Inflight Helicopter Blade Track Measurement using Computer Vision

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Abstract—**Different type of vibrations are inherent in helicopters which cause discomfort to the crew, structural fatigue and other problems which may lead to accidents. Vertical vibrations are due to the out of track conditions i.e. the blades of the helicopter being out of track. The objective of this research work is to minimize the vertical vibrations by improving the blade tracking using image processing. The proposed work is low-cost as compared to the other methods being used by the aviation industry and very simple to understand. This method consists of several steps which include: image filtering, image thresholding, position finding of each blade and conversion of pixels' distance into real-world distance. At the end the difference between tips of each blade is calculated with respect to a reference blade. The experimental results show that the proposed work is very effective and accurate.**

Keywords - blade tracking; rotor tracking; rotor track & balance; vertical vibrations in aircrafts.

I. INTRODUCTION

Due to the unique abilities to hover and take off/land vertically the helicopters are very popular in modern aviation. However the helicopter trips are considered uncomfortable and unpleasant due to high level of vibrations. These vibrations may sometimes lead to structural problems and accidents. Two major types of vibrations in a helicopter are [1]: vertical vibration and lateral vibration. Vertical vibration is typically due to the rotor blades being out of track as shown in Fig. 1. Due to vertical vibration the helicopter bounces up and down. This vibration is produced by one of the blades lifting the helicopter in one quadrant of rotation and suddenly losing lift in the remaining quadrants [1]. When vertical vibration in any aircraft is present once in every revolution, this phenomenon is referred to as a one-per-revolution or 1-to-1 vibration [2].

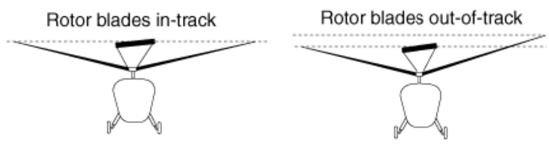

Figure 1: In-track and out of track blades

Blade tracking [1] is a process in which vertical position of each blade's tip is calculated and adjusted according to the requirement based on blades' position in the air. One blade is taken as a reference and blade tip's position of other blades is calculated relative to the reference blade. If this difference of blade tip's position is within a certain threshold then the blades are considered to be in track otherwise they will be considered out of track or out of vertical position. This threshold is usually ±0.25 inches. However it may vary for some helicopters [1]. Blade tracking can be done inflight and on ground.

Various methods have been used in the past for blade tracking. The oldest method used for the rotor track and balance was flag tracking [3]. In this method all the blades are coloured with different coloured wet paint. A flag made is held on a lightweight pole against the blades tips. An operator holding the flag approaches the rotating blades' tips and as soon as the blades touch the flag the operator moves back and marks on the flag left by the coloured blades are observed. The out-of-track values are calculated from these marks [3].

The next tracking method used for rotor tracking was electro-optical tracking [3]. It was based on the contrast of the blades with respect to the background. These systems had no danger in their use like the previous method [3]. Then strobe light tracking systems were invented for inflight tracking. In this technique a skilled operator operates a dial and visually locates a set of targets in space and remembers their relative locations [1]. It was a very competent method but it has a drawback that it requires a skilled operator to perform it [3].

Another method was used by Helitune which utilized the line-scan video camera. A system in the early 90's was introduced that made use of the method to measure track optically without use of a strobe. In 1995, an optical tracker was introduced using a unique method based on a patent of 1970 but it was never produced commercially. This technique used a hand held electronic camera and it had several advantages over the methods currently in use [4].

Several other methods have also been used over the past decades. Radar systems, such as the Micropower Impulse Radar (MIR), were also used for blade tracking [5]. These systems provided very accurate results but were very expensive and complicated [4]. In some methods teetering rotor systems were fitted with potentiometers and strain gauges were installed within rotor blades to calculate the deflection.

However, these systems were not appreciated because they typically required alterations to the blades [6].

Methods based on vibration sensors were also introduced. Vibration sensors were mounted on specific locations at the airframe to track the blades. It was observed that the vertical vibrations were reduced using these methods but the blades were not perfectly in track [3]. Microprocessor-based analysers were also presented which had the capability of performing all of the balance calculations for the mechanic [7]. Along with these developments various optical methods emerged for acquiring track data. This enabled the users to gather track data without attaching tip targets to the blade tips or visually taking the position of the main rotor blades at a distance. The major drawback of these systems is that influence coefficients which are used in the software programs vary from one aircraft to the next of the same make and model.

All the techniques previously used had some drawbacks and those which have no drawbacks are very expensive. So a very simple blade tracking technique is proposed. The objectives of this techniques are: (i) to reduce the vertical vibrations, (ii) to design a system that is capable of working indoor/outdoor and in-flight/on-ground, (iii) to design a system that requires no alterations to the blades and (iv) to design a low-cost system.

This work has been carried out using some image processing techniques and it is divided in several steps which include: image filtering, image thresholding, position finding of each blade and conversion of pixels' distance into real-world distance. This gives precise values and it has covered the drawbacks which were present in the previous techniques.

II. Proposed Methodology

This section explains how the proposed work has been implemented. The proposed work has been implemented using computer vision and it has been divided in two steps. The first step is the calibration, which includes establishing a table which contains pixels to distance ratio by taking images of a rectangular shape. This table is later used for the pixels to distance mapping. The second step is blade tracking which includes taking the images of the blades' tips and processing it for finding the out of track value between the blades.

A. Calibration Process

The purpose of this process to find out how many pixels represent a given rectangular shape at different distances. Using this process a table is maintained which contains the ration of no of pixels values to distance values. This table is utilized later in the second step.

Calibration process involves a camera, a paper and a scaled bench with a movable holder on it. The paper has a rectangular shape printed on it. The length of this rectangle is 3.86cm. This paper is pasted on movable holder and the holder is placed on the 10cm position on the optical bench. The camera is placed on the 0cm scale side of the optical bench in such a way that it is focusing on the rectangular shape.

Now a very simple program is developed which takes image of the paper and it gives no of pixels in one row of 3.86cm long rectangle. These no of pixels are noted down in a table along with the distance. Now the holder is moved on the bench by 5cm position and the new no of pixels are noted and inserted in the table. This process is repeated until the maximum scale is reached on the optical bench. The initial values of this table are provided in the Table 1. This table tells us how many pixels are required to represent a 3.86cm line seen from different distances.

TABLE I: Calibration Data

Distance (cm)	No of pixels
10	393.20
15	299.50
20	242.10
25	203.40
30	175.50

Then the coefficients of a polynomial p(x) of degree n are calculated which fit the first column of Table 1 to the second column of the table (i.e. distance to number of pixels), in a least squares sense.

The calibration process is complete here. The coefficients calculated here are stored in the form of an array and will be used later in the next step.

B. Blade Tracking

The next step is to make an experimental setup which is similar to a helicopter and then develop a program which can find out the out of track values between the blades' tips in the experimental setup.

The experimental setup along with results is explained in section 3 however a brief introduction of the equipment and some basic concepts about helicopter are required to understand the implementation of the program. A block diagram of the experimental setup is given in Fig. 2.

In helicopters a magnetic pickup is fixed on the main rotor's non-rotating shaft, which is used to measure the speed of rotation i.e. revolutions per minute (RPM). The working principle of a magnetic pickup is very simple. It consists of a coil and a permanent magnet, as soon as a piece of metal passes through its magnetic field it cuts the magnetic flux and a pulse is generated. When the rotor starts to rotate, the metal target cuts the magnetic field and generates a signal on the output of the magnetic pickup [8]. A photogate has been used in the experimental setup instead of the magnetic pickup. It sends a pulse in the similar fashion as the magnetic pickup as soon as a blade passes through it.

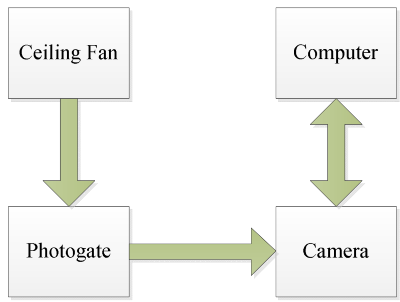

Figure 2: Block Diagram of experimental setup

1) Photogate Triggered?

The first step of the program checks if the photogate has triggered or not. The photogate is triggered when the blade B passes through the photogate sensor. So the program waits for blade B to pass through the photogate. As soon as it passes the photogate sensor generates a pulse and this pulse after passing through an amplifier reaches the camera. The program instructs the camera to take an image as soon as the trigger occurs. The camera is setup in such a way that when the blade B triggers the photogate blade A is in front of the camera so on the trigger the image captured is of blade A. Then the image is stored in the computer for further processing.

2) Blade Tracking

Once the image is stored some steps of image processing are performed for blade tracking. These steps are described in Fig. 4 and a detailed description is as follows:

A ceiling fan is mounted on a table to emulate the helicopter blades and its blades are named A, B and C. A camera is mounted on fan's shaft in such a way that it can capture the tips of the fan blades. The camera works in trigger mode i.e. when it gets a pulse on its trigger input line it captures the image. Photogate sensor is placed in such a way that it only gets triggered by blade B. The details of all the equipment and experimental setup can be found in section 3.

Now we see how the program for blade tracking has been implemented. The flowchart of the program is divided in two segments. First flowchart given in Fig. 3 gives an overview of the methodology while the second flowchart, which is part of first flowchart, given in Fig. 4 gives the steps involved in the blade tracking. Given below is detailed description of each step given in flow chart of Fig. 3.

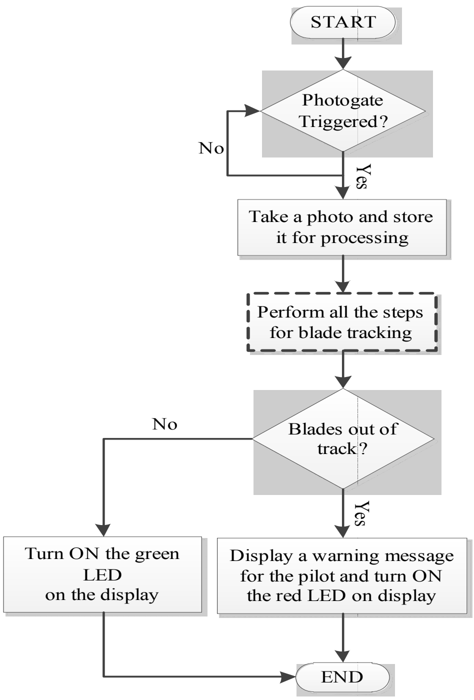

Figure 3: Basic Flowchart of the program

a) Capture images of other blades: In the blade tracking process first two trigger signals are generated by the program and these triggers are sent to the camera. The fan is set to rotate at 300 revolutions per minute (RPM) which means 5 revolutions per second. So each revolution completes in 200ms (1 second / 5 revolutions). As the fan has 3 blades, the time difference between any two blades is 66.67ms (200ms / 3). So when the camera is triggered by blade B, the blade A is in front of camera and its image is captured without a delay. When after 66.67ms the blade B arrives in front of camera, the program sends the trigger signal to the camera and the camera captures image of blade B and then blade C is captured similarly but for blade C the delay is 133.33ms (2 × 66.67ms). This way the images of all the blades are captured.

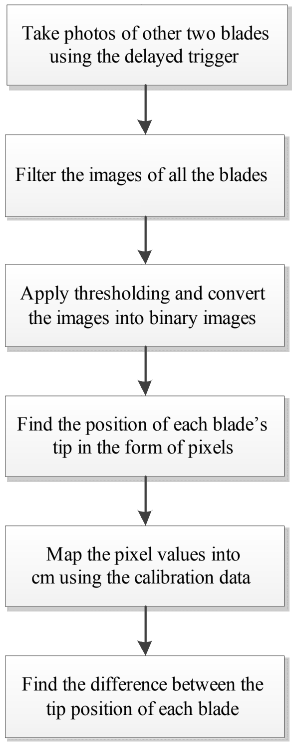

Figure 4: Tracking blades

Captured images of blade B and C are shown in Fig. 5. In this paper the results of blade B and C are shown. These images were taken in a scenario where blade C was set out of track.

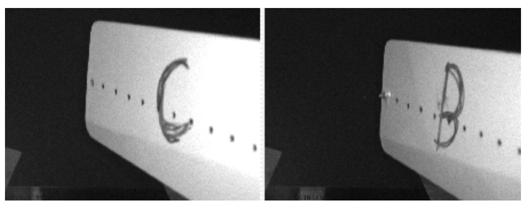

Figure 5: Captured Images

b) Image Filtering and Thresholding: The captured three images are filtered to improve the edges of the blades. Simple edge detection technique has been applied for image filtering and prewitt filter has been used for this purpose. Then image thresholding is applied on the filtered images. Image thresholding converts the filtered images into binary images with the edges of the blades displayed with white colour and the rest of the image is displayed as black. These binary images will be helpful in finding the blade tips' position in the later steps. The filtered images and Thresholded images are shown below in Fig. 6 and Fig. 7 respectively.

The threshold value can be different for different environments, i.e. different in sunny conditions, different in cloudy conditions, different in in-door conditions etc. so the threshold value is not fixed. This threshold value can be varied from its user interface so the crew members can change the threshold value according to the environmental changes. The experimental setup, for the proposed work, was established in a laboratory i.e. indoor environment was used during the experimentation. With the indoor setup the lower threshold value used in the thresholding process was 70 and upper threshold was 255.

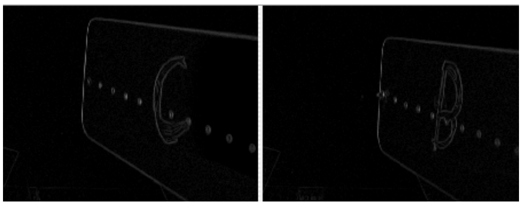

Figure 6: Filtered Images

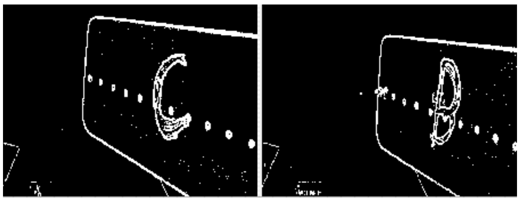

Figure 7: Thresholded Images

c) Find blade's tip position: The images in above figures show that the blade is shown horizontally in the image i.e. along x axis. The tip of the blade is forming a vertical straight line edge in the image. The program finds the vertical straight edge in the image which is tip of the blade. From this edge X position of the blade tip in the image is found. Similarly X position of all the other blades is taken and the difference of each blade's position from the reference blade is calculated. Here blade A is taken as a reference blade and the difference of X position of blade B and blade C relative to blade A is calculated. This value is in the form of no of pixels and this will later be used for finding the out of track values.

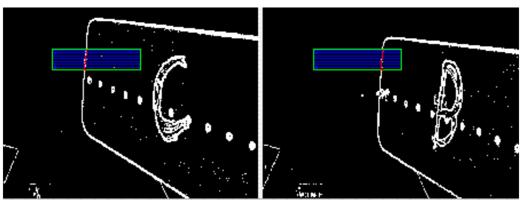

Figure 8: Final Images with ROI

Fig. 8 shows the final images from which the tips' position is calculated by finding a straight edge. A blue coloured window highlights the area which we have chosen as a region of interest (ROI). ROI is selected is selected in such a way that the straight edge resides in it.

d) Mapping the pixels into distance: The next step is to map no. of pixels values calculated in the previous step into distance (i.e. cm) according to the data given in Table 1. The coefficient of the polynomial calculated in the Calibration Process is used here to map the no of pixels into distance.

e) Difference in blade's tip positions: The next step of this method is to find the difference between the tips positions of all the blades with respect to the reference blade A.

Fig. 9 gives an overview of the method being used to calculate the difference between the blades' tip position. The camera is placed at 60cm distance from the tip of reference blade. This distance will be larger when being set up on the helicopter. In Fig. 9 it is assumed that the "Tip of Blade 1" passes at a distance 60cm from the camera while the "Tip of Blade 2" passes at a bit larger or smaller distance. This scenario is considered for the blades being out of track. When the blades are in track the both the blades will pass from the points and hence there will be no difference between the tips' position.

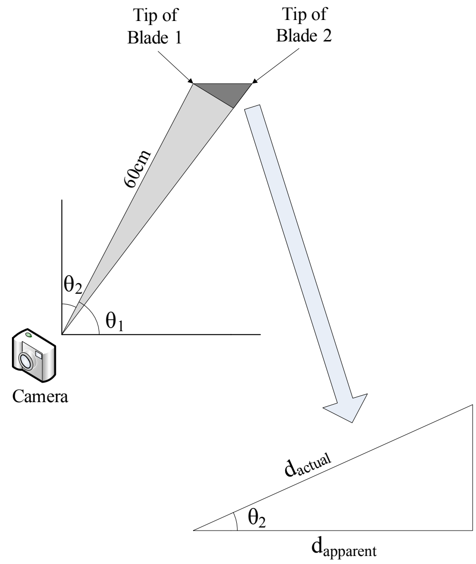

Figure 9: Scenario in the experimental setup

In Fig. 9 a small triangle is formed at the tips' position. This triangle is also shown in a bigger view as well to clarify some details. In this triangle we see that it is a right angle triangle and its base is labelled as dapparent. This is distance we get by simply taking the difference between the tips' position. But it is not the actual distance. The actual distance is labelled as dactual in the triangle, which is the hypotenuse of the triangle. The angle between base and hypotenuse is denoted by θ_2. We have got the value of dapparent by simply calculating the difference between the X coordinates of the tips' position. But the real or the actual distance is the one which is denoted by dactual. We can find the dactual by using the basic trigonometric equations. From the basic trigonometry we know that for a right angle triangle:

$$cos\ \theta = {}^{base}/_{hypotenuse} \quad (1)$$

In our case this equation can be written as:

$$\cos \theta_2 = {}^{d_{aparent}}/_{d_{actual}} \quad (2)$$

In the above equation dapparent and θ2 are known and we are required to calculate dactual which can be calculated using:

$$d_{actual} = {}^{d_{apparent}}/_{cos\ \theta_2} \quad (3)$$

In the above equations θ_2 is 21 degrees which has been calculated from the experimental setup. In case of a three bladed fan two values dactual are calculated. First value is of blade B from the reference blade A and seconds the value of blade C from the reference blade. These two values are compared with a threshold value. This threshold value is the value up to which the out of track blades are acceptable. This threshold varies from helicopter to helicopter. If the out of track values are above this threshold the pilot is alerted about these values.

3) Blades out of Track

Now that all the steps of flowchart 2 are complete the remaining steps of flowchart 1 will now be explained. Blade tracking steps return the out of track values of all the blade B and C with reference to blade A. These values are compared with a threshold value (which may vary for different helicopters). If these values are above threshold then the blades are considered out of track otherwise they are considered in track.

If the blades are out of track then a warning message is displayed for the intimation of pilot and the out of track values are also printed on the screen and a red LED is turned on to issue a warning. If the blades are in track then simply a green LED is displayed to tell the aircraft crew that blades are in track. Although the blades are in track but still there may be a negligible difference between their vertical positions of blades' tips. This difference is also displayed on the screen.

III. EXPERIMENTATION AND RESULTS

As explained earlier that the experimental setup includes a camera, a ceiling fan, a photogate sensor and a computer. The camera should be the same which was used in the calibration process.

An output signal of a magnetic pickup is required to use it as a trigger for the camera being used in the project. A U-shaped photogate sensor has been used to replace the magnetic pick up. The photogate sensor has two arms. From one arm a narrow beam of infrared is focused towards the other arm and it is incident directly on an infrared detector which is fixed in the other arm. As long as there is no object between the two arms, the infrared detector will have the infrared beam incident on it and in this case the photogate sensor will generate 5V on the output line. As soon as some object arrives between these two arms, it cuts the infrared beam and hence the infrared detector has no beam incident on it and the photogate generates 0V. The photogate is mounted near the tip path plane of the blades in such a way that the tips of the blades B and C pass just above the arms of photogate while the extended blade A passes through the arms and cuts the beam. So the photogate constantly produces the 5V and it produces 0V as soon as it is cut by the metallic strip of blade A.

The camera used in the project has only input, i.e. the amplified trigger signal of photogate. This signal is used to trigger the camera and as soon as the camera is triggered it takes an image. It is also connected to the computer. The camera is focused on the tip path plane of the blades. So the images captured are of the tips of all the blades. All the captured photos are sent to the computer for further processing.

A helicopter may have different no of blades (two or more). In the experimental setup a three bladed fan has been used to emulate the helicopter's main rotor's blades. This ceiling fan is mounted on the table using C-clamps. It is powered on through a fan speed regulator, so that the speed of rotation of the fan can be controlled. The maximum speed which can be achieved in this setup is 397 revolutions per minute (RPM) and hence a frequency of 6.6 Hz. The typical speed of rotation of helicopter's main rotor is almost 300 RPM (frequency of 5 Hz) so the speed of the fan can be adjusted to 300 RPM using a fan speed regulator connected to it. Length of blade A is extended by attaching a 2 inch metallic strip on the tip of the blade. This extended metallic strip is used to trigger the photogate.

Figure 10: Experimental setup

The only output of the proposed method is the out of track values of the blades. These values are $n-1$ for a n bladed helicopter because one blade is taken as a reference and out of track value for the $n-1$ blades is calculated with respect to the reference blade. Fig. 11 and Fig. 12 show the output of the program. The results shown in Fig. 11 are shown when the blades are in track while the results in Fig. 12 are taken when the blades are out of track.

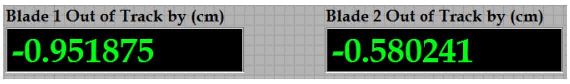

Figure 11: Output for in-track blades

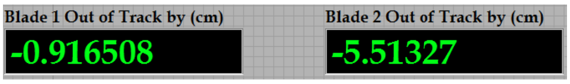

Figure 12: Output for out of track blades

To verify the output of the proposed work a scale was placed near the tips' path of the blades and the blades were passed one by one near the scale and their position was noted down on paper. Then the out-of-track value was calculated for each blade using the proposed method. This process was repeated several times and the out-of-track values using the proposed methods and using scale were noted down for comparison.

The out-of-track values using both the methods are plotted in the charts given below in Fig. 13 and Fig. 14. In the charts given below as we can see one curve, termed as "Calculated Data", represents the data which has been calculated using the proposed technique while the other curve, termed as "Actual Data" represents the data which was taken using the scale. The curves clearly show that the difference between them is very small. Fig. 14 shows the error which between these curves. It can be seen that the error is not linear but random. The plots in Fig. 13 and Fig. 14 justify that the results of the proposed are valid and acceptable. The variance of the resultant data is 2.275677532 which is acceptable by the aviation industry.

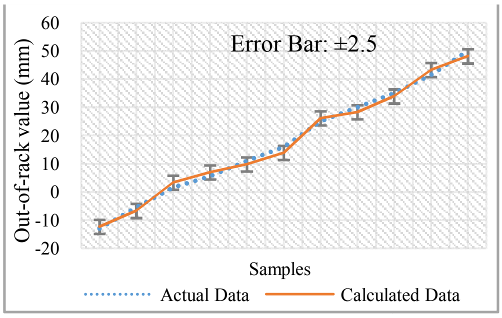

Figure 13: out-of-track values

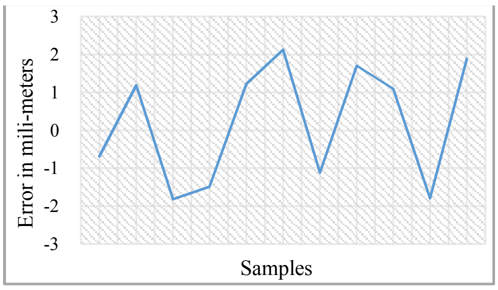

Figure 14: Error Data

The proposed technique covers many drawbacks which were present in the previously used techniques. Some techniques were dangerous, this method has no danger or risk involved. Some techniques were restricted but this can be used to track blades while in flight. It is very simple method and a low cast solution as compared to previously used techniques. It also does not require any alterations to the blades.

The technique currently being used in the Pakistan Aviation industry is based on the visual observation and it does not provide any precise values of out of track blades. It also requires skilled crew members to perform the blade tracking. These two issues have been resolved in the proposed method. It gives precise out of track values and it does not skilled people to perform it. Anyone can run a simple a program and note down the out of track values from the Front Panel.

IV. Conclusion and Future Work

A new blade tracking technique was introduced based on image processing. An experimental setup was done and the helicopter rotor was simulated in this setup. The proposed technique has covered many drawbacks which were present in previous techniques. It is very simple to use and does not require any skilled operators to run it. Any member of the crew can run a simple application and see the out of track values on the Front Panel of the application. It has no danger in its use. It does not require any alterations in the blades and it is a low cost solution as compared to the other techniques.

Work is being carried out on the extension of this work which includes the tracking of the tail rotor. The problem in tracking tail rotor is that it has no magnetic pickup attached to it so there is no reference trigger which was available in case of main rotor. Secondly the camera cannot be mounted at any point in the helicopter where it can see the tail rotor. So it has to be figured out how to track the tail rotor blades.

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