

AI-Driven Blade Alignment for Aerial Vehicles' Rotary Systems Using the A* Algorithm and Statistical Heuristics [†]

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Abstract: In aviation, precise alignment of helicopter blades is paramount for ensuring optimal performance and safety during flight operations. Manual methods for blade alignment often demand extensive calculations and experienced technicians, resulting in time-consuming processes. This research proposes an innovative AI-based algorithm to optimize blade alignment in helicopter rotary systems, integrating the A* algorithm and a statistical heuristic function. The algorithm seeks to minimize the standard deviation of blade distances from the ground, captured using high-speed distance sensors. Firstly, the initial blade positions, along with the swash plate turns' limitations, are given to the algorithm. Later, by exploring all potential adjustments and selecting the most promising sequence to minimize the standard deviation of blade distances (considering the allowable pitch limits), the algorithm achieves precise blade alignment, enhancing helicopter performance and safety. Subsequently, the algorithm outputs the recommended sequence of adjustments to be made in the swash plate. We conducted comprehensive case studies using Mi 17 helicopters as a testbed to validate the algorithm's efficacy. The algorithm was assessed under varying scenarios: near-perfect alignment, single-blade misalignment in upward and downward directions, and multiple blades in asymmetric positions. The results demonstrate the algorithm's capability to swiftly recommend the precise sequence of adjustments for each control rod nut, effectively minimizing blade misalignment and reducing the standard deviation. The implications of this research are far-reaching, with them promising enhanced helicopter performance and safety across diverse application domains. By automating and streamlining the blade alignment process, the algorithm minimizes reliance on human expertise and manual calculations, ensuring consistent and accurate blade alignment in real-world scenarios.

Keywords: AI-driven alignment; A* algorithm; rotor blades; swash plate; statistical heuristics



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1. Introduction

The main rotor's set of blades assumes a crucial role in generating lift and controlling an aircraft's movement. However, the conventional flag-tracking system used to monitor the position and motion of these main rotor blades presents certain limitations in terms of accuracy, reliability, and safety [1]. To address this, a track check is conducted to ensure uniform blade paths during rotation and minimize helicopter vibrations, with a permissible deviation limit of 20 mm.

Presently, the established method for track checking involves coloring all blade tips using a glass marking pencil, followed by extending a sheet of white dense paper from a pole at least 500 mm away. By bringing the pole close to the rotating blades, markings are made on the paper, which are then measured using a scale. However, this approach

suffers from inaccuracies and consumes time, while the preparatory steps involved are laborious and potentially hazardous, risking blade damage and crew fatigue [2]. Thus, the ongoing research aims to evaluate the feasibility of replacing the flag-tracking approach with more efficient, automated alternatives such as artificial intelligence (AI) to overcome these limitations. Furthermore, an advanced process of obtaining the blades' pitch using a high-speed sensor involves the following steps [3]:

1. **Sensor Placement and Calibration:** A high-speed sensor is strategically positioned to ensure accurate readings. Technicians carefully calibrate the sensor to account for any potential offsets or deviations and ensure that its measurements are reliable.
2. **Data Collection during Rotation:** With the engine running and the blades in motion, the high-speed sensor continuously collects data on the distance between each blade's tip and the ground. The rotating blades provide a dynamic set of distance measurements as they pass through their rotation cycle.
3. **Pitch Calculation:** Using the collected distance measurements, technicians calculate the pitch of each blade. The pitch represents the angle at which the blades' rotational plane deviates from the horizontal plane.

Once the pitch of each blade is determined, technicians must decide on the appropriate course of action to bring the blades within the specified range of pitch differences. This task typically involves manual calculations and relies heavily on the expertise and experience of the technicians. The technicians evaluate the pitch data, analyze the current blade alignment, and calculate the necessary adjustments to be made to each control rod of the swash plate to achieve the desired blade alignment. The manual process of determining the course of action can be time-consuming and may lead to suboptimal results due to the complexity of aligning multiple blades accurately. As a result, there is a need for a more efficient and automated approach to this process, which is where the proposed AI-based algorithm utilizing the A* algorithm comes into play. By leveraging AI, the algorithm aims to streamline the course of action determination, reducing the need for manual calculations and human intervention while ensuring swift and accurate blade alignment. This advancement is crucial for enhancing helicopter performance, safety, and maintenance efficiency in various application domains.

2. Methodology

The focal point of the proposed algorithm lies in the utilization of three key inputs to effectively enhance blade alignment within helicopter rotary systems; these inputs are the initial condition of the blades, the turn steps (minimum possible control rod turn), and the pitch and turn limits. As the initial condition, the algorithm takes into account the initial distances of each blade from the ground, along with the specific number of turns applied to the control rod. Furthermore, the algorithm also integrates the concept of pitch and turn limits for each control rod. These limits outline the range within which the control rod can be turned to affect changes in the blade's orientation. Moreover, the algorithm considers the acceptable range between the minimum and maximum pitch values.

Blade Alignment Recommendation System Utilizing the A Algorithm*

The output of the proposed algorithm is the recommended sequence of adjustments for each control rod of the swash plate (in terms of turns), minimizing the standard deviation and achieving optimal blade alignment within the desired pitch difference range. The proposed methodology uses the A* algorithm, which is a widely used search algorithm that efficiently finds the shortest path from a starting node (the initial blade conditions in our case) to a goal node (acceptable solution) in a graph representing the operational space [4]. The technique combines the advantages of Dijkstra's algorithm and greedy best-first search [5]. It intelligently evaluates potential paths by considering both the cost to reach a node from the start and the estimated cost to reach the goal from that node using a heuristic function, ensuring optimal and informed exploration. In our case, the standard deviation of the blades' distance from the ground is used as the heuristic function to be

minimized during the A* algorithm, guiding the optimal alignment of helicopter blades for enhanced precision and efficiency. The stepwise, detailed explanation of the proposed algorithm (Figure 1) is as follows.

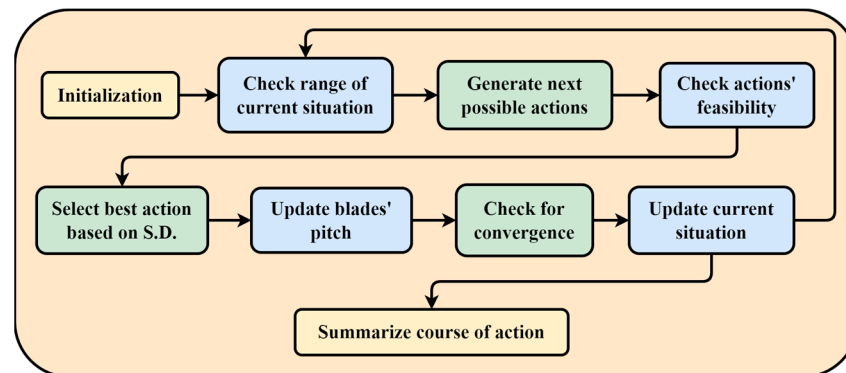


Figure 1. Workflow of the proposed blade alignment-recommender system.

1. **Initialization:** The algorithm starts by initializing various parameters, including the initial conditions of blade distances and swash plate turns, the minimum and maximum pitch limits, the acceptable range of pitch differences, and the minimum step sizes for distance and turns.
2. **Iteration for searching the subsequent operation:** The algorithm enters a loop that iterates until all blades are within the desired pitch difference range. It first checks if all blades are within the range; if so, it prints a message and breaks out of the loop.
3. **Possible Actions:** For each blade, the algorithm considers two possible actions: increasing or decreasing the distance from the ground and the corresponding swash plate turn adjustment.
4. **Feasibility Check:** The algorithm checks the feasibility of each action by calculating the blades' condition after each action. It also checks if the resulting swashplate turns are within the specified limits.
5. **Valid Actions List:** If an action is feasible, it is added to the list, along with relevant information such as the resulting blade distances, standard deviation [6] (Equation (1)), and updated swash plate turns.

$$\sigma = \sqrt{\frac{\sum (X - \mu)^2}{N}} \quad (1)$$

Here, X represents the data point in the distribution, μ is the mean of all of the blades, and N represents the total number of blades.

6. **Selecting the Best Action:** The algorithm stores the possible actions and their corresponding data. It selects the action with the lowest standard deviation from the set, indicating the most promising adjustment.
7. **Updating the Blade Alignment:** The algorithm checks if the best action leads to a reduction in the initial standard deviation. If so, it updates the blade distances and swashplate turns with the new adjustments. It then prints the details of the recommended operation, including the blade number, action taken, resulting blade distances, updated swash plate turns, and the standard deviation.
8. **Iterative Refinement:** The loop continues with further iterations until no further improvement is possible in terms of the standard deviation.
9. **Final Summary:** Once the blade alignment process is complete, the algorithm prints a summary of the recommended operations, displaying the number of turns to be given to each blade's nut to bring the blades within the desired range of pitch differences.

3. Results and Discussion

To assess the effectiveness of the proposed algorithm, researchers focused on the specifications of Mi 17 helicopters equipped with five rotor blades [7]. The algorithm's performance was evaluated using a set of specific input parameters. One of these parameters was the minimum rotation possible for a control rod nut, amounting to 0.1666, which is equivalent to a sixth of a full turn. This small rotation led to a vertical elevation of the blade by 10 mm, showcasing a clear relationship between control adjustments and blade positioning. During algorithm testing, the initial positions of the control rods were standardized at 380 turns. Additionally, the minimum limit for control rod turns was established as 375 turns, while the upper limit was set at 385 turns. These limits played a pivotal role in guiding the algorithm's adjustments and ensuring the controlled nature of the blade alignment process. Furthermore, the researchers considered a permissible track limit of 20 mm, indicating the acceptable extent of deviation in the blade's positioning. The evaluation of the algorithm's efficiency involved the execution of four distinct case studies, each designed to simulate different instances of blade misalignment within Mi 17 helicopters. These scenarios encompassed a range of potential misalignment situations, serving as comprehensive tests for the algorithm's capabilities.

In the first case study, the focus was on a scenario where nearly all blades were appropriately aligned, with each blade's distance from the ground being measured at 352, 353, 350, 349, and 351 cm. Moving to the second case study, the algorithm was tested against a situation of a single blade being misaligned in an upward direction. The corresponding distances for this scenario were 350, 352, 351, 351, and 365 cm. The third case study introduced a more complex misalignment pattern, involving one blade misaligned upward and another misaligned downward. The distances measured for this scenario were 350, 352, 351, 340, and 365 cm. The fourth and final case study presented a scenario in which two blades were misaligned downward while the remaining blades were aligned upward. In this context, the respective distances were recorded as 345, 340, 375, 377, and 385 cm.

For each of these case studies, the algorithm was implemented to optimize blade alignment, with it providing recommendations for necessary adjustments to the control rod nuts. The results of these tests effectively showcased the algorithm's capacity to achieve precise and efficient blade alignment, within the desired pitch difference range. The output of the proposed algorithm corresponding to each of the undertaken scenarios is as follows.

In the first case study, where most blades were already well-aligned, the algorithm's analysis led to two recommended operations for achieving optimal blade alignment (Table 1). Throughout its execution, the algorithm explored two levels within the search space (Figure 2). The initial standard deviation of blade distances was 1.58, which was effectively reduced to the minimum value of 1 after the alignment process was carried out (Figure 3). Moving on to the second case study, which focused on addressing the misalignment of a single blade in an upward direction, the algorithm's outcome indicated the need for a single corrective operation. During its execution, the algorithm traversed 13 distinct levels within the search space. From the outset, the standard deviation was measured at 6.3, which was impressively minimized to 0.83 following the alignment procedure.

Table 1. The recommended actions (turns) corresponding to each blade for each case study.

Case Study	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5
1	0	−0.167	0	0.167	0
2	0	0	0	0	−2.166
3	0	0	0	1.666	−2.166
4	4.498	4.498	−0.5	−0.833	−2.166

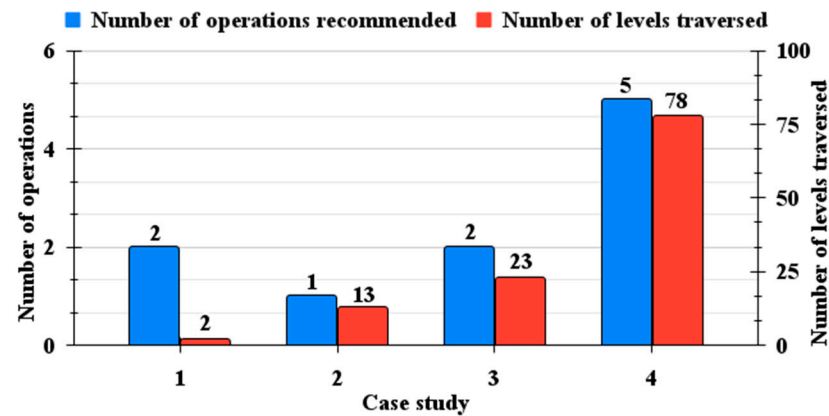


Figure 2. The number of operations recommended along with the levels traversed during the algorithm's execution corresponding to each case study.

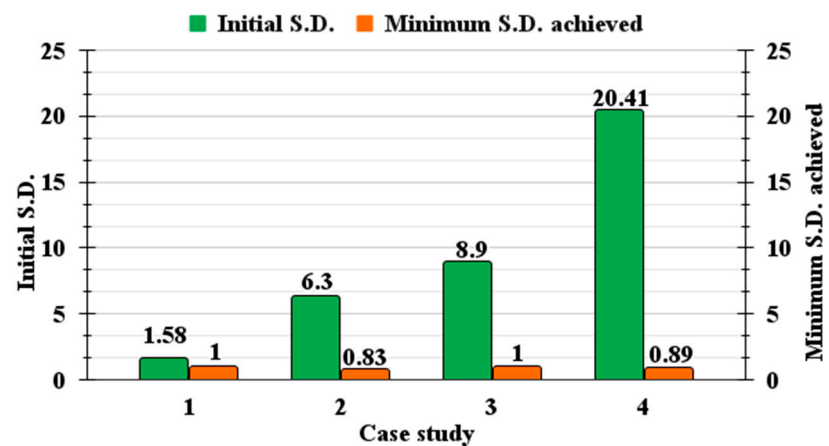


Figure 3. The initial and final standard deviation corresponding to each case study.

In the third case study, where one blade was misaligned upward and another was misaligned downward, the algorithm's optimization process involved suggesting two operations for attaining the best possible blade alignment. As part of its execution, the algorithm navigated through 23 different levels within the search space. The initial standard deviation stood at 8.9, which was substantially reduced to a minimum of 1 after the alignment process was executed. Lastly, in the fourth case study (3.2.4), where two blades were misaligned downward and the remainder were aligned upward, the algorithm's assessment revealed the necessity for five corrective operations to achieve optimal alignment. Throughout its execution, the algorithm traversed a significant 78 levels within the search space. Initially characterized by a standard deviation of 20.41, the alignment process led to a noteworthy reduction, with the minimum standard deviation reaching 0.89. These detailed case studies underscore the algorithm's capability to efficiently analyze and provide practical solutions for a range of blade misalignment scenarios, showcasing its potential for enhancing alignment precision across diverse helicopter configurations.

4. Conclusions

In conclusion, the presented research marks a significant stride towards advancing helicopter maintenance practices through innovative AI-driven solutions. The proposed algorithm's successful application in optimizing blade alignment within Mi 17 helicopters showcases its potential to revolutionize rotorcraft operations. By automating and refining the alignment process, the algorithm not only enhances performance and safety but also reduces reliance on manual intervention. The algorithm's adaptability to diverse helicopter models and potential integration with real-time data acquisition hold promising avenues

for further advancements. As this research bridges the gap between cutting-edge AI technologies and rotorcraft operations, its implications extend beyond the laboratory, offering tangible benefits to the aviation industry's reliability, efficiency, and safety.

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