Parametric Tool for Automated Slot Insulation Insertion in Small-Scale Electric Motor Stator Production

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*Abstract -* The customer specific manufacturing of stators for electric motors in small-scale production is based on a time-consuming and expensive process chain. For this reason, the Institute for Factory Automation and Production Systems (FAPS) from Friedrich-Alexander University Erlangen-Nuremberg (FAU) is researching on solutions centered on the flexible automation of these processes. This paper presents a parametric mechanical tool designed for the robotic-based insertion of slot insulation paper in electric motors. While this task is predominantly performed manually in small-scale production, the proposed tool offers a flexible solution for automation. The parametric funnel enables rapid adaptation to different stator slot geometries by generating customized insertion tools. Given the limited profit margin, the cost-efficiency of the solution is a key factor in its development. The main goal is to improve flexibility in assembling different variants, small batch sizes and customer specifications.

Keywords - electric drive manufacturing; slot insulation insertion; flexible automation; robotic assembly; small-scale production

# Introduction

Electric motor production is experiencing unprecedented growth to meet the rising demand in various industries. As a result, both the design and manufacturing processes are undergoing continuous development.

* High Scale Productions: e.g. Automotive vs.:
* Production of electric motors in small batches is common in industries such as aerospace or ship propulsion where electric motors are custom designed based on the specific requirements [with source]

An electric motor generally consists of three main components: the stator, the rotor, and the housing. The housing is typically produced through pressure die casting, followed by precision machining. The stator and rotor cores are made from laminated electrical steel sheets, which are shaped using either punching or laser cutting methods. These laminations are then assembled using techniques such as riveting or adhesive bonding. Once assembled, slot liners and copper windings are installed in the laminated core. The winding phases are then insulated, formed, and interconnected. The ends of the enameled wires are connected through soldering or welding, followed by processes like bandaging, electrical testing, and impregnation to finalize the stator. [1]

This paper focuses on optimizing the slot liner insertion process. In low-voltage electric motors, the slot liner serves two key purposes: it provides electrical insulation for the winding and facilitates effective thermal dissipation. Enhancing the thermal conductivity of the slot liner while retaining its insulating properties can contribute to improved motor efficiency. [2]

A close up of a plastic container

AI-generated content may be incorrect.

Figure 1. Stator with slot liners

* In such a context, implementation of a dedicated slot-liner insertion machine for every stator size and design is not feasible
* Manual insertion is usually done here, which can be:
* Operator dependent, leading to variability in quality, exhausting/boring
* Less scalable and more expensive
* Automating this task using a general purpose industrial robot or cobots (such as UR10e (it’s a cobot: cheaper and way weaker for human-robot-interaction)) combined with a parametric tool for different stator sizes can significantly improve:

1. Process repeatability
2. Efficiency and cycle times
3. Flexibility for high variable, low volume production
4. Cost efficiency

* But, necesarry to consider: low programming efford required to align the cost efficiency due to high worker costs

# State of the Art

Add a small chapter introduction sentence here as you cannot have to headlines directly in line.

## Solutions for large scale production

In the up-to-date electric motor manufacturing, particularly for distributed windings, advanced slot insulation processes are employed to ensure precise and reliable electrical insulation of the stator slots. One prominent example is the system developed by *Schaeffler*, the ELMOTEC STATOMAT, which uses automated machinery to insert specially shaped insulation paper (e.g., U-, O-, B-, or S-shape) into each stator slot. This process involves a sequential combination of creasing, folding, inserting, and cutting the insulation material to exact specifications. The system ensures accurate paper protrusion on both flat surfaces of the stator stack, protecting the copper winding from sharp edges and avoiding interference during insertion. The machines are designed for both small and large series production, offering high adaptability through features such as an automatic empty cycle mechanism allowing the system to skip specific slots as needed for complex winding patterns or customized slot configurations. With insertion speeds reaching up to three sleeves per second, the system provides a balance of flexibility, precision, and high throughput, thereby supporting efficiency and scalability for motor production processes. [3]

(Somehow a counter argument showing a tool for large- AND SMALL-scale solution, please add a negative point here to highlight our solution (price, Higher Flexibility for following tasks? Less Programming, Higher Range of variations possible?))

A machine with a screen and buttons

AI-generated content may be incorrect.

Figure 2. Dedicated slot liner insertion machine [src, alliance winding equipments]

In addition to Schaeffler’s ELMOTEC STATOMAT systems, several other industrial manufacturers offer advanced solutions for automated slot insulation in electric motors. *Alliance Winding Equipment* offers machines that form, cuff, and insert insulating materials into stator or rotor slots. These systems, exemplary shown in Fig. 2, integrate cam and servo controls for both speed and precision and allow rapid tooling changes to support multiple lamination types with minimal downtime [4]. *GROB* provides programmable insulation machines with user-friendly operation, offering precise control over insulation length, height, width, and cuff formation—delivering high performance in both accuracy and productivity [5]. *Delta S.R.L.* contributes with slot insulation machines that cut, shape, and insert insulators tailored to the specific slot geometry. These machines support robotic stator handling, quick mold changeovers, and automated height adjustment, making them ideal for high-output production environments. (for references is the web page link required? -> I will check that again, as a datasheet as I mentioned is non-permanent too, same with websites, I am not quite sure here)

A metal roller with words

AI-generated content may be incorrect.A diagram of a grooving roller

AI-generated content may be incorrect.

Figure 3. Grooving module and process principle [6] Adjustable grooving module with two gear-coupled rotating shafts; groove depth and width are controlled by roller spacing and track design, forming precise grooves on 0.2 mm thick slot liners.

## Solutions for small scale production

Despite significant advancements in automation, manual insertion of slot liners remains the standard practice in the small-scale manufacture of electric motors. In such setups, operators typically cut, fold, and insert the slot liners entirely by hand, or use machines for cutting and folding as shown in Fig. 3, while performing the insertion manually with simple jigs. This process relies heavily on visual inspection and tactile feedback to ensure proper alignment. However, with the growing demand for electric motors, the need for scalable and streamlined production is increasing. In this context, automation becomes a better alternative, not because manual methods are ineffective, but because they are difficult to integrate into digital workflows, challenging to scale, and not easily documented for consistent reproduction. [Source]

## Automation Principles

This Chapter needs to contain the overall principles of automation, keep in mind that this is still state of the art and has no information about our robot cell. Keep it short, also there is a nice Paper somewhere for sure with maybe a nice graph about automation.

* Define principles for flexible small-scale automation
* Significant less work for worker, more for automation tool.
* Cost efficient alternative to high end machines
* Easy configuration to new variants to keep effective in small scale
* **Scope for expansion –** The system architecture supports modular upgrades. Code and hardware setup remain modular to accommodate future feedback loops or dynamic planning
* Stable processes
* (only a brainstorming by me, if u find a nice source take those information you find)
* Scalability

## Design for flexible automation

This Chapter contains the fundamentals in process design when planning to create a flexible automated process. Keep it short again.

* Parametric tooling for flexibility with different variants. CAD based funnel models are parametrically defined to allow quick adaptation to different geometries and sizes. Advantages – low cost and low lead times when changing configurations
* Robots and standard tools for flexibility
* Potential for modular improvements / adjustments / enlargements like vision feedback or other sensors
* Smart Systems (Digital (like environment knowhow or trajectory commands instead of movement flexible Goal-Poses of robots) or Hardware) for stable adjustment adaptions
* Scalability (also here, as bigger charges are part of flexibility)

## Variety in Electric Motor Stator Designs

Maybe we can include a chapter of typical stator types, like sizes, slot shapes, number of slots, etc. and maybe we even find a graph/picture about the diameter distribution of stators/motors or similar

## Derivation of consequences

This needs to be again a quite short chapter where we show that we need flexibility and an easy configuration setup to match the state of the art

* Actuator (Robot): Flexible in size & movement, cheap, easy programmable (parametric), standard Tools (Gripper)
* Tool: Parametric, cheap in manufacturing, easy to configure
* Process: robust, fast, hardware to software feedback against robot tolerances (searching algorithms, FT-Sensors)

# Hardware Setup for flexible slot liner insertion

The hardware setup centers around a modular robot cell designed to support flexible and precise slot liner insertion in electric motor stators. This cell integrates a collaborative robot, adaptive gripping tools, and sensor feedback, all managed through a compute box that enables real-time control and adaptability. The main components of the setup include:

* UR10e Co-bot
* Sensor integration (HEX- Force-torque sensor) supports modular feedback capabilities, which would improve the funnel and slot liner insertion process
* An RG2 adaptive gripper allows for flexible grasping of slot liners or funnels, supporting different sizes and insertion techniques without mechanical reconfiguration.

A grey robot arm with black handles

AI-generated content may be incorrect.

Figure 4

The robot, sensor, and gripper combination form a modular, reconfigurable automation cell, well-suited for research environments and evolving production needs.

* The automation setup is designed to adapt to varying stator geometries and slot designs, common in production of electric motors in small batches. This is achieved through modular hardware and a parametric tool design.
* Interchangeable parametric tools – Custom funnels are generated through parametric CAD models, enabling rapid reconfiguration for different stator types. These tools can be easily fabricated through 3D printing.
* **Sensor-Assisted Modularity**
  + The integrated **HEX force-torque sensor** actively monitors contact forces during **funnel insertion**, enabling force-based feedback to ensure correct positioning and avoid excessive contact forces or misalignment.
  + This sensor-based interaction enhances robustness during setup and allows the robot to respond to resistance, improving insertion accuracy.
  + The presence of the sensor also makes the system extensible—allowing future integration of **active force-feedback control** during slot liner insertion, enabling more precise and adaptable operation under variable tolerances.

# Parametric Tool For Flexible Slot Liner Insertion

While general guidelines exist for stator slot design, the geometry is typically customized to optimize specific performance characteristics such as electromagnetic efficiency, torque output, thermal management, and harmonic reduction. As a result, slot dimensions and shapes can vary significantly depending on the motor’s intended application [7]. For example, [8] specify slot heights of 30 mm and slot widths of 20 mm. In contrast the stators used in the present study have different dimensions: One stator has a slot height of 20 mm and a slot width of 8 mm, while the other has a slightly larger slot height of 22 mm but the same slot width. This variation highlights the need for parametric tools Different angles of different angles of a metal object

AI-generated content may be incorrect.that can adapt to different geometries to support flexible and efficient insertion of slot inserts.

## Selection of required adjustable Parameters

A diagram of a slot angle

AI-generated content may be incorrect.The parameters selected for the adjustment - Slot width, Slot height and Slot angle - have a direct influence on the geometry of the funnel and therefore on the success of the insertion of the slot liner. These parameters vary between different stator designs due to different electromagnetic and mechanical performance requirements. By determining and adjusting these key dimensions, the insertion tool can be effectively adapted to a wide range of stator topologies.

The selected parameters and their respective roles are as follows:

* Slot-Width - governs the base opening and determines the maximum liner width that can be inserted.
* Slot-Height - dictates the depth of insertion required and impacts on the structural dimensions of the funnel.
* Slot-angle - affects the taper or curvature at the slot entrance, which is critical for guiding the liner during insertion without mechanical interference.

## Fundamental Tool design

To enable reliable and flexible slot liner insertion in small batch electric motor production, a custom design funnel tool was developed and integrated with a UR10e robot equipped with a RG2 gripper and HEX FT sensor. The funnel serves as a mechanically guided insertion aid that aligns the slot liner with the stator slot. The design is parametric, allowing rapid customization for different stator geometries and insertion requirements.

* The tool consists of an **enclosed rectangular body** with an **internal tapered channel** that converges toward the stator slot.
* The inner surface of the funnel features **two gently curved guiding walls**, directing the slot liner into the correct slot while maintaining central alignment
* The central opening ensures that the liner passes through only when aligned, preventing twisting or buckling.
* The **tapered profile** of the funnel not only aligns the slot liner but also **slightly compresses it**, ensuring it holds its shape as it passes into the stator
* The rectangular notch at the front face of the funnel extends inward along the slot profile, forming a continuous guide that aligns with the inner geometry of the stator slot. This ensures that the slot liner is consistently positioned at the correct height relative to the slot, improving insertion accuracy and repeatability.
* A screenshot of a computer

  AI-generated content may be incorrect.Guide rail on the back of the funnel ensures that the funnel is properly aligned with the slot
* Slots on the sides of the guide rails ensures for tighter insertion of the funnel and it also ensures that the funnel is locked to the stator
* The mouth of the funnel is intentionally widened to provide a tolerance margin, accommodating slight misalignments during slot liner insertion.
* The tool is lightweight and fabricated using 3D printing, which allows for quick iteration and low-cost customization in small-batch production environments.
* The sides of the tool were made to be flat so that the robot can properly grip the tool. (a side length of 20 mm is favorable for proper gripping)
* The tail of the tool was intentionally made longer (50 mm) to obtain a better position for the center of gravity. This ensures that the tool does not tilt forward and causes misalignment with the stator.
* A gap of 1 mm was set between the guide notch and the bottom opening of the funnel so that the funnel insertion is done more smoothly. The ends of the guide notch was also tapered off to prevent the slot liner from coming back with the funnel during funnel removal

## Fitting Adjustable parameters for specific use cases

To demonstrate the adaptability of the parametric funnel design, two stators with different slot geometries were selected as representative use cases.

* The first stator (add dia of the stator) featured a slot height of 19.50 mm
* The second stator (add dia of the stator) had a slot height of 22 mm

The funnel geometry was modified in CAD by adjusting the predefined parameters – The slot width and the entry height. The changes were made without altering the core design highlighting the rapid configurability of the tool

The adjusted funnels were then fabricated and prepared for testing with the UR10e robot. These configurations were used in the subsequent validation phase to assess insertion repeatability and alignment accuracy across different stator sizes.

# Parametric Slot Liner Insertion Pipeline

The automation pipeline was designed to execute the slot liner insertion process in a modular and safe manner, utilizing the UR10e robot in conjunction with a custom 3D-printed funnel, a platform for tool positioning, and a platform for slot liner handling. The pipeline is divided into multiple stages, with sensor-based feedback integrated to improve safety and accuracy during funnel insertion.

This pipeline demonstrates a modular, sensor-assisted approach to slot liner insertion that balances flexibility, mechanical guidance, and safety. It is designed to be adaptable across different stator geometries with minimal hardware or software changes.

## Parametric Application Pipeline

The automation pipeline is designed to support adaptation to varying stator geometries by adjusting key operational parameters — specifically, the **funnel approach height** and **insertion depth**. Because stator designs can differ significantly, relying on fixed robot waypoints is not sufficient for consistent performance across different models.

To address this, the system architecture accommodates a **sensor-assisted, parametric approach**. In this configuration, a URScript-driven robot, in combination with a HEX force-torque sensor, can be used to detect contact points and guide the insertion process dynamically. For instance, the robot can position the funnel above the slot and lower it until contact is detected at the funnel tail via a change in force feedback, establishing the correct vertical alignment. Following this, the insertion continues until a predefined force threshold is reached, indicating full engagement with the stator.

This approach enables the pipeline to **adapt to different stator topologies with minimal hardware changes**, providing a flexible foundation for scalable deployment

## Funnel Application

* The robot first picks up the funnel using the RG2 gripper and moves it above the target stator slot.
* It lowers the funnel onto the stator, till the tip of the tail of the funnel is in contact with the stator. This ensures that the correct height is reached.
* The **HEX-E force-torque sensor** monitors insertion forces in real time:
  + If excessive resistance is detected (i.e., above a preset threshold), the robot aborts the insertion to prevent damage from misalignment.
  + Once the funnel makes confirmed contact with the slot (detected by a consistent increase in contact force), the robot completes the insertion.
* The robot then opens the gripper and **leaves the funnel in position** on the stator.

## Slot Liner Positioning and Partial Insertion

* The robot moves to the slot liner platform and picks up a pre-folded slot liner.
* It positions the liner in front of the funnel opening for insertion.
* **Force feedback is not utilized** during this step, as misalignment can cause the robot to lose grip on the slot liner; in such cases, a safety stop is triggered to prevent damage.
* The slot liner is inserted **as far as possible**—typically about three-quarters of the way—**until the gripper reaches the front opening of the funnel**
* The robot releases the slot liner and proceeds for funnel extraction.

## Final Liner Insertion

* After partial liner insertion, the robot re-grasps the funnel and begins a **start-and-stop retraction motion** to carefully withdraw it without pulling the slot liner back with it.
* This discontinuous motion reduces the chance of the slot liner being dragged back due to friction or inadequate slot fit
* Once the funnel is fully removed, the robot uses the funnel itself as a **pushing tool** to complete the insertion of the slot liner into the stator slot.
* This ensures that the liner is securely seated and flush with the stator surface.

# Tool Process Testing and Validation

To validate the effectiveness of the proposed funnel design and automated pipeline, insertion trials were conducted on two stators with different slot geometries—one with a slot height of **19.50 mm** and the other with **22.00 mm**. For each stator, the funnel was adapted using parametric design changes, and the corresponding version was 3D printed for testing.

The system was evaluated through repeated robotic insertion trials, simulating realistic usage conditions. For each stator “n” number of trials were performed, and the robot followed the same insertion pipeline described previously, using the HEX force-torque sensor and the RG2 gripper.

## Setup for Testing and Validation

To carry out the insertion trials and validate the automation process, a dedicated test setup was designed and implemented. The setup consists of the following key components:

* Funnel Platform: A custom 3D-printed platform was developed to securely hold the funnel in a fixed position, allowing the robot to reliably pick it up from the same location in every iteration for consistent operation.
* Slot Liner Platform: A separate platform was created to hold a single pre-folded slot liner in a fixed position, enabling reliable gripping by the robot. This setup supports repeatable pick-and-place operations for insertion trials, although the slot liner must be manually reloaded after each cycle.
* Rotating Clamp for stator mounting: The stator is fixed to a **mechanical rotating clamp**, which allows it to rotate by a fixed angle after each successful insertion. Since the stator contains **36 slots**, the clamp is configured to rotate by **10 degrees** per step, ensuring the next empty slot is always aligned with the funnel for subsequent insertions.  
  This design enables **sequential testing** of multiple insertions without manually repositioning the stator.

All components, including the mechanical clamp, funnel platform, and slot liner platform—were arranged within the UR10e robot’s workspace to ensure easy and efficient access. This layout enables smooth and repeatable execution of the insertion pipeline across multiple trials and different stator types.

(add photos of funnel platform and slot liner platform and the robot)

## Validation Conditions

* No of stators used
* Dimension of Stators
* Dimension of funnel
* How many trials were done per Stators

## DOE and its Variants

* Success rate
* Cycle time

# Result Discussion

Lorem Ipsum

# Outlook

Lorem Ipsum

* **Remaining challenges and future work:** The current system does not automate the full slot liner cycle (grooving, folding, and cutting). Integration of pre-folding tools and a slot liner dispenser mechanism could significantly improve the robustness of the system

##### References

Capitalize only the first word in a paper title, except for proper nouns and element symbols.

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