.

These ML types are used according to our need. Our solution focuses on implementing Reinforcement Learning.

D. TinyML Tools

TensorFlow Lite for Microcontrollers (TFLite Micro)

- Description: A lightweight version of TensorFlow Lite, specifically optimized for microcontrollers and other devices with limited memory (often just a few kilobytes). It allows developers to run pre-trained ML models on embedded systems.
- Key Features: Supports quantization, works offline, and integrates with C/C++ for deployment. Compatible with platforms like Arduino, ESP32, and STM32.
- Use Case: Ideal for audio processing (e.g., keyword spotting), gesture recognition, and sensor data analysis.

Edge Impulse

- Description: A user-friendly platform for building, training, and deploying TinyML models, tailored for edge devices. It simplifies the entire workflow from data collection to model deployment.
- Key Features: Supports data ingestion from sensors, model training in the cloud, and deployment as C++ code. Compatible with devices like Arduino Nano, Raspberry Pi, and Nordic nRF boards.
- Use Case: Popular for IoT applications, such as predictive maintenance and anomaly detection.

cuTensor

- Description: An open-source, lightweight inference framework designed for running ML models on microcontrollers with minimal resources.
- Key Features: Written in C++, supports TensorFlow models, and focuses on low memory usage and portability.
- Use Case: Suitable for basic inference tasks on ARM Cortex-M series microcontrollers.

NanoEdge AI Studio

- Description: A tool by STMicroelectronics focused on generating TinyML models for anomaly detection and classification without requiring deep ML expertise.
- Key Features: Automated model generation, supports STM32 devices, and works with sensor data directly.
- Use Case: Great for quick prototyping of condition monitoring and predictive maintenance solutions.

OpenMV

- Description: A platform specializing in computer vision TinyML applications, built around the OpenMV Cam (ARM Cortex-M7 processor).
- Key Features: Supports MicroPython, image processing, and pre-trained models for tasks like object detection.
- Use Case: Perfect for embedded vision projects, such as facial recognition or motion tracking.

E. Future Scope of TinyML

Since Tiny ML is an emerging field, there is a really small amount of implication in the current industries. Higher level of integration can help the company to process live data to the ML models and predict defects instantaneously. Some of the future scope of TinyML are:

- AI-Powered Defect Detection at the Edge: This helps in identification and mitigation of the defects in a faster rate, saving time. It also ensures accuracy, according to the model used.
- Wireless PCB Communication and RF Tuning: It can significantly adjust the antenna parameters in real-time, for better signalling strength and interference reduction in woreless communication PCBs. It can optimize PCB antennas for 5G, Wi-Fi, and IoT applications.
- Predictive Maintenance for PCB Manufacturing Machines: It is used to monitor vibrations, temperature, and acoustic signals of PCBA machines to predict failures before they happen. It reduces doentime and inproves manufacturing efficiency.
- AI-Optimized Power Management for IoT PCBs: TinyML is used to analyze energy usage in IoT devices and dynamically adjust power consumption to extend battery life. For example, a TinyML-powered IoT PCB monitors energy usage and adjusts clock speed dynamically to optimize power efficiency.

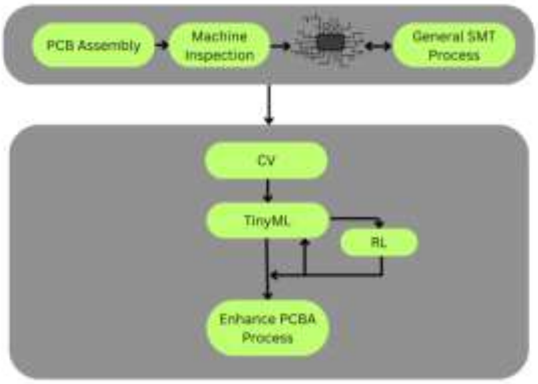

Figure 3 Workflow of TinyML in PCBA Process

REINFORCEMENT LEARNING

Reinforcement Learning is used in this proposed solution, as it is one of the model which has the ability to rectify itself from its mistakes. Since it is a reward-based system, when implemented using TinyML, it has more power to predict and rectify itself.

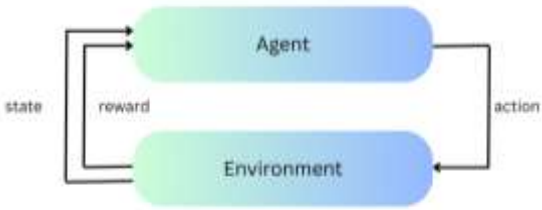

Figure 4 Working of Reinforecement Learning

Implementing RL in TinyML for PCBA results in:

A. TinyML for Edge-Based PCB Inspection & Data Collection

- Deploying lightweight ML models on microcontrollers and edge devices to detect defects in real-time.
- Using sensor fusion (camera, thermal, vibration, and ultrasonic sensors) to collect PCB manufacturing data efficiently.
- Implementing compressed deep learning models such as MobileNet or TinyCNNs, to run efficiently on resource-constrained PCBA machines.

B. Reinforcement Learning for Adaptive PCB Assembly Optimization

- Training an RL agent to optimize pick-and-place machine movements, reducing misalignment errors.
- Using reward-based learning to adjust soldering parameters dynamically, improving joint quality.
- Enabling real-time feedback loops so the model learns from past assembly errors and improves accuracy over time.

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C. Self-Correcting PCBA Systems Using RL & TinyML

- Integrating RL-based error correction in PCB placement machines to auto-adjust misaligned components during assembly.
- TinyML models can detect and classify defects instantly, while RL-based controllers take corrective actions autonomously.
- Deploying TinyML-based predictive maintenance to avoid breakdowns by monitoring machine performance trends.

D. Energy-Efficient Optimization with TinyML + RL

- Training an RL model to optimize PCB manufacturing power consumption, reducing energy waste.
- Using TinyML to monitor real-time machine efficiency, and let the RL agent adjust speed, pressure, and temperature for maximum efficiency.

E. TinyML & RL for Automated PCB Repair & Self-Healing

- RL-powered micro-robots can perform precision-based PCB repairs based on TinyML defect detection. Even though these implementations are not fully implemented right now, but it’s in its budding stage.
- TinyML-enabled AI circuits can detect damage and trigger self-healing mechanisms, such as conductive ink printing for broken traces.

F. Deployment & Future Scope

- Using low-power hardware (like ARM Cortex-M, ESP32, or Raspberry Pi) to run TinyML + RL models in real-world PCBA environments.
- Improving efficiency by integrating cloud-assisted RL training, while keeping real-time inference on TinyML devices.
- Future applications include fully autonomous PCB factories with self-learning AI systems.

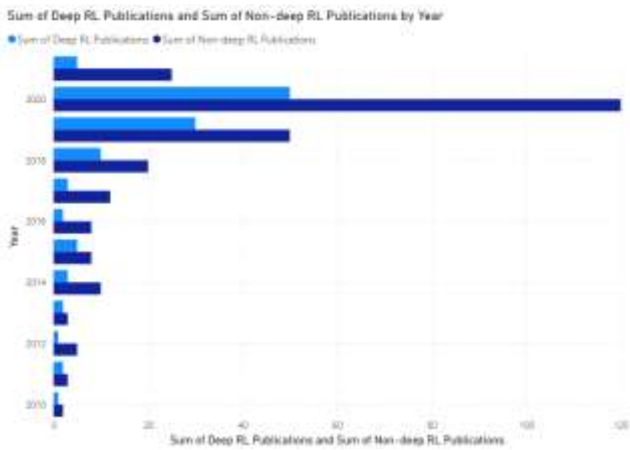

Figure 5 Trends Over the Years in Deep RL and Non-deep RL Publications

The graph illustrates the increasing research interest in deep RL, particularly peaking in 2020, compared to non-deep RL publications

AI IN PCB ANTENNAS FOR WIRELESS COMMUNICATION

PCB antennas, or Printed Circuit Board antennas, are antennas integrated directly onto a printed circuit board (PCB) as part of its design. Unlike traditional external antennas (e.g., whip or dipole antennas), PCB antennas are created by etching conductive traces onto the PCB substrate, typically using copper. These antennas are widely used in wireless communication devices due to their compact size, cost-effectiveness, and ability to be seamlessly incorporated into electronic circuits.

A. Working

PCB antennas function by radiating or receiving electromagnetic waves to enable wireless communication. The antenna's shape, size, and placement on the PCB determine its resonant frequency, radiation pattern, and efficiency. A radio frequency (RF) signal from a transceiver is fed into the antenna trace, which then converts the electrical signal into electromagnetic waves (for transmission) or vice versa (for reception).

B. Including TinyML and RL

Real-Time Learning: TinyML can host a lightweight RL agent on the PCB, allowing the antenna to learn and adapt in real time. For example, the agent could adjust impedance matching based on environmental feedback, with TinyML ensuring the model fits within memory constraints (e.g., <256 KB).

Edge Intelligence: Combining TinyML's local processing with RL's decision-making creates an intelligent, self-optimizing antenna system that operates offline, reducing latency and enhancing privacy.

Use Case: A PCB antenna in an IoT device could use TinyML to run an RL-trained model that optimizes beam direction in a dynamic environment, improving connectivity without external intervention.

CONCLUSION

In this research, we've shown how blending TinyML, Computer Vision, and Reinforcement Learning into PCB Assembly can reshape the future of electronics manufacturing. Traditional methods like Automated Optical Inspection and manual checks often fall short, lacking the flexibility and foresight needed for today's complex PCBs. By harnessing TinyML for on-the-spot defect detection, RL to fine-tune assembly processes, and CV for spot-on component placement, we've outlined a system that's not just smart—it's constantly learning and improving.

Our approach doesn't just boost efficiency and cut costs; it paves the way for self-healing PCBs powered by AI-driven repairs. Thanks to TinyML's low-power AI capabilities, these innovations can roll out across factories without demanding hefty hardware upgrades, making widespread adoption a real possibility.

With PCBs growing ever more sophisticated, leaning on AI for adaptive learning and real-time tweaks will be key to keeping quality top-notch. Down the road, we see this work tying into Industry 4.0, linking up with IoT for predictive upkeep, and even enabling AI-powered wireless PCB communication—unlocking a new era of manufacturing. This study sets the stage for PCB assembly that's intelligent, self-correcting, and energy-savvy, raising the bar for precision and dependability across the electronics field.

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