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OPTIMIZING CABLE CLIP PLACEMENT WITH A POKA-YOKE APPROACH FOR HIGH-PRECISION AUTOMOTIVE ASSEMBLY

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Abstract: In automotive manufacturing, securing plastic cable clips with cable ties might seem like a simple task, but it is critical for wire harness integration. Misalignment can lead to faulty connections, wasted materials, and production slowdowns. This study presents a tool designed to improve the accuracy of clip placement. It uses a mechanical release system with springs and applies Poka-Yoke principles to prevent errors. The goal is to make the process more precise, reliable, and cost-effective. Measurement techniques and coordinate metrology show that the tool can keep placement deviations within 0.5 mm, and in some cases, as low as 0.2 mm. Statistical Process Control (SPC) is introduced for real-time quality tracking, improving efficiency and reducing inspection needs. Flexibility is ensured through rapid prototyping, enabling adaptation to different cable sizes and insulation materials. The study also opens pathways toward full automation of the process.

Key words: Cable clip placement, Poka-Yoke principles, Automotive manufacturing, Statistical Process Control, Process reliability, Real-time quality, Manufacturing flexibility, Waste reduction.

1. INTRODUCTION

In automotive manufacturing, the integration of wire harnesses is particularly delicate, as decision-making regarding the assignment and placement of cable clips warrants attention down to the system-level granularity. Although the task may appear trivial, the misplacement of plastic cable clips associated with wire harnesses can lead to electrical faults, increased production costs, and inefficiencies in assembly processes [1].

Traditional manual operations, particularly those involving high-repetition tasks, are susceptible to operator fatigue and human error [2]. This underscores the necessity for a more reliable and precise approach. Error-proofing techniques, such as Poka-Yoke [3], have effectively mitigated human-induced defects across repetitive assembly operations [3], [4]. Similar implementations within the automotive sector have demonstrated measurable gains, including improved first-pass yield and reduced quality assurance overhead by adopting mechanical guidance systems [1], [5].

This methodology aligns with lean manufacturing principles by addressing defect prevention at the source and minimizing the need for downstream inspections [5]. Additionally, the application of Statistical Process Control (SPC) enables the real-time monitoring of critical parameters, offering a systematic framework to control variability and maintain process stability [6], [7], [8], [9].

The integration of non-contact optical metrology further strengthens process control capabilities by facilitating the rapid and accurate validation of clip placement without interrupting the production flow [10], [11]. These techniques enhance short-term inspection efficiency and long-term product consistency [12].

Rapid prototyping played a pivotal role in tool development, enabling quick adaptation to various cable types and geometries [13], [14]. Polylactic acid (PLA) was selected for early-stage prototypes due to its dimensional accuracy and mechanical reliability [15], [16], [17]. The final design, however, incorporated aluminum components for enhanced structural strength and durability [18], [19]. Studies on rapid tooling validate this approach, emphasizing reduced

iteration cycles and support for high-mix, low-volume production environments without sacrificing quality [20].

Material performance evaluations under industrial conditions confirmed the durability of the selected components [19], [14]. As the automotive industry increasingly adopts Industry 4.0 paradigms [21], such integrated mechanical systems, enhanced with real-time data acquisition and adaptive feedback control, position themselves as enablers of intelligent, connected manufacturing environments [22], [13].

This multidisciplinary strategy combines principles from design for manufacturability [1], [23], quality assurance, lean philosophy, and smart factory integration [21], [13] to enhance reliability, traceability, and overall process efficiency in wire harness assembly operations.

This study aims to investigate how mechanical Poka-Yoke principles can be applied to enhance the precision and reliability of cable clip placement in automotive assembly, and to what extent this approach can reduce errors and improve process capability compared to current manual methods. The underlying hypothesis is that a spring-loaded, geometry-guided placement tool can ensure consistent clip alignment within a 0.5 mm tolerance band, thereby significantly reducing error rates and variability without relying on electronic validation systems.

2. TOOL DESIGN AND POKA-YOKE IMPLEMENTATION

2.1 Concept and Design Requirements

The innovative tool boasts a sophisticated mechanical release mechanism, expertly designed to utilize preloaded springs that regulate both the movement and secure attachment of cable clips. These springs exert a consistent and reliable force, allowing the clips to remain firmly affixed in their precise positions throughout the critical preparation phase. To enhance precision, the tool incorporates geometrically constrained guides, which significantly reduce potential lateral or angular misalignment. This design feature ensures that the clips are released only when

they are optimally positioned, guaranteeing good operation and efficiency.

Designed with simplicity, the mechanical design of this tool ensures strong and consistent performance, and intensive tasks, thereby improving the system's overall performance. The spring tensions have been precisely adjusted to correspond with the exact measurements of the cable and clip, guaranteeing ideal functionality. This purposeful design serves as a physical Poka-Yoke (as shown in Fig. 1), effectively preventing mistakes at their source. Consequently, it reduces dependence on operator decision-making and removes the necessity for intricate electronic feedback systems, promoting a more efficient and error-resistant process.

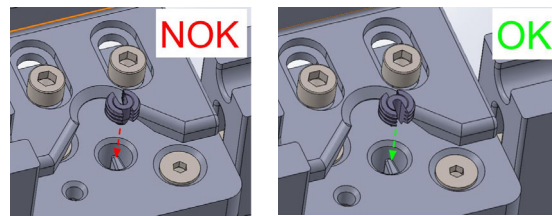


Fig.1. View of the Poka-Yoke assembly components showing correct placement.

Embedding the error-proofing directly into the mechanical design has multiple benefits. It reduces operator training time, minimizes human error, and accelerates assembly processes. Additionally, it ensures a highly consistent placement quality crucial for downstream processes such as harness mounting and electrical testing. The passive nature of the Poka-Yoke system also ensures minimal maintenance and high system reliability over extended production cycles.

2.2 Working Principle

The device uses a straightforward mechanical locking and unlocking system to ensure the accurate positioning of cable clips (see Fig. 2. for device bill of materials and exploded view).

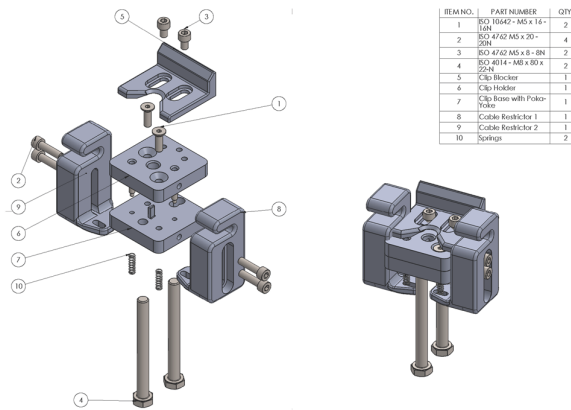


Fig. 5. Device Bill of Materials and Exploded View.

When the operator places the clip into the tool, it is firmly secured by mechanical restraints that prevent accidental movement. The system includes preloaded springs, as shown in Fig. 3, that apply a steady holding force.

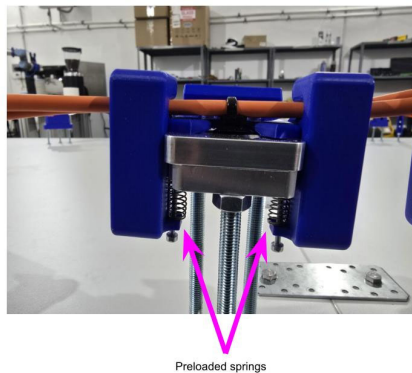


Fig.3. Tactile feedback mechanism with a spring-loaded.

When the operator inserts the cable clip into the tool, it is firmly held in place by strong mechanical grips, eliminating any accidental displacement also the system has preloaded springs, as illustrated in Fig. 2, which ensures that the next cable part is placed in the same position, ensuring repeatability and helps to reset the device automatically. Simultaneously, detailed geometric guides play a crucial role in aligning the clip seamlessly with the designated mounting surface. It stays securely locked until the clip reaches this perfect alignment, stopping advancement. When the operator places the cable clip into the tool, it is firmly secured by robust mechanical constraints, a key safety feature that prevents unwanted movement.

Furthermore, the tool's intricate design, including complex geometric templates, ensures the clip is positioned precisely onto the designated mounting surface. The clip remains securely in place until it reaches this precise alignment, preventing it from advancing to the fastening phase.

When the operator sets the clip at the designated mounting spot, a tactile feedback system indicates that the clip is securely in place. This reaction, characterized by a mechanical 'click,' comes from the mechanical compression or release of the internal springs designed within the tool which ensures also that the part is not moving when is not actuated by the operator, as illustrated in Fig. 3 It is only upon receiving this reliable mechanical confirmation that the tool's locking mechanism releases, permitting the operator to fasten the clip with a cable tie or an alternative securing method. This dependable series enhances the operator's assurance. It eliminates the possibility of early or incorrect fastening, ensuring that every placement conforms precisely to the specified positional tolerances without the need for electronic sensors.

After the operator adeptly positions the clip against the assigned mounting location, a dependable tactile feedback system activates, indicating that the clip is securely in place. This response, marked by a satisfying mechanical 'click,' stems from the delicate compression or release of internal springs carefully crafted within the instrument, as shown in Fig. 3. Only after this comforting mechanical confirmation does the tool's locking mechanism release, allowing the operator to proceed with securing the clip via a cable tie or alternative fastening means. This innovative method guarantees that every placement adheres strictly to essential positional tolerances, independent of electronic sensors. The lack of electronic components is a fundamental advantage of this approach, increasing the reliability of the process. The operator places the clamps in defined assembly locations, ensuring that a highly effective haptic feedback system is activated and that the terminals are securely positioned. This feedback is characterized by a soothing mechanical "click," resulting from the internal compression

of the spring and its precise release, as shown in Fig. 4. The tool's locking mechanism is only deactivated when it undergoes this unmistakable mechanical check, and the operator secures the ends using a cable sheet or other fastening method. This process has been carefully developed to maximize efficiency, communicate confidence with the operator, and significantly reduce the risk of early or false claims. It ensures that each placement meets the required positional tolerances without the need for electronic sensors, setting a new standard for reliability and accuracy.

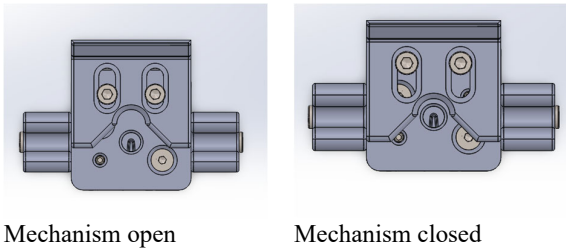


Fig. 4. Tactile feedback mechanism.

The simplicity of the passive mechanical system brings numerous operational benefits. It minimizes the device's complexity, making it highly durable and requiring minimal maintenance over time. Additionally, it reduces the need for extensive operator training since the tool inherently guides correct behavior without requiring continuous monitoring or adjustment. The lack of electronic components or active control systems also enhances reliability. Overall, the tool's working principle embodies core Poka-Yoke philosophies: preventing errors by design, enhancing process repeatability, and supporting consistent high-quality outcomes in automotive cable clip placement operations.

2.3 Material and Manufacturing

A hybrid manufacturing approach was used to promote good properties between strength, durability and flexibility. The construction foundation of the tool is CNC machined from aluminum and is chosen for its ability to maintain dimensional accuracy under its excellent strength, corrosion resistance and repetitive demands. This ensures the stability and durability of the cores required by production environments with different operating cycles.

3D printing using polylactic acid (PLA) film was used for non-critical components. PLA was chosen for its ease of printing, dimensional stability, mechanical strength and cost-effectiveness. PLA offers excellent dimensional stability. This ensures that the shrinkage rate is typically less than 0.3%, thereby maintaining the tight strength of complex geometries during production. It has a tensile strength of approximately 60 MPa and an elastic modulus of approximately 3.5 GPa, making it robust enough for elements that are not exposed to high loads.[15] Furthermore, the pressure-temperature is around 60°C, so PLA has a low warping tendency, allowing surface quality and geometric accuracy to be maintained without the need for a heated space [16]. The latest research confirms the reliability and effectiveness of PLAs to highlight biological degradation and minimal thermal expansion. A recent study has shown that correctly printed PLA can achieve greater strength and stability in challenging applications. This is a perfect and economical option to create the instructions and forms needed to design your tool, allowing for rapid iterations and reliable assembly services. The integration of aluminum and PLA-based 3D printing (see Fig. 5.) enables rapid prototyping and facilitates swift design changes. This method allows for pressure on the elements while simultaneously preventing the strong core structure, demonstrating the mobility and adaptability of the manufacturing process.

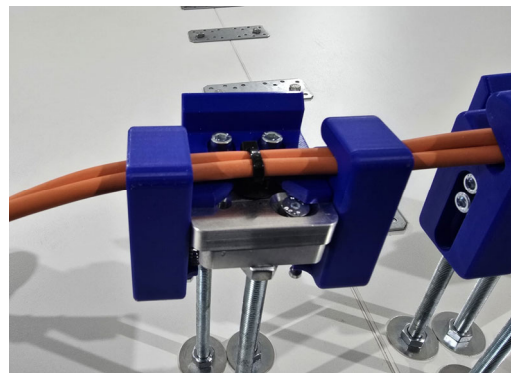


Fig. 5. View of the Poka-Yoke tool for cable clip placement with 3D Printed Materials(PLA).

3. MEASUREMENT AND VALIDATION

3.1 Optical Measurement and CMM Techniques

Validation of clip placement precision involved the use of high-resolution optical measurement systems capable of sub-millimeter accuracy. The optical systems enabled non-contact inspection of critical dimensions, minimizing the risk of measurement-induced deformation of delicate components. Placement accuracy was verified against reference geometries established on mock-up wire harness assemblies, replicating real production conditions.

The portability of optical measurement equipment allowed inline assessments without interrupting production flow. Measurement repeatability tests demonstrated variations of less than 0.1 mm, confirming the reliability of the optical system in quality assurance tasks.

In addition, regular calibration of the optical devices ensured long-term consistency. The measurement protocol included fixed sampling intervals and pre-defined measurement angles to standardize data collection. Overall, the use of advanced optical techniques provided a practical and efficient solution for validating clip placement precision, aligning with lean manufacturing goals, and promoting faster feedback for process optimization.

3.2 Statistical Results

Over a set of 100 placements, the measured average deviation was 0.32 mm with a standard deviation of 0.09 mm, confirming the tool's ability to keep placements within 0.5 mm tolerance limits. Maximum recorded deviation was 0.47 mm, well within acceptable thresholds. Table 1 summarizes the key measurement results.

Table 1. Summary of placement deviations

Metric	Value
Average deviation	0.32 mm
Maximum deviation	0.47 mm
Standard deviation	0.09 mm

The Statistical Process Control analysis conducted on 100 cable clip placements revealed a stable and capable process. The X-bar control chart (see Fig. 6.) showed that all subgroup means were within control limits, with a center line at approximately 0.31 mm, and no

violations of control rules, confirming consistent placement accuracy.

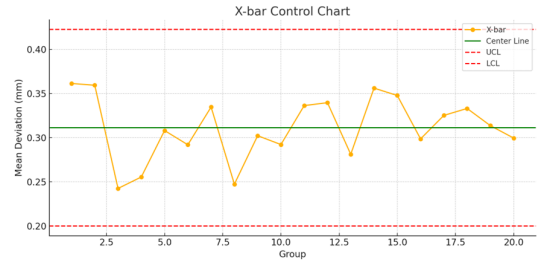


Fig. 6. X-bar control chart

The R chart (see Fig. 7.) further validated process stability, with all range values falling below the upper control limit, though some approached it, indicating minor internal variability.

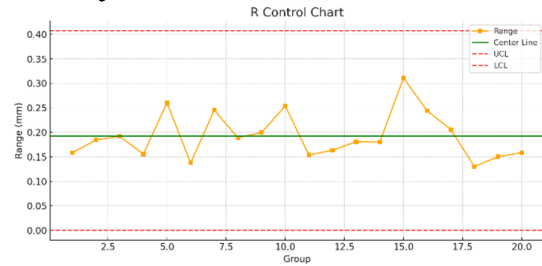


Fig. 7. R chart

Overall, the results demonstrate that the poka-yoke tool effectively maintains placement deviations well within the 0.5 mm tolerance, supporting high-precision assembly in an automotive context.

3.3 Statistical Process Control (SPC) Integration

To maintain ongoing quality assurance, an SPC framework was implemented using X-bar and R control charts specifically tailored for placement deviation measurements. Optical measurement data were collected at defined intervals during production, and control limits were calculated based on historical baseline data. Operators and quality engineers monitored real-time control charts displayed on a dedicated workstation near the assembly line. Any detected trend shifts, rule violations, or points outside control limits trigger immediate corrective actions, such as tool inspection or retraining of operators. As a result of the SPC implementation, rework rates decreased by 27% during the trial production period. The process capability analysis yielded

$C_p = 1.05$ and $C_{pk} = 0.79$. While the C_p indicates the process has adequate spread relative to the tolerance limits, the C_{pk} suggests a slight offset from the center of specification. Control charts further confirm process stability and support the tool's effectiveness in maintaining consistent placement quality within the 0.5 mm tolerance band.

4. FLEXIBILITY AND RAPID PROTOTYPING

4.1 Adaptability Challenges

3D printing technologies enabled the rapid and cost-effective modification of the tool for new cable shapes and clip designs. Thanks to the flexibility of additive manufacturing, alterations to tool geometry were easily incorporated, allowing design teams to prototype and verify new configurations quickly. The design cycle duration was significantly shortened compared to conventional machining methods, which typically required weeks for alterations, thereby improving production effectiveness.

3D printing played a crucial role in reducing reliance on external suppliers. New versions were refined and evaluated within 48 hours, reducing model change downtime. The internal capability to produce and evaluate new tool parts diminished reliance on outside vendors and enhanced the feedback cycle between design and manufacturing. This ability was essential for responding to changing cable sizes and clip designs, guaranteeing that manufacturing lines operated continuously at peak efficiency.

4.2 Rapid Prototyping Approach

3D printing technologies have significantly reduced design cycle time, enabling quick and cost-effective tool modification for new clip designs and cable shapes. The use of additive manufacturing techniques has enabled design teams to rapidly prototype and verify new arrangements, a process that previously could take weeks when using standard machining techniques.

New iterations developed and examined within 48 hours have drastically reduced downtime during model changes. 3D printing technology has allowed the beneficiary company to manufacture parts in-house, reducing

externalization costs. This technology offers significant economic benefits and simplifies communication and testing between the manufacturing and design teams, eliminating the need for external companies.

4.3 Modular Design Benefits

The fundamental mechanical characteristics were standardized to ensure the necessary dependability and consistency of performance across multiple tool configurations. Such consistency enabled straightforward maintenance and ensured the functionality of essential parts and alignment markers across varying operational conditions. This improvement, alongside increased cyclic dependability, reduced the complexity of trust during production.

On the other hand, the tool's efficiency is enhanced by using 3D modules printed with additive manufacturing for diverse outline shapes and wiring clips, thanks to predetermined designs for each harness and clip type. The modular configuration and the tool's speed enable rapid switching across multiple product versions. Standardization was performed for all pertinent features to ensure the tool's consistent performance and uniform dependability across different settings. This mechanical reliability, with consistent critical components and markings, allowed for adequate maintenance across various operational scenarios without burdening upkeep tasks. Such production procedures protected the complexity, bringing about the assurance of cyclic trust.

These flexible module designs further improve the tool's efficiency.

5. FUTURE WORK AND AUTOMATION POTENTIAL

The next phase of the research will focus on implementing an advanced collaborative solution that integrates poka-yoke mechanisms with cutting-edge measuring and detection cameras, as well as optical sensors. These innovative tools are specifically designed to automatically identify defects and deviations in processes, significantly enhancing the reliability and precision of our solution while facilitating

the development of a scalable manufacturing process.

Additionally, we will introduce a digital twin solution that enables the system to detect and adapt to new configurations autonomously. This capability will eliminate the need for external integrator teams for adjustments, thereby promoting greater agility within the system. We will make it easier for our system to adapt to various operations, thereby enhancing the collaboration and growth of our applications. This transforms our application into a more intelligent system that can fully leverage the benefits of Industry 4.0. By being proactive, we will boost efficiency and support ongoing improvements in various industrial applications.

6. CONCLUSIONS

This study demonstrates the successful design and implementation of a Poka-Yoke tool for high-precision cable clip placement in automotive manufacturing. Through mechanical error-proofing, placement deviations were consistently maintained at less than 0.5 mm. Integrating optical metrology and SPC reinforced quality assurance, highlighting early process deviations. Flexible modular design supported adaptability to varying vehicle platforms. Rapid prototyping techniques significantly reduced tool iteration cycles.

The proposed approach improves manual operations today and establishes the technical foundation for future robotic clip placement systems, advancing precision manufacturing principles in the automotive sector.

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OPTIMIZAREA PLASĂRII CLIPULUI DE CABLURI CU O ABORDARE POKA-YOKE PENTRU MONTAJ AUTOMOTIVE DE ÎNALTĂ PRECIZIE

În producția de automobile, asigurarea clemelor din plastic pentru cabluri cu coliere de cablu poate părea o sarcină simplă, dar este esențială pentru integrarea cablajului de sârmă. Nealinieră poate duce la conexiuni defecte, risipa de materiale și încetinirea producției. Acest studiu prezintă un instrument conceput pentru a îmbunătăți acuratețea plasării clipurilor. Utilizează un sistem mecanic de eliberare cu arcuri și aplică principiile Poka-Yoke pentru a preveni erorile. Scopul este de a face procesul mai precis, mai fiabil și mai rentabil. Tehnicile de măsurare și metrologia coordonatelor arată că instrumentul poate menține abaterile de plasare cu 0,5 mm și, în unele cazuri, până la 0,2 mm. Controlul statistic al proceselor (SPC) este introdus pentru urmărirea calității în timp real, îmbunătățirea eficienței și reducerea nevoilor de inspecție. Flexibilitatea este asigurată prin prototipare rapidă, permițând adaptarea la diferite dimensiuni de cablu și materiale de izolație. Studiul deschide, de asemenea, căi către automatizarea completă a procesului.

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