AI-Powered 5-Axis Robotics deployment for Enhanced Manufacturing Accuracy in Slot Machining by substituting Typical Injection Molding from Long Fiber Reinforced Thermoplastics

Dhrudipsinh Dabhi

Technical Program Manager

Abstract:
In this paper, I describe the development and successful implementation of a 5-Axis AI-powered robotic system that machines precision slots in a 50-inch-long part made of Long Fiber Reinforced Thermoplastic material. The challenge of maintaining slot tolerances during the molding process was unachievable due to the 0.010" ± 0.002"-dimension requirements and the risk of mold breakage caused by thin steel conditions. Therefore, we had to NO-Quote this business for this customer. These conditions made it impractical to include the slots in the mold itself. To overcome these challenges, I worked closely with the Customer's Engineering Department and an automation company to develop an AI-powered post-molding solution, which allowed for the precise machining of slots and the use of a 0.012" trimming blade to remove flash and prevent debris blockage. This system has been operational since March 2020 and has significantly reduced operational risks while improving product quality and production efficiency.

Keywords: AI-powered robotics, 5-axis robot, Long Fiber Reinforced Thermoplastic, precision slot machining, 0.010" ± 0.002" tolerance, flash removal, mold tolerance issues

Introduction:
Injection molding is a widely used process in manufacturing, but achieving precision in certain features, especially when working with complex materials like Long Fiber Reinforced Thermoplastics, can present significant challenges. In this particular project, I was tasked with producing a 50-inch-long part that required multiple small, precise slots. The slots, which had to be machined to a dimension of 0.010" ± 0.002", were critical for the functionality of the part. Initially, the idea was to incorporate the slots into the molding process, but this quickly proved impractical. Given the small size of the slots and the overall length of the part, it became clear that molding the slots directly would not achieve the necessary tolerance.
I've faced similar challenges before when designing molds for complex parts, and I know how difficult it is to maintain tight tolerances in such situations. The combination of small slot dimensions and a long part introduces additional issues like thin steel conditions in the mold, which increase the likelihood of breakage. These breakages can cause significant downtime, leading to increased costs and production delays. Moreover, working with Long Fiber Reinforced Thermoplastics adds another layer of complexity due to the nature of the material, which can lead to dimensional variations during molding. Fiber-filled thermoplastics tend to

behave differently during the cooling and solidification process compared to non-reinforced materials, making it difficult to maintain precise dimensions.

Figure 1: Close-up of the intricate slots requiring post-molding machining.

Recognizing the risks of attempting to mold these slots directly, I decided with the Customer company to explore an alternative approach: creating the slots post-molding through automation. I collaborated with an automation company along with my customer company to develop a 5-axis AI-powered robotic system capable of machining the slots after the parts were fully molded. The goal was to ensure that each slot met the required tolerance without compromising the integrity of the part or the mold itself. This approach not only addressed the tolerance issue but also minimized the risk of mold breakage and improved the overall production process.
The challenges I faced during the design phase of this project underscored the importance of integrating advanced technologies, such as artificial intelligence, into manufacturing. By leveraging AI and automation, we were able to achieve the required precision without the limitations that traditional molding methods would have imposed. In the following sections, I will describe the specific challenges encountered during this project and the solutions that were implemented to overcome them.

Problem Statement:

The challenges I faced in this project can be broken down into three primary issues:

1. Maintaining Tight Tolerances During Molding:

The first challenge was maintaining the required 0.010" ± 0.002" tolerance for the slots during the injection molding process. The part was 50 inches long, and the slots, which were 0.012 inches wide, needed to be accurately produced along this length. Achieving this level of precision in a single molding operation was extremely difficult, primarily due to the risks associated with thin steel conditions in the mold. Thin steel areas, created by attempting to mold such small features, would be prone to breakage under the high pressures used in injection molding. Each mold breakage would result in significant downtime, expensive repairs, and delayed production schedules—issues I had encountered in previous projects.

2. Material-Specific Challenges with Long Fiber Reinforced Thermoplastics:

Another major issue stemmed from the material itself. Long Fiber Reinforced Thermoplastics, while offering excellent strength and durability, are difficult to work with in terms of maintaining dimensional accuracy during molding. The fibers within the material influence the way the plastic flows and cools inside the mold, which can result in dimensional variations, particularly for small and intricate features like the 0.010" ± 0.002" slots. These variations can cause the parts to be out of tolerance, which would negatively impact the overall functionality of the part. Controlling all variables—like pressure, temperature, and cooling times—was crucial, but even with strict process control, achieving consistent results with such small features was challenging.

3. Complexity of Pin Mechanism and Synchronization:

The third challenge related to the pin mechanism that would have been necessary if we had attempted to mold the slots directly. To form the slots during molding, pins would need to move in and out of the mold with extreme precision during the mold's opening and closing. However, past experiences taught me that synchronizing pin movements is incredibly difficult, especially when dealing with such tight tolerances. Even minor misalignments in the pin movements can cause excessive wear on the mold or, in the worst cases, catastrophic mold breakages. The frequent mold failures caused by pin misalignment in previous projects made me highly cautious of attempting this approach for slot creation in this part.

Given these challenges, it became clear that trying to mold the slots directly would lead to unacceptable risks, including frequent mold breakage, inconsistent part quality, and production delays. The best solution was to machine the slots post-molding, which would allow us to achieve the required precision while minimizing risk. The AI-powered 5-axis robotic system was designed specifically to address these issues, providing precise slot machining and flash removal while ensuring that the mold remained intact and operational.

Design and Implementation of the 5-Axis AI-Powered Robot:

To address these challenges, I worked with the customer company's engineering group and an automation company to design a 5-axis AI-powered robotic system specifically for machining the slots after the part had been molded. The robot was programmed to detect each of the slot locations on the 50-inch part using advanced sensors and machine learning algorithms. These systems ensured that the robot could adjust to any slight variations in the part's shape or size, which is especially important when dealing with long fiber-reinforced materials.

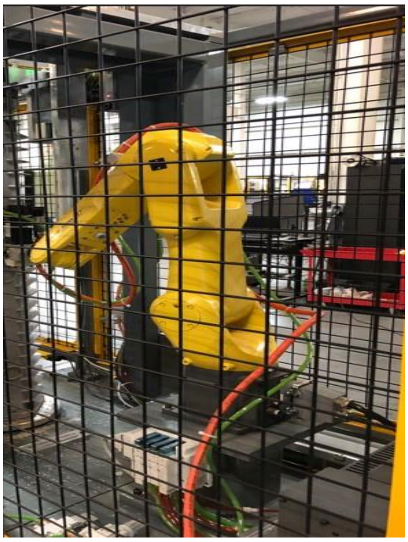

Figure 2: The 5-axis AI-powered robot performing the slot machining post-molding.

Once the robot detected the correct positions, it used high-precision cutting blades to machine the 0.010" ± 0.002" slots. The design of the robot allowed it to move along the part's entire length, machining each slot to the correct size and position. The AI-driven system also monitored and adjusted the cutting process in real time, ensuring that any deviations in the material were corrected during machining.

Figure 3: The robotic arm precisely machining the slots in the Long Fiber Reinforced Thermoplastic part.

One critical component of this system was the trimming blade used to remove flash from the slots. The blade was designed to ensure that the debris was effectively removed without damaging the surrounding material. The use of this blade, in conjunction with the precision of the robot, ensured that no debris would block the slots, thereby guaranteeing the part's functionality.

Challenges in Molding and Slot Creation:

1. **Thin Steel Conditions**:

The major challenge in molding the slots directly into the part was the creation of thin steel conditions in the mold. With the small slot size and the length of the part, any attempt to incorporate the slots into the mold would have resulted in areas of the mold that were too thin to withstand the pressures of injection molding. These conditions lead to frequent mold breakage, resulting in costly downtime, scrap, and repairs.

2. **Pin Movement and Synchronization**:

A secondary issue was the need for cylindrical pins to create the slots during molding. These pins would need to retract during the mold opening process and re-enter during mold closing. If not perfectly synchronized, these movements could cause significant wear on the mold or even catastrophic breakages. Past experiences with similar systems showed a high failure rate due to this complexity, which further reinforced the need for a post-molding solution.

3. **Material Challenges**:

Long Fiber Reinforced Thermoplastics introduce additional complexity due to their fiber content, which makes precise molding difficult. The fibers can affect the flow of the material, leading to variations in part dimensions. This made post-molding slot creation even more necessary to maintain tight tolerances.

Results:

Since the implementation of the 5-axis AI-powered robotic system in March 2020, the results have been remarkably positive. The robotic system has proven to be extremely reliable in maintaining the tight tolerances required for the slots—0.010" ± 0.002"—along the 50-inch part. This consistency has been achieved even with the inherent challenges of machining Long Fiber Reinforced Thermoplastic material, which has a tendency to exhibit variations in dimensions due to its fibrous content.

The AI-powered system’s real-time adjustment capabilities have been instrumental in achieving this level of precision. By continuously monitoring the part's dimensions and making micro-adjustments as needed, the robot has been able to maintain slot accuracy throughout the entire machining process. This has resulted in a significant improvement in part quality, as every slot meets the required specification without deviation. Prior to implementing this system, it would have been virtually impossible to achieve this level of precision manually or through traditional molding processes.

The trimming blade, sized at 0.012", has also played a crucial role in ensuring the success of this operation. Flash removal is a critical step, as any debris left in the slots could obstruct the functionality of the final product. The blade’s ability to cleanly trim the flash without damaging the surrounding material has ensured that all slots remain free from obstructions, preventing potential issues down the line. In fact, I’ve been able to validate that post-trimming, the slots are consistently clear and fully operational, eliminating any need for rework or manual inspection in this regard.

Figure 4: The trimming blade removing flash to ensure clean, debris-free slots.

Operational efficiency has also seen significant improvements. By automating the slot creation process, we were able to eliminate the need for complex pin mechanisms that, in the past, have caused a range of issues, from misalignment to mold breakage. The robot's precision has drastically reduced the amount of downtime associated with mold maintenance and repairs, which had previously been a frequent and costly issue. Additionally, scrap rates have decreased because parts are consistently machined within specification. This reduction in waste has not only saved on material costs but also ensured that production timelines are met more consistently.

Figure 5: Final machined part with slots clean and free from flash and debris.

The AI-powered system's ability to detect and adapt to the exact spot where each slot needs to be created has also greatly improved throughput. Because the system can autonomously locate the proper positions and make any necessary adjustments, there is no need for manual intervention, reducing labor costs and increasing the speed at which parts can be produced. The increased production efficiency, combined with the reduction in downtime and scrap, has resulted in a substantial improvement in overall operational performance. I am now able to meet production quotas with far fewer interruptions, which has had a positive impact on customer satisfaction and product delivery timelines.

In summary, the results of implementing the 5-axis AI-powered robotic system have exceeded my expectations. The precision, efficiency, and reliability of the system have not only solved the technical challenges posed by the part's design and material but also provided substantial benefits to the overall production process. The success of this system has affirmed the importance of integrating advanced AI technologies into manufacturing operations, especially when working with complex materials and designs.

Conclusion:

Reflecting on the journey of developing and implementing this 5-axis AI-powered robotic system, I can confidently say that this project has been one of the most impactful in my professional career. The challenges we faced—maintaining the precise 0.010" ± 0.002" tolerance on small slots, managing the limitations of Long Fiber Reinforced Thermoplastic material, and overcoming the risks of mold breakage—seemed almost insurmountable at the outset. However, through collaboration with the customer company and the automation company and a dedication to innovation, I was able to design and implement a solution that not only met these challenges head-on but also improved the entire manufacturing process.

The decision to opt for a post-molding solution, rather than attempting to mold the slots directly, was critical in avoiding the thin steel condition and the resulting mold breakage issues that had caused frequent downtime in the past. I learned through previous experiences with cylindrical pins that the complexity of aligning mold opening and closing sequences often resulted in equipment failures, which is why it was so important to find an alternative. The post-molding robotic system offered a way to bypass these risks entirely, providing a robust and reliable method for slot creation.

What makes this system particularly impressive is the integration of artificial intelligence, allowing the robot to detect and adapt to any variations in the molded part. The flexibility and precision of this system have set a new standard for what can be achieved in the manufacturing process, particularly when working with complex, long-fiber reinforced materials. I take great pride in the fact that the AI system was designed and programmed with input from my own hands-on experience in the field, ensuring that the solution was tailored to the specific needs and challenges of the operation.

Furthermore, the custom-designed 0.012" trimming blade has proven to be highly effective in removing flash without compromising the integrity of the slots. This attention to detail has been essential in ensuring that the final product meets all functional requirements. The system’s ability to maintain cleanliness within the slots, combined with its precision in machining, has delivered parts that consistently meet customer specifications without requiring additional manual inspection or rework.

In conclusion, the success of this project illustrates the importance of innovation in overcoming manufacturing challenges. The 5-axis AI-powered robotic system not only solved the immediate issue of creating precision slots but also transformed the production process by improving efficiency, reducing scrap, and minimizing downtime. As I continue to explore new ways to enhance manufacturing operations, this project stands as a testament to the power of combining advanced technology with hands-on experience. The lessons learned here will undoubtedly influence future projects and further solidify the role of AI in precision manufacturing.

Acknowledgments

I would like to express my deepest gratitude to everyone who supported me throughout the development and implementation of this project. First and foremost, I would like to thank the Automation Company for their expertise and collaboration in developing the 5-Axis AI-powered robotic system, which was crucial to the success of this project. Their dedication and innovative approach were invaluable in overcoming the technical challenges we faced.

I also extend my sincere appreciation to our Customer Company, specifically their Engineering, Quality, and Research and Development departments, for their trust, technical feedback, and ongoing collaboration throughout this process. Their commitment to excellence and their partnership were key to achieving the precision and quality standards required for this project.

Additionally, I am grateful to my colleagues and team members at our Company Name, whose contributions and insights were instrumental in refining the processes and ensuring the smooth integration of the robotic system into our production line.

Lastly, I want to acknowledge the unwavering support of my family and friends, whose encouragement and understanding kept me motivated throughout this challenging but rewarding journey.

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