

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

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Abstract— The increasing trend toward automation in electric motor manufacturing has led to the development of robotic systems for processes such as winding insertion, lamination stacking, and stator assembly. One critical step, slot liner insertion, is typically automated in large-scale production using dedicated Slot Liner insertion machines. However, in small-scale manufacturing, this process is predominantly performed manually due to low production volumes and the impracticality of configuring specialized machines for each variant. This paper presents a flexible and scalable approach by using a parametric funnel in conjunction with a UR 10e robot equipped with a HEX Force-Torque sensor and a RG2 Gripper to insert the slot liner into the stator. The parametric funnel, modeled using CAD, enables rapid adaptation to different stator slot geometries by generating customized insertion tools. This method aims to reduce manual effort, setup time, and cost, making it suitable for low-volume, high-variability production environments. Experimental validation demonstrates the feasibility and repeatability of the proposed system, indicating its potential for improving flexibility in motor manufacturing.

Keywords— Slot Liner Insertion, UR10e Robot, Parametric funnel, low-volume high variability production

I. 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 optimization. An electric motor generally consists of three main components: the stator, rotor, and 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]



Fig.1 Image of Stator with slot liner insertions. Elmotec Statomat

Need for Small scale Automation –

- Production of electric motors in small batches is common in industries such as aerospace where electric motors are custom designed based on the specific requirements
- 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:
 1. Operator dependent, leading to variability in quality
 2. Less scalable and harder to document
 3. Prone to errors and physically straining when repeated over long durations
- Automating this task using a general purpose industrial robot (such as UR10e) 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

II. STATE OF THE ART

A. Solutions for large scale production

In state-of-the-art 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 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]

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 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?)



Fig 2 Dedicated slot liner insertion machine from alliance winding equipments

B. 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 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.

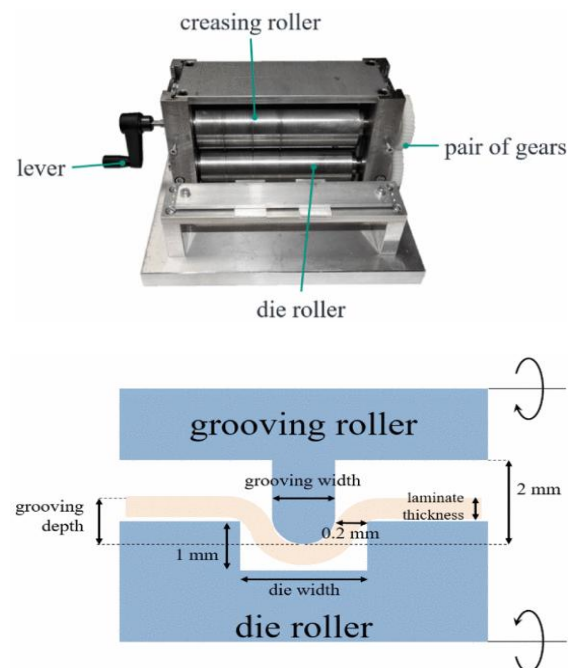


Fig 3, 4 grooving module and process adapted from [6]

C. Automation Principles

1. **Parametric tooling for flexibility with different variants.** CAD based funnel models are parametrically defined to allow quick adaptation to different slot geometries. Advantages – low cost and low lead times when changing stator configurations
2. **Low-cost automation for small scale production.** The focus is on creating a cost-effective alternative to high end slot liner machines for small scale high variability production. A UR10e robot is used here, due to its balance of affordability, ease of deployment and a user-friendly interface for programming
3. **Mechanically guided precision** - Use of a parametric funnel helps mechanically align the slot

liner with the stator slot, minimizing the reliance on sensors or vision systems.

4. **Scope for expansion** – The system architecture, including the force-torque sensor and gripper, supports modular upgrades such as real-time force feedback or adaptive control. Potential to integrate vision in future stages. Code and hardware setup remain modular to accommodate future feedback loops or dynamic planning

D. Flexibility in automation

- The use of a parametric funnel design enables rapid customization of insertion tools to match different stator slot dimensions.
- 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.
- The robot, sensor, and gripper combination form a modular, reconfigurable automation cell, well-suited for research environments and evolving production needs.



Fig 5.6 Hex FT sensor and RG2 gripper

E. Parametric tools and processes for flexibility enlargement

- 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-E 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.

F. Derivation of consequences

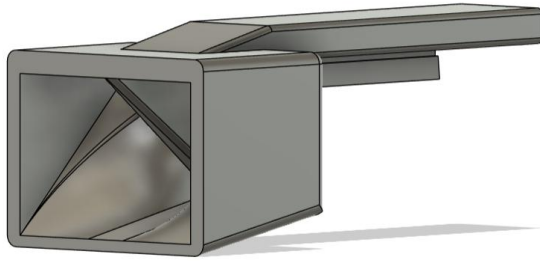
- **Effectiveness of a mechanically guided system:** The use of a parametric funnel enabled proper alignment of the slot liner even without the implementation of complex sensors such as vision. This confirms that mechanical guidance is a viable method for small batch automation where sensor complexity is undesirable
- **Impact of HEX Force-Torque Sensor:** Using a FT sensor during funnel insertion reduced the risk of over-pressing and misalignment which would otherwise damage the funnel. (add FT to list of abbreviations)
- **Scalability for high variant manufacturing:** The parametric nature of the funnel allows rapid adaptation to different stator geometries. This demonstrates a clear path for scaling the system towards high-variability low volume environments such as prototyping or small batch electric motor production
- **Process sensitivity to slot-liner geometry:** The success of the insertion process was found to be dependent on the profile of the slot liner. If the slot liner is not pre-bent into the exact requirements, it tends to return with the funnel during retraction. This highlights the need for precise slot-liner preparation to ensure a successful insertion process
- **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

III. PROPOSED PARAMETRIC TOOL AND PROCESS

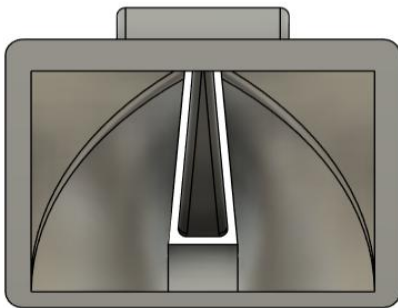
To enable reliable and flexible slot liner insertion in small batch electric motor production, a custom design funnel tool was developed and integrated with a UR10e robot equipped with a RG2 gripper and HEX FT sensor. The funnel serves as a mechanically guided insertion aid that aligns the slot liner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

A. Fundamental Tool design

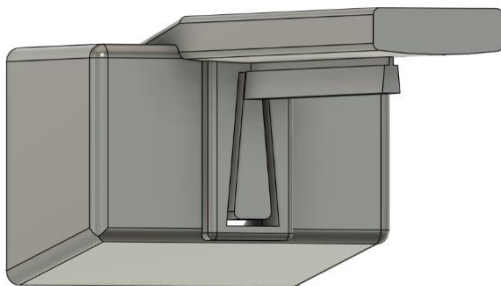
- The tool consists of an **enclosed rectangular body** with an **internal tapered channel** that converges toward the stator slot.



- 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 notch in the front of the funnel extrudes to the inner portion of the slot geometry, ensuring that the correct height of the slot-liner with the slot is always maintained (could use more clarity)



- 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.

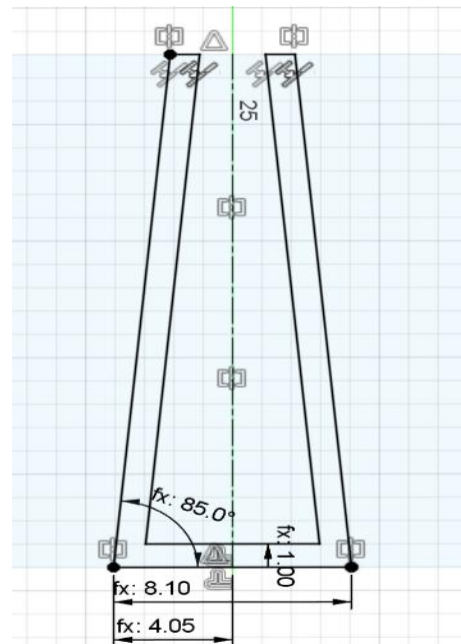
- The sides of the tool were made to be flat so that the robot can properly grip the tool. (a side length of 20 mm is favorable for proper gripping)
- The tail of the tool was intentionally made longer (50 mm) to obtain a better position for the center of gravity. This ensures that the tool does not 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



B. Selecting of adjustable Parameters

Required parameters:

- Slot-Width
- Slot-Height
- Slot-angle



(how many images of the funnel are required?)

The slot height has been mapped to the height of

the funnel so that the entire height of the funnel changes in accordance with the slot height.

C. 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 a few predefined parameters such as slot and 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.

D. Proposed automation 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.

1. Funnel Placement

- 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.

2. 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.

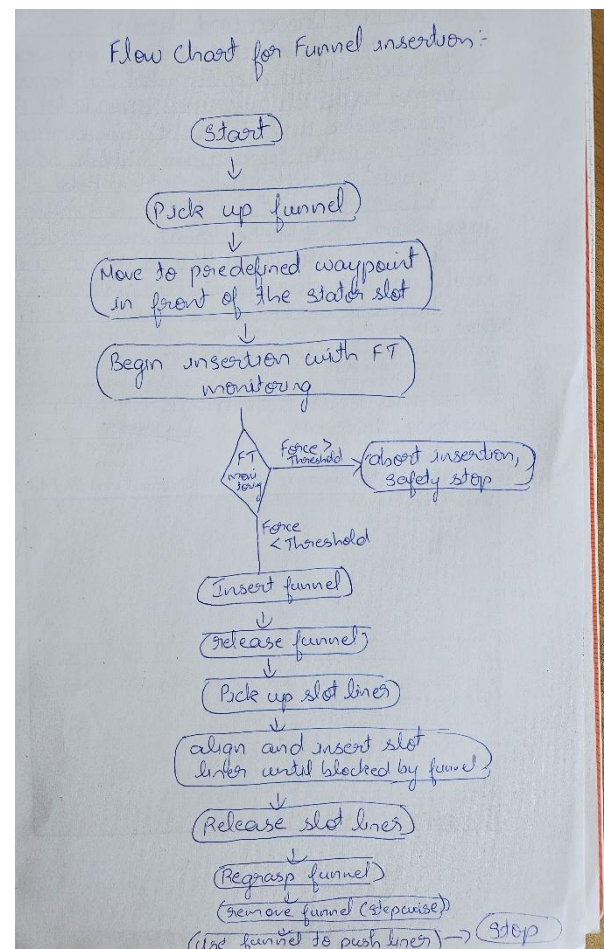
- **Force feedback is not utilized** during this step, as misalignment can cause the robot to lose grip on the slot liner; in such cases, a safety stop is triggered to prevent damage.
- The slot liner is inserted **as far as possible**—typically about three-quarters of the way—**until the gripper reaches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

3. Funnel Removal

- 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

4. Final Liner Insertion

- 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.



(Mention about UR Script, use of waypoints, teach pendant ?)

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.

IV. 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.

A. 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.

B. Validation Conditions

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

C. DOE and its Variants

- Success rate
- Cycle time

RESULT DISCUSSION

The preferred spelling of the word “acknowledgment” in America is without an “e” after the “g”. Avoid the stilted expression “one of us (R. B. G.) thanks ...”. Instead, try “R. B. G. thanks...”. Put sponsor acknowledgments in the unnumbered footnote on the first page.

REFERENCES

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

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V. REFERENCES

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