

Simulation-Based Investigation of the Feasibility of Robotic Machining of On-Wing Engine Components

Vincent Ahrens, Lukas Bath, and Thorsten Schüppstuhl

Abstract

Foreign object damage on the compressor blades of a turbofan engine reduces engine efficiency and compromises safety. This necessitates to repair such defects as soon as possible. As it is time-consuming and costly to disassemble the entire engine to access the compressor blades, it can be advantageous to perform such repairs on-wing, while the engine is still assembled. The main challenge in machining compressor blades on-wing is the limited accessibility within the engine, which precludes the use of traditional machining tools and demands the development of new solutions. To address these obstacles, this work proposes a flexible simulation framework including a shape optimization technique to aid in the development of suitable robotic kinematics for space-constrained machining tasks. Further simulation functionalities such as an interactive mounting simulation foster detailed feasibility studies of kinematic concepts.

Keywords

Simulation • Robotic machining • On-wing • MRO • Foreign object damage

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1 Introduction

Defects on compressor blades of turbine engines can pose significant safety risks and reduce operational efficiency. Repairing these defects on-wing, while the engine is still assembled, promises to reduce costs while enhancing safety and efficiency. The first kind of prevalent defects addressed in this work includes nicks and dents on the leading edge (Fig. 1 left), caused by the impact of larger foreign object debris such as birds, ice or hail [1]. They can cause instability in the airflow, stress concentration, and potential crack initiation, which may ultimately result in rapid fatigue-induced failure [2]. Another relevant type of defect is erosion caused by the impact of fine particles such as sand and dust (Fig. 1 right), which blunts the leading edge, degrades its surface and results in reduced engine efficiency [3]. These defects are particularly pronounced in the first stage of the high pressure compressor, making it a focal point for repair efforts.

Blending and recontouring are crucial processes for addressing these defects. Blending (Fig. 2a) involves smoothing and rounding nicks and dents to prevent crack initiation and impede crack propagation. This is typically achieved using a rotary grinding tool. Although manual on-wing blending is currently practiced, ongoing research is exploring automated solutions [4]. Recontouring (Fig. 2b), on the other hand, entails grinding and reshaping blunted leading edges to restore their aerodynamic profile, with the aim of improving engine efficiency and longevity. This process also causes a minor loss of chord length, which is neglectable. Recontouring is currently not possible on-wing and only performed on removed blades.

Performing such repair processes on-wing introduces several challenges, primarily due to space constraints within the engine. This applies especially if robots shall be used for the machining operations to improve quality and save time through automation. These challenges include inserting a grinding tool into the engine, reaching the required poses on the blades with the grinding tool and, if a robot is inserted into the engine, actuating it with size

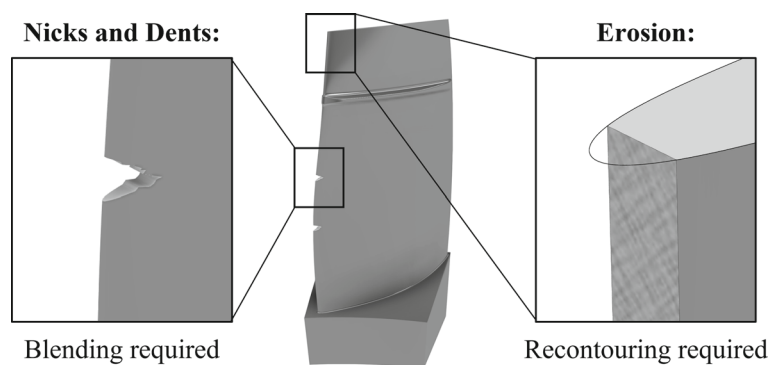


Fig. 1 Blade damage

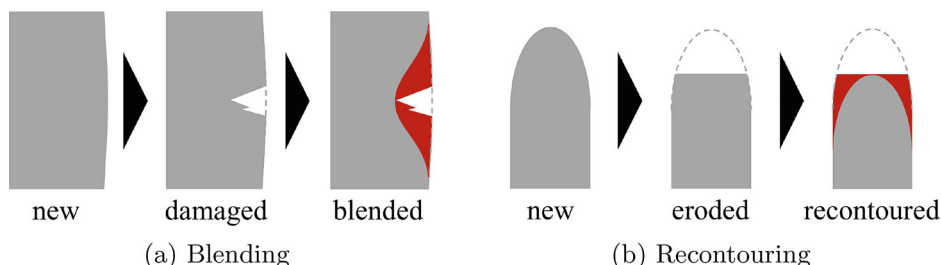


Fig. 2 Blade repair processes

limited actuators. Given the limitations of real-world testing and the resource-intensive nature of prototype development, simulations emerge as promising tools for addressing these challenges. This paper introduces a simulation process tailored to the development and evaluation of space-restricted machining solutions, addressing collision and design constraints. The simulation process is tested using two use-cases of innovative concepts for both on-wing blending and recontouring through bypass valves in order to reach to the blades of the high pressure compressor.

2 Related Work

This section provides an overview of the current state of research concerning on-wing blending, covering both manual and automatic blending methods, as well as the emerging use of continuum robotics for on-wing blending tasks. The complex tasks to be carried out in combination with the highly constrained access possibilities to the inside of the engines result in the very little number of known approaches. Especially for on-wing recontouring there are no known solutions.

2.1 Boreblending

Currently, on-wing blending is carried out manually, involving skilled technicians and is limited to the use of specialized handheld grinding tools developed by Richard Wolf [5] or Schoelly Fiberoptic [6] that are inserted into the engine through narrow inspection ports, to blend and smooth out defects on compressor blades. This operation is called boreblending. While it has been effective to some extent, it is labor-intensive, time-consuming, and may lack consistency in results. In recent years, efforts have been directed towards automating the

blending process, leading to the development of automatic boreblending systems [4]. These systems utilize robotic machining techniques to automate the blending process, offering potential advantages in terms of efficiency, accuracy and repeatability compared to manual methods.

2.2 Continuum Robotics

The emerging field of continuum robotics presents a novel approach to on-wing blending tasks. Continuum robots, characterized by their long, slender, snake-like structures and high degrees of freedom, offer unique advantages in accessing confined spaces within the engine. By using the redundant degrees of freedom they can maneuver around complex geometries to reach damaged areas on compressor blades. The current research efforts are mostly focused on performing blending in the intermediate pressure compressor, through the main engine inlet [7]. While these solutions promise to perform automated blending on-wing they are not currently able to recontour the leading edges of compressor blades.

3 Simulation for Concept Development and Evaluation

The aim of the simulation is to aid in the development and evaluation of specialised machining solutions, with a particular focus on addressing the aforementioned challenges. The following chapter discusses the fundamental concept of the simulation process and its objectives. Afterwards, the individual simulation functionalities are described.

3.1 Simulation-Based Design Process

In order to develop new concepts for on-wing machining solutions, the design process must be able to evaluate whether the concepts can overcome the key challenges that hinder the on-wing blending and recontouring of compressor blades in fully assembled aircraft engines. These challenges include inserting the tool into the engine, reaching the required workspace with the tool, and, if a robot is inserted into the engine, actuating it inside of the confined space. In addition to three simulation functionalities implemented to assess these properties, an additional functionality is integrated into the design process, as shown in Fig. 3, to generate collision-optimized shapes for robot components. The simulation environment CoppeliaSim [8] was chosen for its stability and wide range of features based on a quantitative comparison of robot simulation tools [9], to provide supporting functionalities and modeling capabilities.

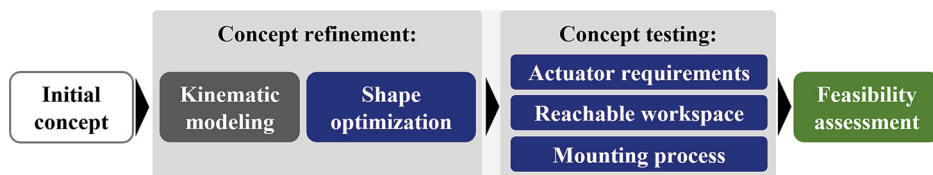


Fig. 3 Process for simulation-based design and testing of kinematic concepts

3.2 Calculation of Actuator Requirements

As the selection of actuators is considerably limited by the restricted space inside the engine it is crucial to ensure that actuators with the required performance are technologically feasible. For this, the required joint speed and torque are determined for each joint on every reachable tool pose in the workspace. The joint speed is calculated using the tool speed and the inverse of the Jacobian provided by CoppeliaSim for each robot configuration. To determine the required joint torque based on the process force and the weight of the robot components the physics engine Bullet [10] is used. It was chosen for its stability and special ability to deal with collisions of concave bodies in the simulation of the mounting process.

3.3 Workspace Evaluation

The different machining operations necessitate reaching various areas of the compressor blades. Recontouring the leading edge requires precise tracking of its shape and orientation, while blending requires reaching both the leading edge and the area immediately behind it, albeit tolerating a less restricted orientation. Given the confined space within the engine and the precision required by the machining process, forward kinematic methods are too computationally intensive due to frequent collisions and are thus not suitable for determining the robot's workspace. An inverse kinematic approach is therefore chosen and presented in Fig. 4. For this, discrete target poses are defined which describe the task space on the blade that needs to be reached in order to perform blending and recontouring. For each target pose, an inverse kinematic search for joint values is performed using the pseudoinverse method. If suitable joint values are found, they are applied to the robot. Collision checks are then performed between the robot and the engine. If collisions occur, the inverse kinematic search is repeated until a collision-free configuration is found or a predefined maximum number of iterations n is reached.

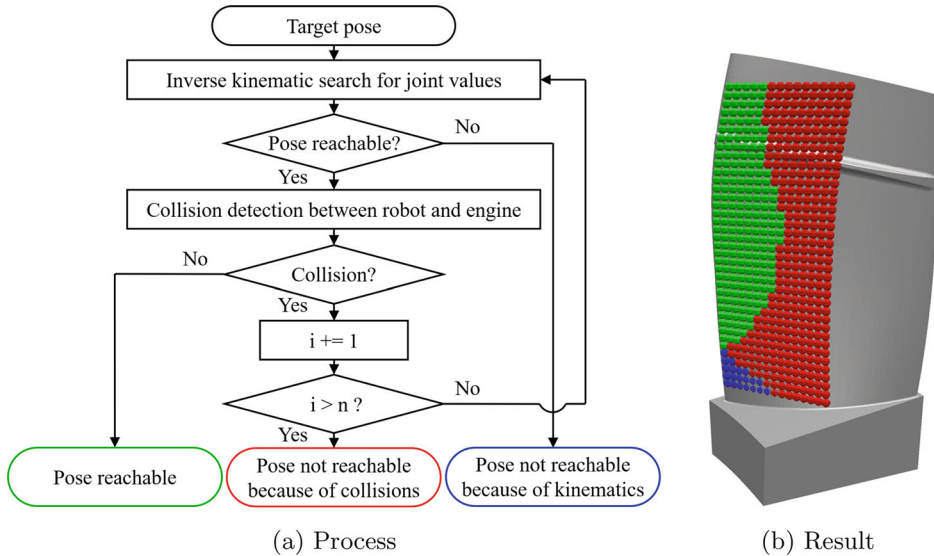


Fig. 4 Discrete evaluation of the workspace's reachability

3.4 Shape Optimization of Robot Components

In order to perform the machining tasks, the robot must be able to move inside the confines of the engine. This requires components to be shaped in a way that balances sufficient stiffness with the ability to maneuver without colliding with the engine's structure. Achieving this balance often necessitates highly intricate shapes that exceed the capabilities of conventional design techniques. A novel approach to shape optimization tailored to restricted work environments is proposed to address this challenge. The proposed methodology generates collision-optimized shapes for robot components by considering the required tool poses, an initial search volume representing approximately the eventual moving component of interest and the collision geometry. The search volume is defined as a cuboid that is evenly discretised into voxels. The tool poses required for the various machining operations are then defined as a multitude of target poses on the compressor blade. Based on these, the poses for all robot components can be determined via the inverse kinematics. The cuboid with the voxels is then iteratively transformed in place of the robot component to be designed. For each of the poses every voxel is checked for collision with the engine. Finally, any voxel that has been subject to a collision is removed from the cuboid. The resulting shape (shown in blue in Fig. 5) represents the volume that the final robot component to be designed must not exceed in order to operate free of collisions. This allows the designer to judge the achievable cross-sections of collision free robot components to easily achieve good geometric compromises.

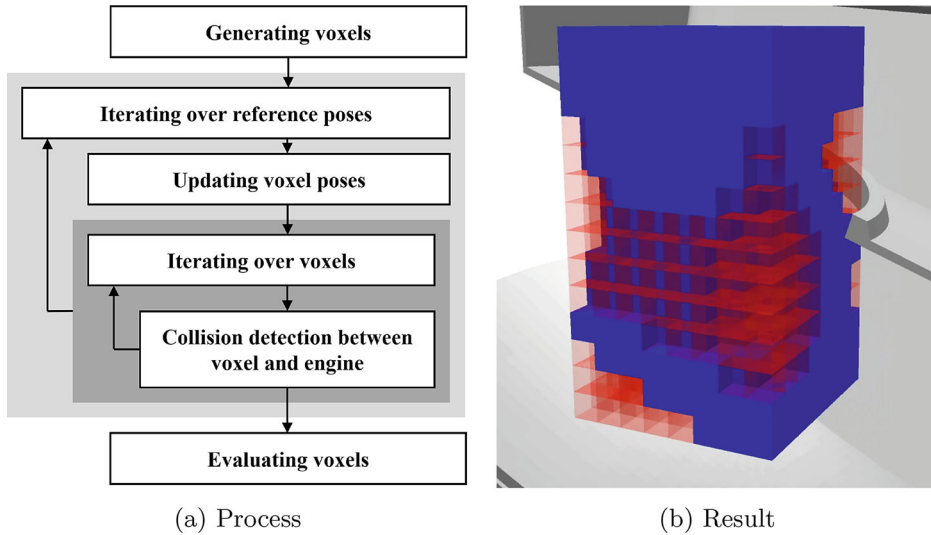


Fig. 5 Voxel-based creation of collision-optimized components

3.5 Simulation of the Mounting Process

Due to the limited space within the engine, it is difficult to determine whether a robot can be inserted. To overcome this challenge, an interactive simulation approach, illustrated in Fig. 6 has been proposed. This simulation allows the user to plan and test the mounting process virtually, without the need for a physical prototype. At the beginning of the simulation, the robot is positioned outside the engine. By using a 6-degree-of-freedom input device, the user can control the robot's movement and steer it into the engine. Collisions between the robot and the engine are continuously monitored throughout the process. The simulation's physics engine enforces collision responses, ensuring that insertion paths that are not possible in the real world are also not possible in the simulation. Through its visualization, intuitive control mechanisms, and collision enforcement, this simulation enables users to explore insertion strategies intuitively, without the need for access to an engine or robot prototypes. An example of such an insertion strategy is shown in the centre of Fig. 6 as an overlay of all robot poses along the insertion path.

4 Trial of the Design Process

The design process is tested using two exemplary use-cases of machining solution concepts. These use-cases address deficits in current solutions for on-wing machining which are limited in their ability to perform recontouring operations on the first stage of the high

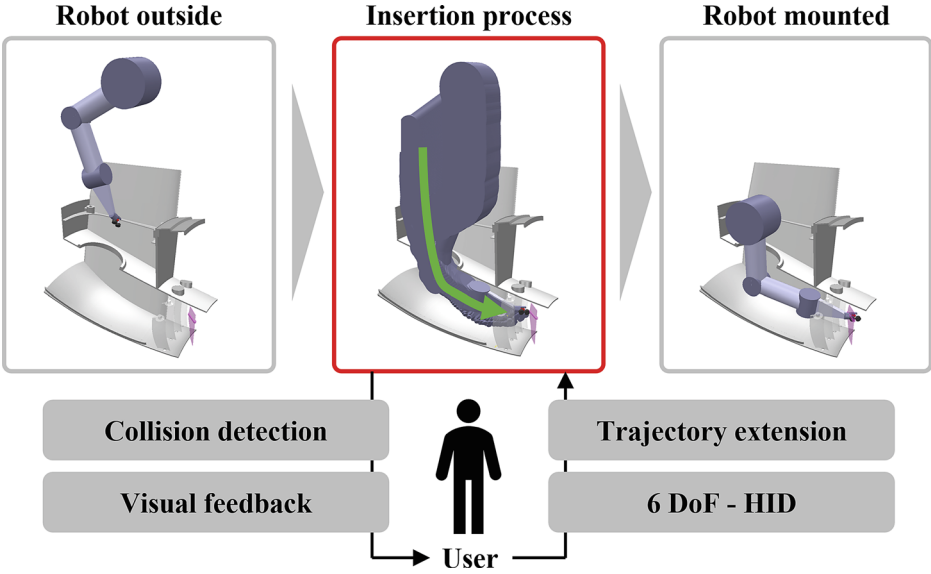


Fig. 6 Simulation of mounting process

pressure compressor. The restricted entryway, through inspection ports or the main air inlet, significantly hinders the machining operation. Therefore, an alternative entryway through the bypass valve is used for the two use-cases presented below. The use-cases were selected to provide contrasting examples and do not represent the full range of potential solutions.

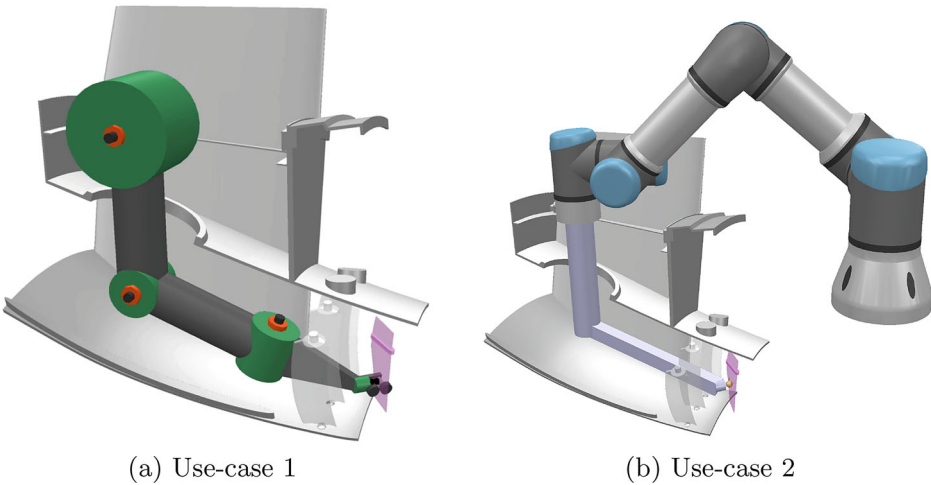


Fig. 7 Use-cases for the simulation-based design process

4.1 Use-Case 1

Use-case 1 places the robot and most of its joints inside the engine. The implementation, as shown in Fig. 7a, aims to perform the machining operation with only three degrees of freedom. This reduces the design's complexity but also limits control over the tool's orientation relative to the blade. In assessing the feasibility of the first use-case, the simulation plays a crucial role, particularly in evaluating whether the actuators are small enough to fit inside of the engine while providing the required speed and torque. The simulation results in Fig. 9 promise the feasibility of use-case 1. Suitable servo drives can be found that fit into the limited space, provide the required maximum torque $\tau_{max} = 1.17 \text{ Nm}$ and the required angular speed $\dot{q}_{max} = 0.73 \frac{\text{rad}}{\text{s}}$ (Fig. 9), respectively. Most of the target workspace can be reached without collisions and the mounting process is also feasible.

4.2 Use-Case 2

In contrast to use-case 1, the concept of use-case 2 places the robot and its joints outside of the engine. The advantage of this approach is that the size of the robot is not limited by the engine and standard industrial robots can be used to perform the machining. The problem with this approach is that a rigid extension is required to connect the tool inside the engine to the robot on the outside. This extension makes the tool position sensitive to orientation errors from the robot's joints. Furthermore, a specific extension must be designed for every engine type. As the initial design for the extension (shown in Fig. 7b) was prone to collisions and significantly limited the reachable workspace on the blade, the shape optimization was used to improve the shape of the extension. In Fig. 8a the result of the shape optimization is shown and in Fig. 8b the final geometry manually derived from it. It can be seen where material had to be removed from the original shape to avoid collisions with the valve rim and compressor vanes. As in use-case 1, the results in Fig. 9 for use-case 2 also promise feasibility. In this case, a small industrial robot can be used to provide sufficient actuation capabilities and the improved extension can be inserted into the engine and reaches the majority of the target workspace.

5 Conclusion and Future Work

In this work, multiple simulation functionalities were developed to assess the feasibility of on-wing machining solutions and to aid in their development. Even for diverse engine types that lack of geometric synergies between them this can help to develop highly individualized tools without significant additional effort. The proposed design process was applied to two use-cases to evaluate their potential feasibility in regard to real-world applications and to test the simulation-based design process. A notable contribution of this work is a novel

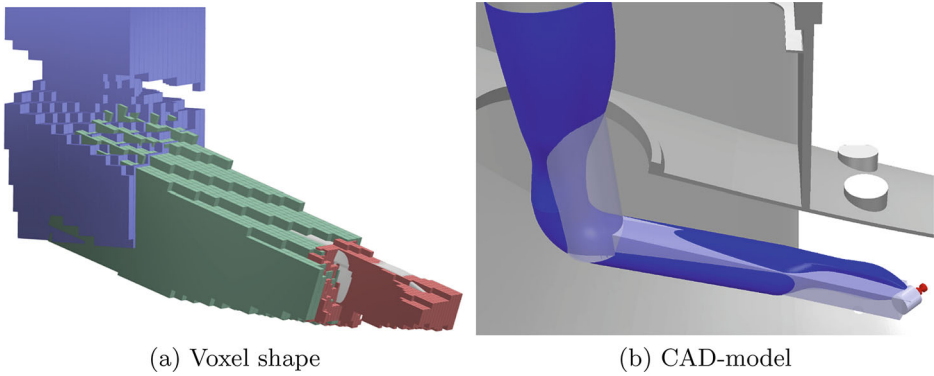


Fig. 8 Design of robot extension

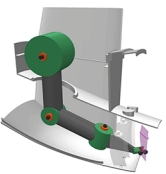
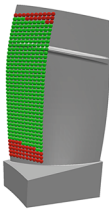
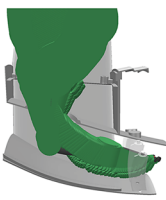
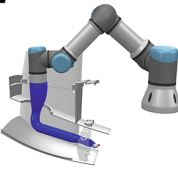
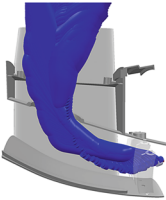
Concept	Actuator requirement	Reachable workspace	Insertion path
1 	$\dot{q}_{max} = 0.73 \frac{rad}{s}$ $\tau_{max} = 1.17 Nm$		
2 	$\dot{q}_{max} = 0.03 \frac{rad}{s}$ $\tau_{max} = 23.21 Nm$		

Fig. 9 Simulation results to assess the feasibility of the concepts

shape optimization technique, enabling the design of components that would be challenging to create without this approach. This optimization significantly enhances the performance of the machining solution in use-case 2. Additionally, the interactive mounting simulation was vital in assessing the feasibility without the need for physical prototypes. The results of the simulations conducted so far are promising, indicating that both use-case concepts have potential for addressing the challenges of on-wing machining. However, further investigation is necessary to validate their performance under real-world conditions. In future work, functionalities that not only assess feasibility but also evaluate performance could be implemented. This requires modeling the machining task in greater detail, incorporat-

ing accurate tool trajectories, and a realistic representation of process forces. This research lays the groundwork for future advancements in on-wing machining, potentially enhancing aircraft maintenance and improving operational efficiency.

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