

NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Washington, D.C. 20594

November 5, 2020

Video Study

NTSB Case Number:
WPR19FA188

A. ACCIDENT

Location: Hayward Executive Airport (HWD), Hayward, California
Date: July 15, 2019
Time: 1426 Pacific daylight time (PDT)
Aircraft: Robinson R-44 II helicopter

B. AUTHOR

Dan T. Horak
NTSB

C. ACCIDENT SUMMARY

On July 15, 2019, about 1426 Pacific daylight time, a Robinson R-44 II helicopter, N144TG, was substantially damaged during a low altitude maneuver at Hayward Executive Airport (HWD), Hayward, California. The commercial pilot was fatally injured and the student pilot received serious injuries. The airplane was registered to and operated by Pacific Helicopters, LLC as an instructional flight, conducted under the provision of Title 14 Code of Federal Regulations Part 91. Visual meteorological conditions prevailed and a flight plan was not filed for the local flight.

D. DETAILS OF INVESTIGATION

The goal of this investigation was estimating the ground track, roll angle and heading (yaw angle) of the helicopter during the final seconds of the flight that ended in ground impact. Analysis was based on a video recorded by a camera installed on a commercial building located south of the crash location. The video had 2304x1296 resolution and frame rate of 30 fps. The video only recorded the shadow of the helicopter on the ground. Parts of the airborne helicopter's shadow were visible for 5.4 seconds but most of the shadow was in the field of view of the camera for only about 3.5 seconds.

Camera Calibration

The analysis of this accident required a calibrated mathematical model of the camera optics. The mathematical model of camera optics requires seven parameters. Three are the X, Y and Z camera location coordinates. Three are the yaw, pitch and roll camera orientation angles, and the seventh parameter is the camera horizontal field of view (HFOV). The three location coordinates of the camera were measured by NTSB investigators. The four angles had to be estimated.

The estimation was based on references that were visible both in aerial images and in video frames. The references used for calibration included buildings, fences and railroad tracks. A computer program that simulates camera optics was used to project the references onto a frame from the video in an iterative process in which the four unknown camera model parameters were varied so as to align the projected references with their images. When the projected references were aligned optimally with their images in the frame, values of the four parameters were their optimal estimates. At that point, the model of the camera optics was calibrated.

Airplane Ground Track, Roll Angle and Heading Estimation

Estimation of a helicopter location based on its image in a video frame is based on the calibrated model of camera optics. A wireframe model of the monitored helicopter is constructed, consisting of points on its nose, tail, fuselage, tail boom, landing skids, rotor mast, etc. An analysis program then overlays the wireframe model on the video frame. The location and orientation of the wireframe model are then varied in an iterative process until the overlaid wireframe model optimally matches the image of the helicopter in the video frame. Once optimal match is achieved, the location and orientation of the wireframe model are the optimal estimates of the location and orientation of the monitored helicopter at the time the analyzed video frame was recorded.

Estimation Based on Helicopter Shadow

Analysis of this accident was unique because the video only showed the shadow of the airborne helicopter on the ground rather than showing the image of the helicopter. This required significant modifications of the analysis software. Using the modified analysis software, as the wireframe model was iteratively moved and rotated, its shadow on the ground was overlaid on the video frame. When the shadow of the wireframe model optimally matched the shadow of the helicopter, the location and orientation of the wireframe model were the optimal estimates of the location and orientation of the monitored helicopter. The software generated the image of the shadow of the wireframe model using the known sun altitude of 67.6° and sun azimuth of 228.6° at the location and time of the accident. The source of these values was the NOAA Solar Calculator.

Estimation of the location and orientation of a helicopter based on its shadow on the ground placed some limits on what can be estimated and how accurately it can be done. It is impossible to estimate the altitude of the helicopter because the size and

shape of the shadow, generated by parallel sun rays, are independent of the altitude. As the altitude changes and the helicopter X-Y location remains constant, the shadow on the ground moves along the sun azimuth direction. However, this does not help with determining the helicopter altitude because there are infinitely many combinations of altitudes and X-Y locations (along the sun azimuth direction) that place the helicopter shadow at the same location.

The ground surface in this accident was uneven and was covered with grass, weeds and bushes. Consequently, the image of the shadow that the camera recorded was incomplete and distorted compared to what it would have been if the surface was even and smooth, such as the surface of a runway. Figure 1 shows the image of the helicopter shadow in one of the video frames that were analyzed.



Figure 1. Image of the Helicopter Shadow in a Video Frame

One of the goals of the analysis was estimation of the roll angle of the helicopter. Figure 2 shows the schematic drawings of the R44-II helicopter. Examination of the helicopter schematics in Figure 2 and its shadow in Figure 1 reveals that a reasonably accurate roll angle estimation will have to rely on helicopter references that are maximally spaced in the vertical direction, i.e., the landing skids and the main rotor retaining nut (the top of the rotor mast). The accuracy of the roll angle estimates depends on the visibility of the landing skids and the main rotor retaining nut in the shadow of the helicopter. As seen in Figure 1, their visibility was limited. Furthermore, in most of the video frames the landing skids were not visible at all, making roll angle estimation impossible.

The camera was mounted about 17 feet above the surface over which the helicopter was flying and the camera pitch angle with respect to horizontal was 21° down. The shadow was located 100 feet or farther from the camera. This geometry resulted in high sensitivity of helicopter location estimates to surface elevation variations. Elevation variations were not known down to fraction-of-a-foot accuracy. Therefore, it had to be assumed that all of the helicopter shadow was located 17 feet below the camera. If the shadow of a helicopter component was actually at a slightly different elevation, it resulted in an estimate of the location of that component on the actual helicopter that was significantly incorrect.

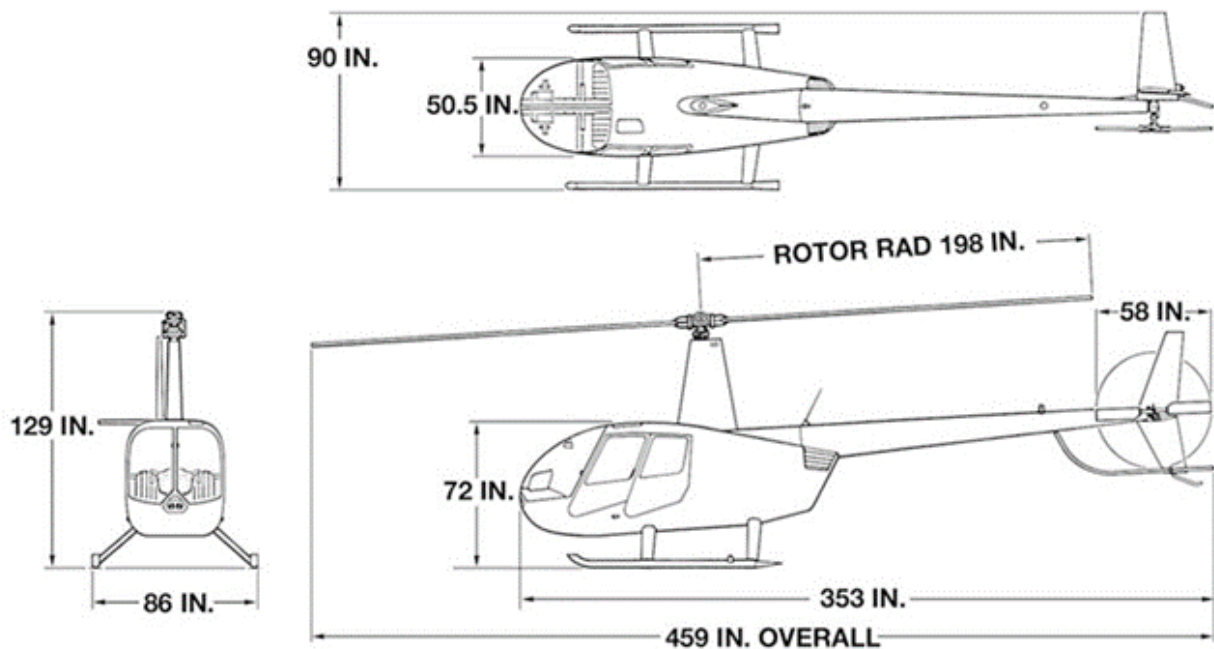


Figure 2. Schematics of the Robinson R44 II Helicopter

In some video frames, depending on the location and orientation of the helicopter, the amplification factor of the errors due to uneven surface elevation was as high as a factor of ten. This means that a surface elevation deviation of one inch from the assumed 17 feet below the camera could have caused a helicopter component location estimate that was off by as much as ten inches. As mentioned above, estimation of the roll angle depended on the distance from the landing skids to the main rotor retaining nut (see Figure 1). If the shadow of the landing skid and/or of the retaining nut was over a surface that was not at the assumed 17 feet below the camera, their distance as seen in the video frame was distorted and this error propagated to the estimate of the helicopter roll angle.

Analysis Process and Results

As explained above, estimation of the helicopter roll angle required visible shadows of a landing skid and of the main rotor retaining nut. Very few video frames met this requirement. It was also desirable that analyzed video frames be spaced by at least 0.1 seconds. There were nine frames in the video that met both the visibility and the spacing requirements. These frames were analyzed as described next.

As explained above, analysis based on shadows did not provide any information on the altitude of the helicopter. However, as shown below, the roll angle was -86° when the video showed dust due to the rotor blades contacting the ground. As seen in Figure 2, the helicopter rotor radius was 198 inches, or 16.5 feet. Therefore, it was decided to set the altitude of the helicopter to 15 feet at that time. It was not known what the altitude was before that time. Therefore, analysis was performed with altitude set at 15 feet for all the analyzed video frames. Since the altitude was likely decreasing when the shadow

of the helicopter was in the field of view of the camera, analysis was also performed with the altitude set at 40 feet, as described below.

For each of the analyzed video frames, the shadow of the wireframe model of the helicopter was overlaid on the frame. The wireframe model was then moved and rotated until its shadow optimally matched the shadow of the helicopter. When optimal match was achieved, the X-Y location of the wireframe model and its yaw, pitch and roll angle were the optimal estimates of these quantities of the monitored helicopter.

The poor visibility of the shadow did not affect the accuracy of the estimate of the X-Y location of the helicopter or its heading (yaw angle). It did affect the accuracy of the roll angle estimate because of the poor visibility of the landing skids and of the main rotor retaining nut. To improve accuracy, for each analyzed frame the frame before it and the frame after it were used to improve the accuracy of pinpointing the shadows of the landing skids and the main rotor retaining nut in the analyzed frame.

The yellow circular markers in Figure 3 shows the estimated locations of the nose of the helicopter at the time when the nine analyzed video frames were recorded (refer to Figure 5 or Figure 6 for the times corresponding to these nine points). The red lines originating at the yellow markers are the longitudinal axes of the helicopter. The lengths of the red lines correspond to the length of the helicopter. The orientation of the red lines are the estimated headings (yaw angles) of the helicopter. The yellow numbers indicate the estimated roll angle of the helicopter for each of the nine analyzed video frames.

Since the helicopter altitude could not be estimated based on its shadow, the X-Y locations were also estimated assuming the altitude was 40 feet. Since the altitude could not be 40 feet when the rotor blades were contacting the ground, only the first seven X-Y locations were estimated. Figure 4 shows the estimated X-Y locations for both the assumed altitudes of 15 feet and 40 feet. The dotted lines connect helicopter nose locations corresponding to the same analyzed point. The orientation of these lines is 228.6° , the sun azimuth angle. The yellow numbers again indicate the estimated roll angle of the helicopter.

The relative proximity of the 15-foot locations and the corresponding 40-foot locations in Figure 4 suggests that the unknown helicopter altitude will not have a significant effect on the results from this study. Note that the shadow-based estimates of the helicopter yaw, pitch and roll angles are independent of the altitude.

Figure 5 is a plot of the estimated heading (yaw angle) of the helicopter, i.e., the orientation of the red lines in Figure 3. The markers are the nine estimated values and the curve interpolates in between them.

Figure 6 is a plot of the estimated roll angle of the helicopter. The markers are the nine estimated values and the curve interpolates in between them. Negative roll angles correspond to left side down.



Figure 3. Estimated Helicopter Locations and Headings (altitude: 15 feet)



Figure 4. Estimated Helicopter Locations (altitude: 15 feet and 40 feet)

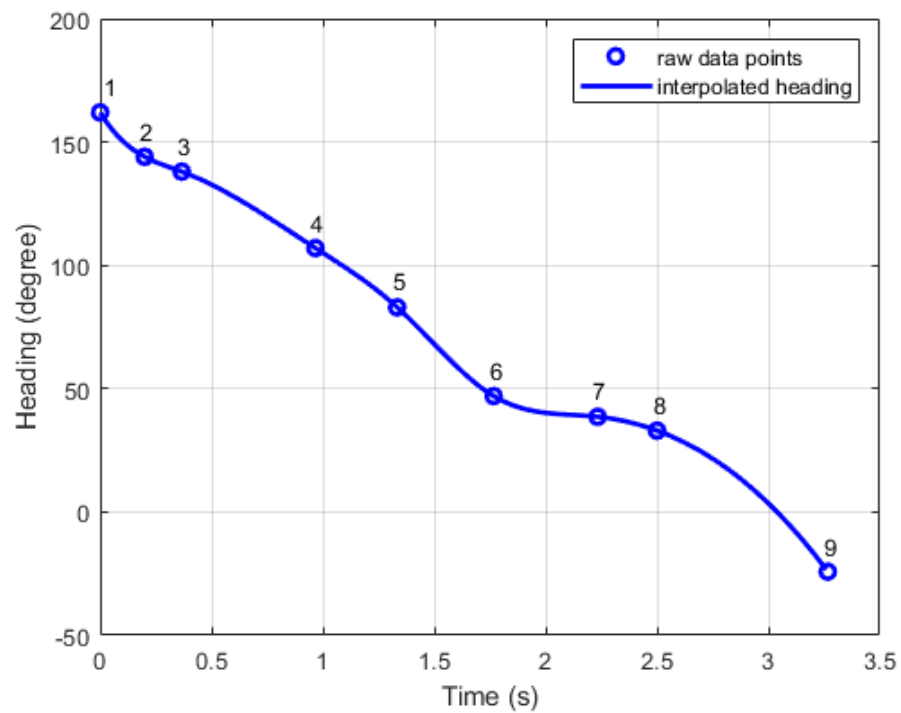


Figure 5. Estimated Helicopter Heading (Yaw Angle)

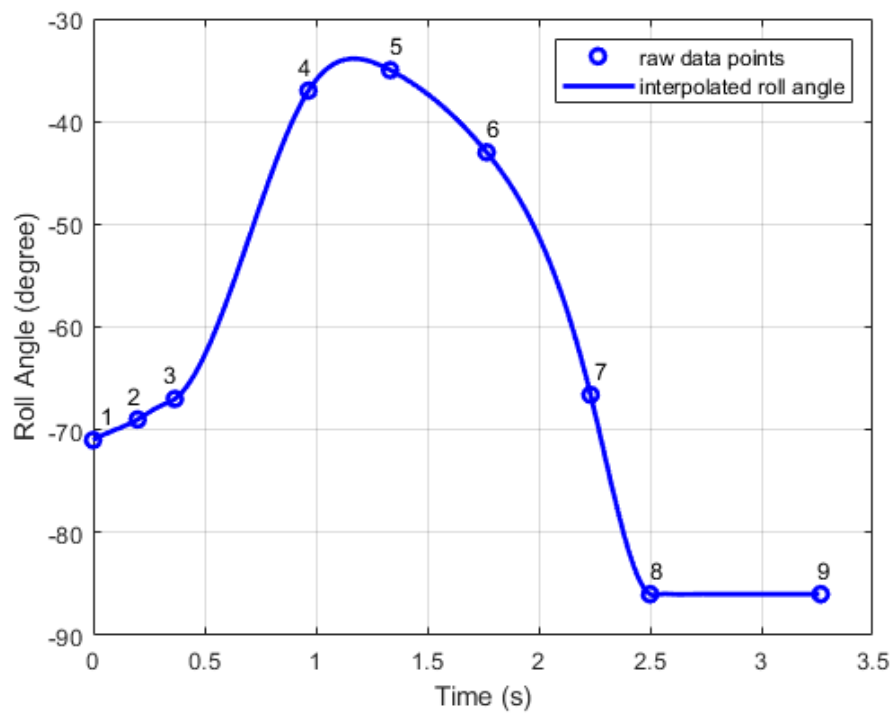


Figure 6. Estimated Helicopter Roll Angle

E. CONCLUSIONS

The ground track, heading and roll angle of a crashing helicopter were estimated based on a video that showed only the shadow of the helicopter. The video was recorded by a camera installed on a commercial building. The helicopter roll angle was close to ninety degrees left-side-down when its rotor blades contacted ground.