Combined Maneuvering Analysis, AIS and Full-Mission Simulation

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ABSTRACT: This paper deals with a method for identifying the main parameters of a maneuver using both real-time full mission simulators and positioning data obtained from the Automatic Identification System of the same area. The effort required for experiments in real time maneuvering is naturally larger than the effort required to collect already available data. Analysis of both data sources is presented. We show how the curvature of the ships track can be related to the wheel-over point and further used to estimate the main parameters of a course-changing maneuver. The southern approach to the Risavika harbor in the southwest of Norway is used as a demonstration. The approach angle and turning circle diameter was accurately identified in both AIS and simulator data, but significant navigational markings was only quantifiable in simulator data.

1 INTRODUCTION

To investigate the effect on navigation decisions and external effects on ship maneuvering it is convenient to test these scenarios in a simulator with controlled conditions and good opportunities for data collection. If such simulations are to represent the real world it is important that the processes that are simulated are similar to their real world counterparts. In traditional fully automated maneuvering simulations (Hutchinson, 2003, Merrick, 2003), a regular control-theoretic guidance and autopilot combination is often used to represent the maneuvering decisions on the bridge of the ship. This control theoretic construct is not well suited to represent the decisions on the bridge, as it does not follow the same guiding rules as a human would. The first step to replace this control theoretic construct is to identify the proper maneuvering processes and then to quantify their main parameters. These main parameters can later be used as input to a numerical navigator for fully automatic maneuvering simulation. Quantification of the main features and parameters can be made from expert opinion and simulator studies with human operators. Simulator studies are a costly and time consuming process, but offers the best accuracy and provides control of the environment in which the maneuver is executed. Simulator studies can also be augmented by real world data whenever possible, with simulator studies providing the entry point into analysis of coarser real world data.

Data from the Automatic Identification System (AIS) has a potential to reveal the preferred navigational patterns and maneuver parameters in use in a specific area. The AIS system is implemented by all IMO member states as per requirement of SOLAS. The system represents an opportunity to study the traffic and navigational patterns in costal areas. Data available from AIS introduced in recent years has not been used for this purpose.

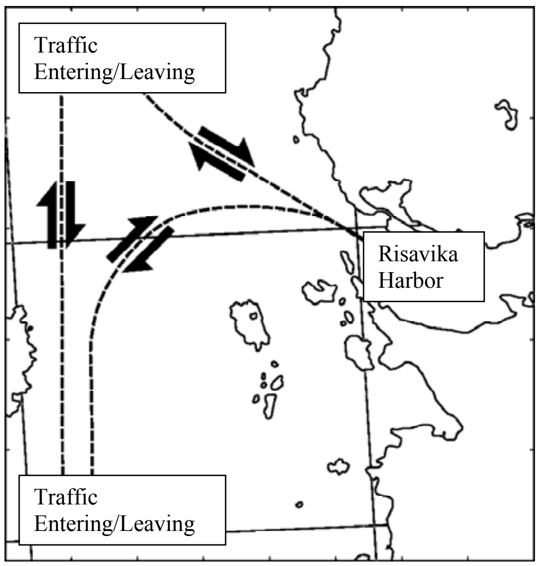

Fig. 1. Risavika With Main Traffic Concentration

In this paper we will show how the main parameters of maneuvering can be quantified by use of simulator trials and AIS data. We will focus on the area around the Risavika harbor in the southwest of Norway. An overview of the area and the main traffic routes is seen in Figure 1. The routes of traffic shown are extracted from AIS data from the area.

1.1 *Representation of maneuvering*

Maneuvering of a ship in transit can be represented as a combination of course keeping and course changing maneuvers stringed together to form a complete plan for the voyage. This representation is described in (Lüzhöft, 2006) where it is presented as the standard planning procedure for pilots and shipmaster operating in the costal areas around Stockholm in Sweden. The voyage plan is in the form of straight sections with the heading for both passage directions noted with turning diameters for each turn. In addition the significant landmarks and navigation aids used to determine when and where to transit between these maneuvers are noted. The maneuvers of the vessel is joined together at points where the wheel of the vessel is either used to initiate a turn (wheel-over-point) or the point where action is taken to exit the circular turn path (pull-out-point). The approach to Risavika harbor is modeled as a section with constant course followed by a Rate-of-turn maneuver to change the vessels course to a more beneficial course for entry into the harbor.

1.1.1 *Course keeping*

Course keeping is the simplest of maneuvers and is the task of keeping the vessel on a straight course. The only variability one expects is the individual error tolerances in deviation from desired course or the variability in entry of autopilot targets. The main parameter of this maneuver is the desired course.

1.1.2 *The rate-of-turn maneuver*

The rate of turn maneuver is marine craftsmanship and is based on simple rules of thumb calculations of an object speed and the curvature of the path it follows. An object will travel on a circle of diameter *D* if the ratio of the speed and rate of turn is constant; the constant determined by the circle diameter is a defining parameter of the maneuver. The rate-of-turn of the vessel is reported as degrees per minute on the bridge of the vessel. The time in minutes for a vessel with speed *V* m/s to complete a turn of 360° on a radius of *r* m is

$$t = \frac{2 \cdot \pi \cdot r}{V} 60 \qquad (1)$$

To get the rate of turn in ° per second needed to stay on the circle of radius *r* we divide 360° with time from Equation (1).

$$ROT = \frac{360^\circ}{\frac{2 \cdot r \cdot \pi \cdot 60}{V}} = \frac{3^\circ \cdot V}{r \cdot \pi} \approx \frac{V}{r} \qquad (2)$$

The final simplification is to transfer the expression into an easy to remember rule of thumb. This simple rule is the foundation for the rate-of-turn maneuver where the master of the vessel actively will use the controls to keep the relationship between the vessel speed and rate-of-turn constant. The constant determines the radius of the turning circle. The turning circle radius is then the defining characteristic of the rate-of-turn maneuver. In a nautical setting the rule is applied with knots as speed and nautical miles as measure for the radius. With a given turning radius of 0.5 nautical miles, this relationship between rate of turn and speed in knots easily gives the required rate-of-turn for this maneuver.

$$ROT = \frac{V}{0.5} = 2 \cdot V \qquad (3)$$

1.2 *Quantification of parameters*

From the AIS data and simulator trials the following maneuvering characteristics were identified in the northbound approach to Risavika:

- Approach course angle
- Number of turning maneuvers used
- Wheel-over-point position
- Pull-out-point position
- Mean and max turning circle radius for each turning maneuver

The Rate-of-turn maneuver used in the simulator study has characteristics, which we also can calculate from the data available from AIS. This will be done in turn to show the accuracy of these calculations. The radius of the turning circle used in the maneuver is identifiable from the rate-of-turn vs. speed ratio maintained by the vessel during the maneuver.

The curvature of the track line can be used to extract the number of turning maneuvers used on a section of the passage.

From the charts of the area and the simulator environment we have the location of the significant navigational lights in the area. The positions of these lights are used together with the wheel-over and pull-out points to try to determine the most probable navigational light used. The position of the navigational lights in the simulator area was used both in the simulator trials and in the analysis of the AIS data.

2 SIMULATOR TRIALS

Full mission simulator data was recorded from training exercises at the Ship Maneuvering Simulator Centre (SMSC) in Trondheim, Norway. Simulator trials were used to determine a benchmark maneuver and used with the greater fidelity of the synthetic environment to analyze the time series of available variables. Simulations where carried out with human operators on the bridge simulators piloting the vessel into Risavika harbor. The simulator centre has three full mission simulators in operation and by introducing an automatic logging application on the simulator network the communication from each simulator was intercepted. The start of logging was triggered by the start of the exercise for the Risavika maneuver. Data was written to disk and made both the simulated vessel state as well as the control inputs for rudder and engines available as time series for offline analysis. Data was sampled at 1 sec intervals to limit file size.

2.1.1 *Trial maneuver*

The trial maneuver selected for study was a maneuver to enter the harbor in Risavika from the south starting at a course of 0° N. The starting position for the ship has no obstructions on the initial heading, and will with the initial speed in a relatively short amount of time be in a position to initiate the turning maneuver into the harbor. The turning maneuver into the harbor is predefined. The bridge crews were instructed to change the ship's course using a rate of turn maneuver with a radius of 0.5 nautical miles until they were on a course suitable for the final approach. By inspecting the rudder time series in the simulator trials the wheel-over-point for the transition between the first course keeping section and the rate-of-turn maneuver was identified. This point for each dataset allowed calculation of the heading at the time of maneuver transition, and the angle between the vessels and all the visible navigation lights in the simulated area. The same procedure was used to identify the pull-put-point, completing information about the maneuver.

2.1.2 *Results*

In total 44 maneuvers were recorded from SMSC exercises with a variety or bridge crews. Some exercises were discarded due to approach path. The discarded exercises followed a radically different path with fundamentally different features than the typical maneuvers, 36 cases remained in the end. Maneuver transition points and track curvature was extracted form this data. The mean and max value of the relationship between rate-of-turn and the speed during the rate-of-turn maneuver is seen in Figure 2. Figure 2 shows a median value of the mean rate-of-turn/speed relationship of *1.75*. This translates to a turning circle radius of *0.571* nautical miles. If we account for the introduction of *3/3.14 = 1* in the rule-of-thumb simplification of the formula, the theoretical turning circle has a radius ≈ *0.54* nautical miles. The deviation then becomes only *0.03* nautical miles and is in good agreement with the theoretical value. Both mean and max values shows skewed data. The mean rate-of-turn/speed relationship packed tight around the median. The results showed very good agreement with the ideal turning circle radius one should expect from the briefing. Some of the deviations are from the exercises following a slightly different path into the harbor.

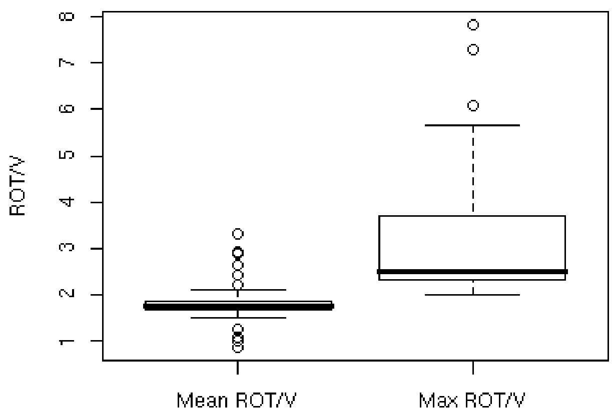

Fig. 2. Distribution of rate-of-turn/speed from simulator trials

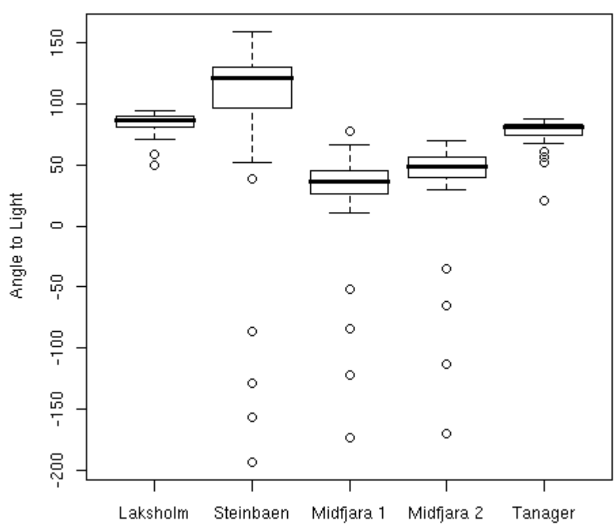

Fig. 3. Angle from vessel to navigational lights in simulator trials at the wheel-over-point

The results from the calculation of the angle between the wheel-over-point and the visible lights in the simulator were plotted as a boxplot to determine correlation. The results are seen in Figure 3, where the angle to the first landmark seems to be very consistent across trials and at an angle of 90° it is preferable since it is indifferent to cross track deviations (the last landmark is in close proximity, and shows a very similar distribution). If the first landmark is taken as the significant maneuvering landmark used, then we can find a statistical description of the variability of the wheel-over-point in relation to the angle to the landmark. We see a skewed distribution around a median of about 90° for the first landmark, with a few outlier cases, again from a different approach path.

Another result from the simulator experiments was the relation between the Wheel-over-point, Pull-out-point and the local extreme values of the track curvature. The wheel-over point was always located near a local minimum while the pull-out point was located near a local maximum. An example time series is seen in Fig. 4 where the relevant points are indicated. The nonzero curvature for zero rudder angles shows the tendency of single-screw ships to turn at zero rudder angles due to propeller inertia and asymmetric flow around the stern

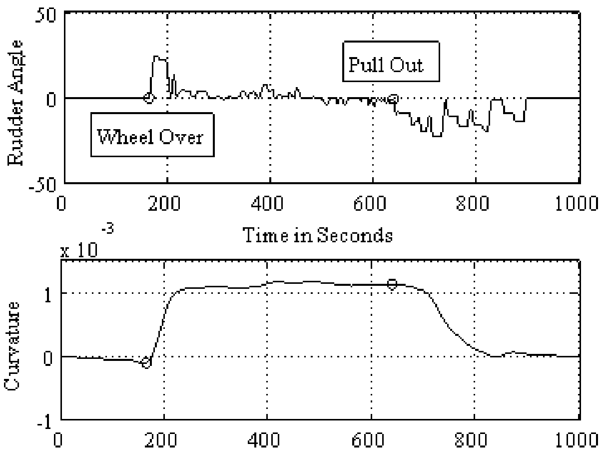

Fig. 4. Rudder angle and curvature in relation to wheel-over and pull-out points

In the simulator studies the difference in time between the Wheel-over-point and the local minimum was computed and is shown in Fig. 5. This proximity can be used to make a qualified guess about the location of these points based on rate-of-turn and speed data. The local extreme value behavior will be used later to find good candidates for wheel-over and pull-out points in the AIS data for the same area.

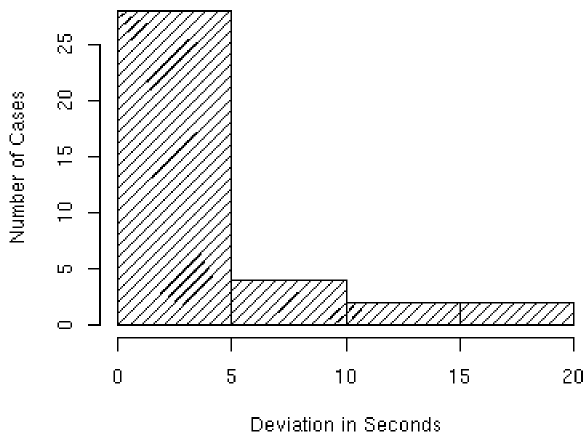

Fig. 5. Wheel-over-point deviation from local extreme value of the track line curvature

3 AIS DATA ANALYSIS

The Norwegian Costal Administration provided AIS data in form of position reports for April, May and June 2006 for the presented area. The position reports where then restricted to the immediate area around Risavika before it was grouped according to each ships unique MMSI number (IMO, 1974). Requiring the track line to start to the south and end in the harbor was used to restrict the AIS data further. The data for each MMSI number was then further sorted by time and grouped in space to form datasets of track lines continuous in these dimensions. This procedure was necessary due to the presence of misconfigured AIS transponders making identification solely based on MMSI number difficult. The AIS data received contained time, position, speed over ground, rate of turn and course over ground. The sample rate of the AIS data depends on the ships speed and state of the vessel and will during transit and turning maneuvers for moderate speed be in the area of *0.3 – 0.5* Hz (IMO, 1974).

The AIS data does not contain information that makes it possible to pinpoint the transitions between the different maneuvers, such as the instantaneous position of the rudder. We can however find features from the maneuvering techniques used in the data in form of the speed, rate-of-turn and position in the AIS data with an accuracy of about 5 seconds as presented in Fig. 4 and Fig. 5. The AIS data does not contain rate-of-turn information for all vessels, but calculation of the curvature of the track line of the vessel will accurately identify the value of the speed/rate-of-turn relationship. The ratio between the vessels rate-of-turn and the speed relationship corresponds to the curvature of the ship track. Calculation of the curvature will work regardless of the absence of rate-of-turn information in the signal. The total number of AIS track lines was 429, which was further subdivided into 308 single turn maneuvers, 107 two turn maneuvers and 14 maneuvers with 3 or more turns which were discarded due to accuracy of the procedure and implied poor accuracy in the position reports.

3.1.1 *Calculating curvature from position data*

The curvature κ of the ships track can be calculated from the position and time data. This can done by filtering the position data to remove noise and then use a numerical expression for the curvature calculated by solving the equation for a circle passing through the three consecutive points. κ can also be directly from the time domain signals for the position $x=x(t)$ and $y=y(t)$. The curvature of these two signals in Cartesian coordinates with ϕ as the tangential angle of the signal.

$$\kappa = \frac{d\phi}{ds} = \frac{d\phi / dt}{ds / dt} \tag{4}$$

$$\kappa = \frac{d\phi / dt}{\sqrt{(dx/dt)^2 + (dy/dt)^2}} = \frac{d\phi / dt}{\sqrt{(\dot{x})^2 + (\dot{y})^2}} \tag{5}$$

The need for $d\phi/dt$ can be eliminated by the following identity

$$\tan\phi = \frac{dy}{dx} = \frac{dy/dt}{dx/dt} \tag{6}$$

$$\frac{d\phi}{dt} = \frac{1}{\sec^2\phi}\frac{d}{dt}(\tan\phi) \tag{7}$$

$$\frac{d\phi}{dt} = \frac{1}{1+\tan^2\phi}\frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{\dot{x}^2} \tag{8}$$

Equation (8) substituted into Equation (5) gives the final expression for the curvature

$$\kappa = \frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{(\dot{x}^2 + \dot{y}^2)^{3/2}} \tag{9}$$

This expression for κ relies on the derivative and double derivative of the vessel track line positions. Numerical calculation of these derivatives from noisy position data is inherently error prone. Instead of calculating the derivatives numerically, the derivatives are evaluated by fitting polynomials to the $x(t)$ and $y(t)$ signals. It is impossible to find a general polynomial to describe the complete track with sufficient accuracy for the entire ship track. To calculate the curvature at a specific track sample, a 5^{th} order polynomial is fitted at a section spanning 20 samples both forward and backward in time. This provides both a theoretical form for the evaluation of the derivatives and suppresses the noise in the positioning data. The derivatives and double derivatives can then easily be evaluated from the corresponding formulas for polynomials. The polynomial fit was computed using MATLAB's 'polyfit' function using both centering and scaling to improve the numerical properties of the fitting procedure.

3.1.2 *Detection of turning maneuvers*

Detection of turning maneuvers was done by discretizing the number range for the curvature into regions of size *1e-4*. The curvature signal was then compared to this interval forming an array of *0* and *1* values. The array represents the image of the area between the x-axis and the curvature signal. This representation made it easy to determine where the curvature crossed certain numerical values, and how many crossings it did of a particular value. The curvature level used to detect significant changes in track curvature was *3e-4*; the number of crossings over this value was easily extracted from the line of the kappa image array corresponding to this value. The number of up-crossings over this value was an initial estimate of the number of turns in the maneuver. The area beneath each turn was compared and if the area during one turn of a two-turn maneuver was less than 10% of the area of the other turn, the maneuver was reclassified as a one-turn maneuver. After the turning maneuvers were identified the Wheel-over and pull out point where assigned to the local extreme values.

3.2 *Results*

The results from the AIS data processing showed a deviation in the preferred route into the harbor for the southern approaches compared to the simulator experiments. The difference concerns the approach angle towards the harbor, making the turn into the harbor less severe in reality than in the simulator. The AIS data further showed that the traffic entering the harbor was divided into one and two turn approaches. The one turn approach still followed the same basic principle as the simulator experiments, while the two turns approach used an additional course-changing maneuver before the final turn into the harbor. The two-turn approach followed a separate pattern with a course change roughly the same place as the one turn maneuver but with a final sharp turns used to enter the harbor. Only data for a single turn maneuver is used to calculate the approach angle, curvature, wheel-over and pull out points.

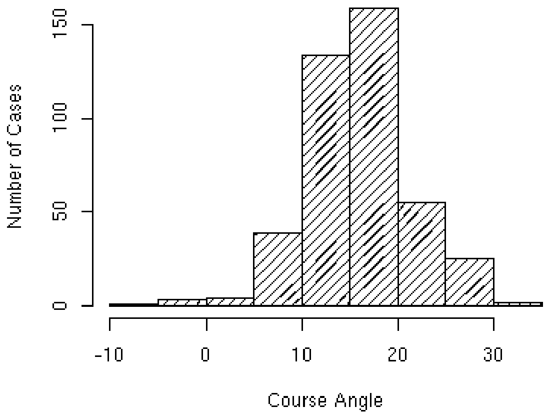

Fig. 6. Course angle at the wheel-over-point

The curvature of the track line was calculated as described in Section 3.1.1 and is shown in Fig. 7. The mean and max curvature is calculated using values between the wheel-over and pull-out point identified in the manner described in Section 3.1.2. The results are similar to those of the simulator study but with more variation and a larger discrepancy between the mean and max curvature. The median of the mean curvature is *0.00101* corresponding to *990m ≈ 0.535* nautical miles. This result fits nicely with the numerical values for the turning circle diameter estimated from the simulator trials. The curvature distribution from AIS is less skewed and follows a more normal distributed form. Outlier cases are fewer as shown in Fig. 7, but the maximum curvature shows a far greater range.

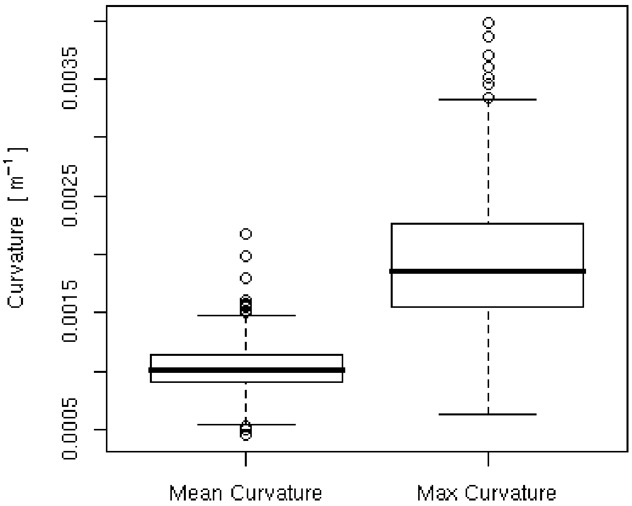

Fig. 7. Curvature of AIS Track Lines During Turn

The wheel-over and pull-out point for the AIS data was harder to quantify, and only a qualitative conclusion could be drawn from the data. No clear candidate as in the case of the simulator trial emerged.

4 DISCUSSION

The approach angle, number of turns and turning circle diameter was well estimated with a good accuracy in comparison with the values found in the simulator trials. The relatively small number of simulator trials highlights a drawback: the limited amount of time and resources to study a maneuver. However a more intense simulation program can mitigate this effect.

The position of the wheel-over and pull-out point is harder to relate to the navigational lights in the area. This may be because of the inherent error in estimating these points from the curvature or due to the numerical effects on the calculation due to the proximity of the navigational lights to the track line, exaggerating any errors in the angle estimate. Another cause for the difficulty in identifying a pattern in the wheel-over and pull-out points in the AIS data is the possibility that its high dependence of vessel dynamics makes it a poor candidate for analysis across a wide selection of vessels. The points where the track line curvature exceeded 1e-4 were more clustered around a specific point. This effect is possible with a large selection of ships with different dynamic responses all aiming for the same turning circle starting at the same point, a pattern we have seen in the AIS data. This effect can be further investigated using static ship data available from the ITU’s Maritime mobile Access and Retrieval System database linked with ship statistics for dynamic response.

The turning circle diameter used and the number of turns used was more accurately identified in both the simulation trials and the AIS data from the same area. Ships entering Risavika use a turning circle diameter of 0.5 nautical miles for one course change approaches to the harbor. The main difference from the simulator trials here is the approach angle which was 15° in service compared to 0° in the simulator studies. Ships using a 0° approach angle used navigational light 1, “Laksholm” initiating the turn at 90° angle. This pattern was also visible in AIS where a very limited number of vessels used the 0° approach.

5 CONCLUSION

It has been shown that analysis of the ship track line can be used to estimate the parameters of standard maneuvers. This can be useful either in conjunction with simulator studies or by itself. The parameters of the rate-of-turn maneuver extracted from the combination of simulator and AIS data can be used later as input to a numerical navigator to mimic the behavior of the real navigator. AIS present itself as an easily available source of information about the desired maneuvering patterns in a specific area. More importantly the parameters of the maneuvers are quantifiable from this data. The navigational aids used are best identified using full-mission simulation or expert opinion.

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