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Error analysis of dynamics model for satellite attitude estimation in Near Equatorial Orbit

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Abstract: Satellite attitude estimation is one of the important processes in accomplishing a satellite mission. All the state estimation process requires dynamics model and filtering algorithm to estimate the state. Most of the estimation algorithm such as well-known Kalman filter and its variation assume the underlying noise in the dynamics model is Gaussian white noise. Hence, the objective of this paper is to investigate whether the noise in satellite attitude dynamics model in Near Equatorial orbit is Gaussian white noise process or not. This is important because if the assumption regarding the noise is incorrect, this will lead to unreliable and inaccurate estimation. In this paper, the noise is analyzed using normality characterizations and autocorrelation function. The result shows that the noise in the attitude dynamics at Near Equatorial orbit is not Gaussian white noise process.

Index Terms- Satellite attitude; Estimation; Dynamics; Gaussian; White noise

I. Introduction

Attitude of a satellite is defined as its orientation in the space. Attitude analysis of a satellite is constantly being computed in attitude determination and control subsystem (ADCS) throughout in space for mission accomplishment. Examples of satellite mission are Earth observation, communication, scientific research and many other missions. One of the attitude analysis processes is satellite attitude estimation, a process to estimate the attitude under the noise presence. Its role is to provide the estimate of the current attitude to be fed back into the controller for attitude control purpose. The accuracy of the estimated attitude is very important since it will be used for the attitude control purpose, which determines the successful of a specific satellite mission.

Early applications relied mostly on the Kalman filter for attitude estimation. Kalman filter was first applied for attitude estimation in 1960s for the Apollo space program [1]. Since these applications, several new approaches have been developed that have proven to be superior to the Kalman filter. Several of these approaches maintain the basic structure of the Kalman filter, but employ various modifications in order to improve other performance characteristics such as extended Kalman filter (EKF) and unscented Kalman filter (UKF) [2]. EKF is developed to estimate the state of the nonlinear system whereby the nonlinear equation is approximated by linearized equation through Taylor series expansion. However, for highly nonlinear model, the linearization of the underlying model can lead to particularly poor performance and may diverge [3]. A new approach called unscented Kalman filter (UKF) that has been introduced by Julier et al [4] is shown as an alternative to the EKF. UKF uses a deterministic sampling technique known as the unscented transform to pick a minimal set of sample points called sigma points to propagate the non-linear functions. This approach removes the need to explicitly calculate the Jacobians which is a daunting task [3]. UKF was first implemented in satellite attitude problem by Crassidis and Markley [5] and the simulation results indicated the performance of the UKF exceeds the standard EKF for large initialization case. However, these approaches assume the noise in the system model is Gaussian white noise process. Other approaches that do not require this assumption is particle filter which is developed by Gordon et al [6].

All the estimation algorithms mentioned above require dynamics model to estimate the state [3]. It is well-known that Kalman filter and its variation such as EKF, UKF etc assume the nature of the noise or errors in the dynamics model is Gaussian white noise [3]. However, in real application this is not always true [7]. Hence, it is the intention of this work to investigate whether the noise in the satellite attitude dynamics is Gaussian white noise or not. This is important because if the assumption regarding the noise is incorrect, this will lead to unreliable and inaccurate estimation [7]. Kalman filter has been found as most widely used algorithm for state estimation due to its simplicity for implementation and theoretically attractive in the sense that minimizes the variance of the estimation error. Hence, with advantage of having real attitude data from the world first remote sensing satellite launched into Near Equatorial Orbit (NEqO), RazakSAT, the purpose of this work is to analyze the type of noise inherent in the dynamics model for the attitude estimation. With the knowledge regarding the underlying noise of the system, a more accurate estimation can be implemented for the next mission.

The rest of this paper is organized as follows: Section II is about the methodology including the detail descriptions of data collected, dynamics model of satellite attitude and Gaussian white noise; Section III is the result and some discussion; and lastly the conclusion is drawn in Section IV.

II. METHODOLOGY

A. Data of RazakSAT

RazakSAT is a Malaysian satellite and was successfully launched in 2009. It is the world first remote sensing satellite launched into Near Equatorial Orbit (NEqO) at 685 km altitude and 9 degrees inclination. It is a small satellite with mass of 180 kg. RazakSAT's mission was carrying a high resolution camera to provide images of Malaysia that can be applied to land management, resource development and forestry [8].Figure 1 shows the structure of RazakSAT.

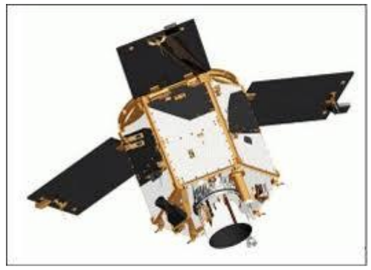


Figure 1: Structure of RazakSAT

RazakSAT was in normal sun pointing mode most of the times for maximum power generation and attitude maneuvers are required for the imaging mode as shown in Figure 2.

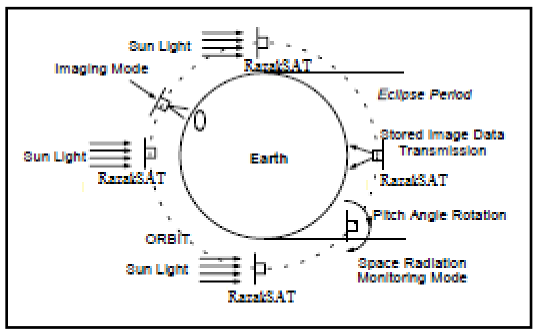


Figure 2: Operation modes of RazakSAT

During this mode operation, the angular velocity of the satellite is intended to be zero so that all its three solar panels face towards the sun for maximum power tracking. However the satellite is exposed to the environmental space disturbances that disturb its equilibrium state. The environmental space disturbances could arise from gravity gradient, aerodynamic, Earth magnetic, solar radiation pressure, etc. In practice, the angular velocity is measured by gyroscopes, and the measurement is feedback to the controller and hence input the commanded control torque to the actuator so that the actuator will counteract the exerted disturbances.

The data used in this work is during sun pointing mode about six consecutive orbits. The orbital rate of RazakSAT is 97 minutes per orbit. The data was provided by Astronautic Technology SdnBhd (ATSB), the Malaysian company that responsible for RazakSAT's mission.

B. Dynamics model of satellite attitude

The mathematical model of satellite attitude dynamics is given by Euler moment equation [9]

$$I\dot{\omega} + \omega \times I\ \omega = T \tag{1}$$

with$I = diag[I_x, I_y, I_z]$, $\dot{\omega} = [\dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z]$, $\omega = [\omega_x,\ \omega_y,\ \omega_z]$, $T = [T_x, T_y, T_z]$ represent satellite's moment of inertia, angular acceleration, angular velocity and total external torque respectively.

From the theory of differential equation, a system will remain in its equilibrium state unless external inputs, T exerted on the system and disturb the motion. In RazakSAT case during sun tracking mode, the angular velocity ω is intended to be zero and it will remain in its equilibrium state unless the disturbance torque disturb its motion. Hence it the intention of this work to analyze the disturbance torque that exerted on RazakSAT using the obtained angular velocity data.

C. Gaussian white noise

In this paper, the disturbances which represent the noise are analyzed whether they are Gaussian white noise or not. This is because if the underlying noise is not Gaussian white noise process, but the filtering designer insists to use Kalman filter due to its simplicity for implementation, this will lead to the inaccurate or unreliable estimation.

Gaussian or normal distribution is always being assumed as the underlying model in many applications such as engineering and economics areas. A Gaussian distribution is symmetric and bell-shaped. There are several techniques to assess the normal distribution of the data such as through a normality test, histogram plot, or normal probability plot (some refer as Normal Q-Q plot).

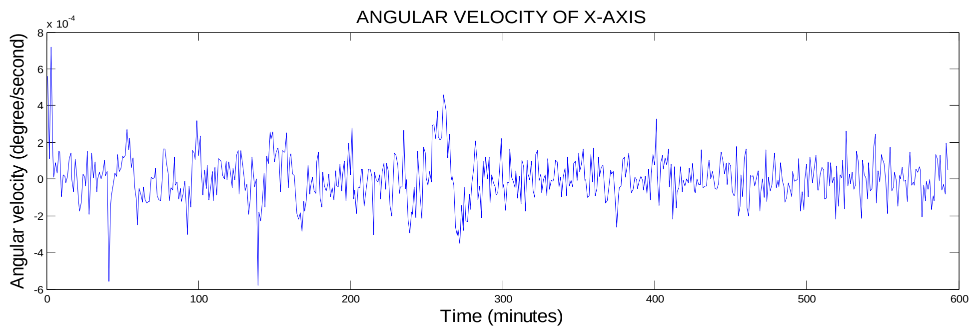
While, a process is called a white noise process if it is serially uncorrelated [10]. To test whether the data series is white or not is by using autocorrelation. For a given time series $\{x_1, x_2, \ldots, x_n\}$ the autocorrelation function, ρ_k is defined as [10]

$$\rho_k = \frac{Cov(x_i, x_{i+k})}{\sqrt{Var\,(x_i)}\sqrt{Var\,(x_{i+k})}} \quad , k = 1,2,3,\ldots \tag{2}$$

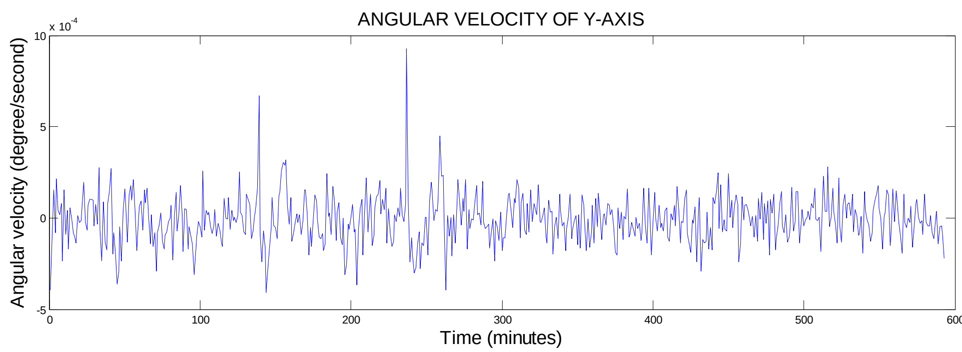
It is white noise process if autocorrelation values are near zero statistically [3] which show there is no correlation between the series.Autocorrelation function of a data series can be computed and plotted with aid of SPSS or Minitab software.

III. RESULT AND DISCUSSION

Figure 3 shows the angular velocity measurements of RazakSAT during sun tracking mode. Instead of having zero values of angular velocity, some excitation of non-zero values are observed from the figure.



(a)



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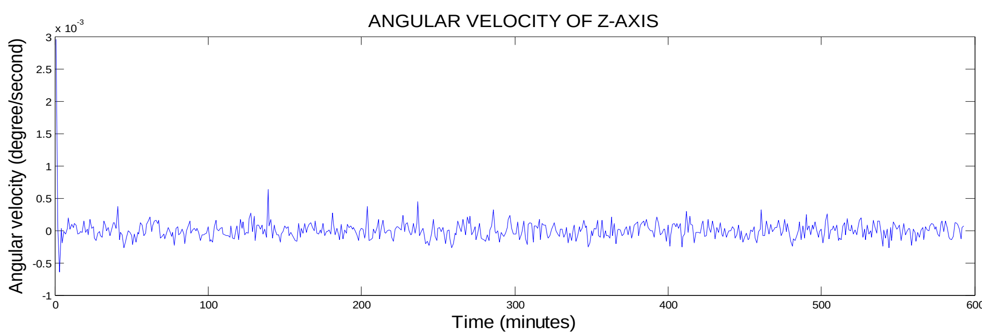


(c)

Figure 3: Angular velocity of RazakSAT during sun tracking mode for (a) X-axis, (b) Y-axis, (c) Z-axis.

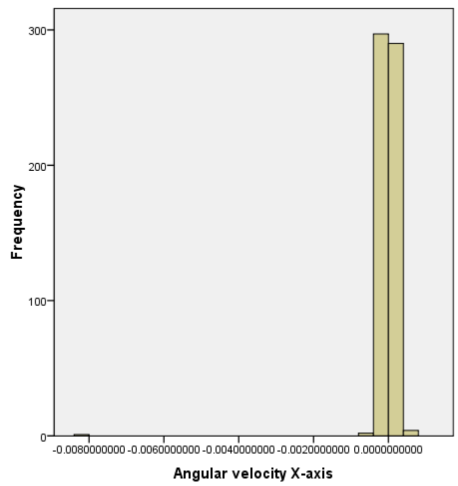
In this work, Kolmogrov-Smirnov test is used to test for normality of the disturbance. The result of the test is shown in Table 1. From the table, the Sig. value is less than 0.05 for each axis, suggesting non-normality of the distribution.

Table 1: The results of Kolmogrov-Smirnov statistic.

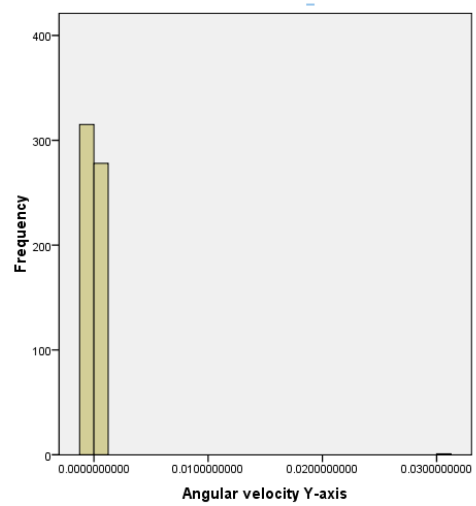
	Kolmogorov-Smirnov test

	Statistic	df	Sig.
Angular velocity X-axis	.263	594	.000
Angular velocity Y-axis	.417	594	.000
Angular velocity Z-axis	.448	594	.000

The actual shape of the distribution for each axis can be seen in the histogram plot in Figure 4. For all axes, the disturbances appear to be non-normal distributed. This is also supported by an inspection of the normal probability plots (labeled as Normal Q-Q Plots) in Figure 5. In these plots the observed value for each axis is plotted against the expected value from the normal distribution. A reasonably straight line suggests a normal distribution. However in the plot for each axis they do not lie along the straight line, hence suggest the disturbances do not follow Gaussian distribution.



(a)



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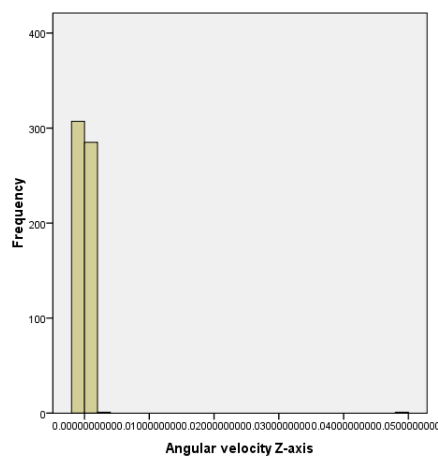
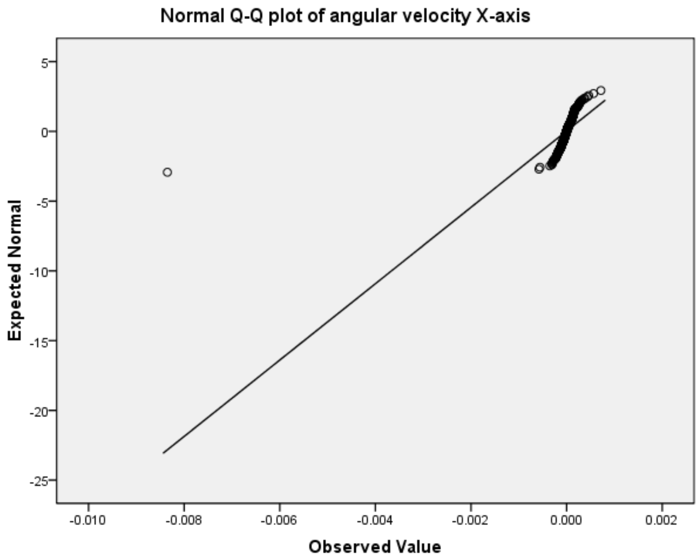
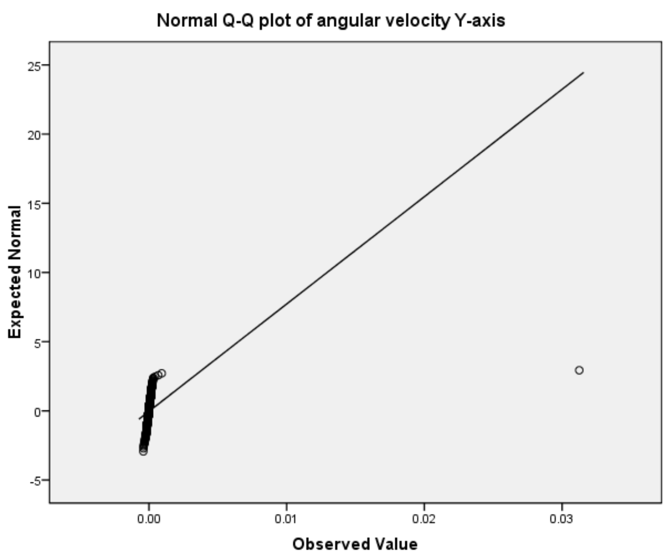


(c)

Figure 4: Histogram plot of the angular velocity (a) X-axis, (b) Y-axis, (c) Z-axis.



(a)



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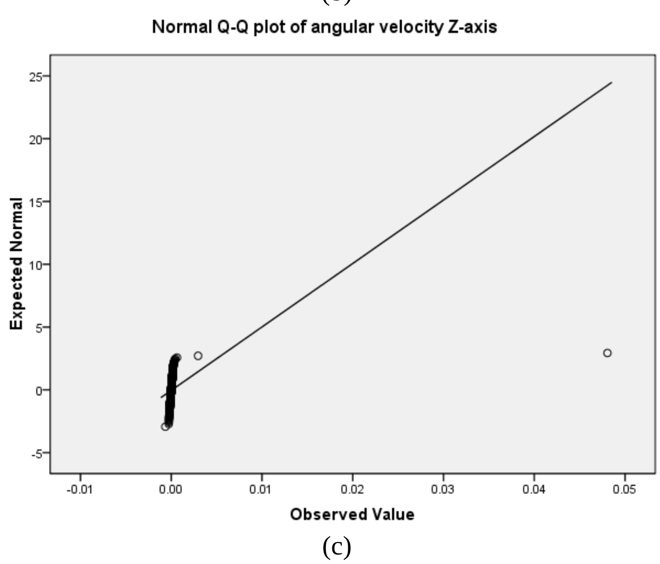
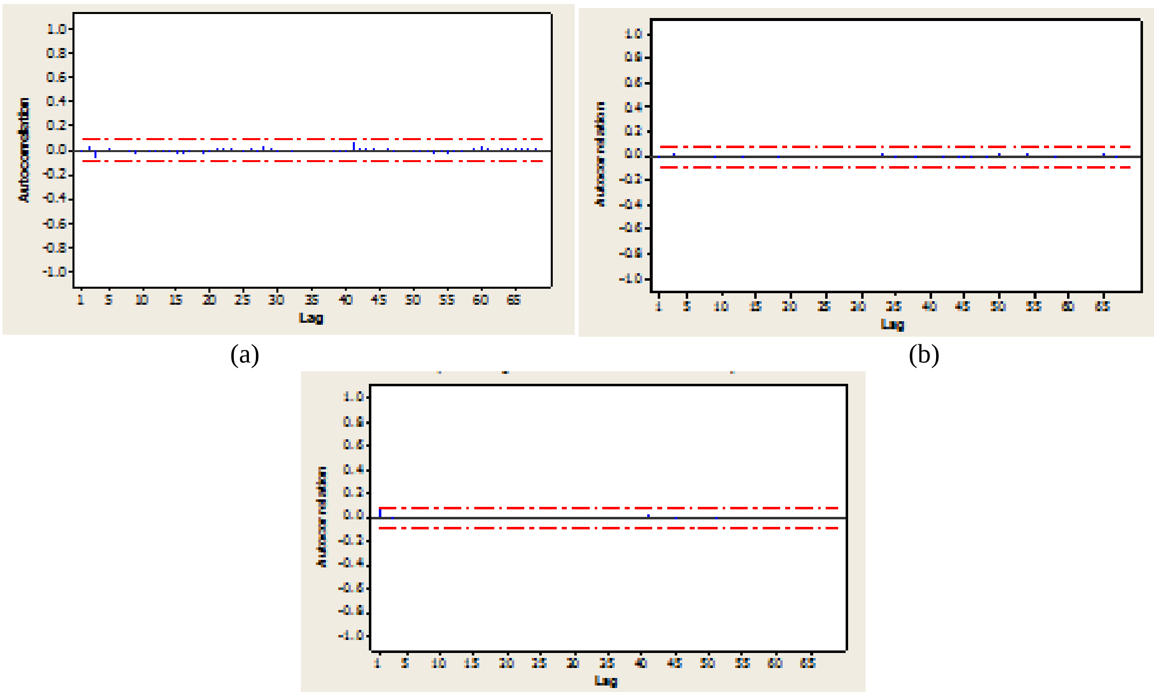


(c)

Figure 5: Normal Q-Q plot of the angular velocity (a) X-axis, (b) Y-axis, (c) Z-axis..

While the whiteness or randomness of the disturbance is assessed using autocorrelation function. The plot of autocorrelation function is shown in Figure 6. The figures show that most of the autocorrelation values lie in the rectangular dashed box, hence it can be said that all autocorrelation are approximately zeroat95% confidenceinterval. It is concluded that the dynamics model noise is random white noise process.



(a) (b)

(c)

Figure 6: Autocorrelation function plot of angular velocity (a) X-axis, (b) Y-axis, (c) Z-axis.

IV. Conclusion

In this paper, the type of noise in dynamics model for satellite attitude estimation problem is investigated using real attitude data of Malaysian satellite. The mathematical model for satellite attitude dynamics has been presented and analysis of the error or noise has been assessed using normality characterizations and autocorrelation function. The results show that the noise in the satellite attitude dynamics model is not Gaussian white noise process. As implication, if Kalman filter is used in the ADCS for estimation algorithm, the estimation is not performing in optimal fashion because the assumption regarding the noise in the process is incorrect. Hence, for subsequent work a study on suitable filter which does not assume the underlying noise is Gaussian white noise is required.

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References

[1] M. S. Grewal and A. P. Andrews, "Applications of Kalman filtering in aerospace 1960 to the present," *IEEE Control Systems Magazine*, pp. 69-78, 2010.

[2] F. L. Markley, J. L. Crassidis, and Y. Cheng, "Nonlinear Attitude Filtering Methods," in *AIAA Guidance, Navigation and Control* Greenbelt: NASA Goddard Space Flight Center, 2005.

[3] J. L. Crassidis and J. L. Junkins, *Optimal Estimation of Dynamic Systems*. Boca Raton: CRC Press, 2004.

[4] S. J. Julier, J. K. Uhlmann, and H. F. Durrant-Whyte, "A new approach for filtering nonlinear systems " *Proceeding of American Control Conference*, pp. 1628-1632, 1995.

[5] J. L. Crassidis and F. L. Markley, "Unscented filtering for spacecraft attitude estimation.," *AIAA Journal on Guidance, Control and Dynamics.*, 2003.

[6] N. J. Gordon, D. J. Salmond, and A. F. M. Smith, "Novel approach to nonlinear/non-Gaussian Bayesian state estimation," *IEE Proceedings F*, vol. 140, pp. 107-113, 1993.

[7] B. Ristic, S. Arulampalam, and N. Gordon, *Beyond the Kalman Filter: Particle Filter for Tracking Applications.* . Boston: Artech House., 2004.

[8] A. S. Arshad, S. A. S. Omar, and H. M. Nasir, *RazakSAT Concept, Design and Development.* Kuala Lumpur: Astronautic Technology (M) Sdn. Bhd., 2004.

[9] M. J. Sidi, *Spacecraft Dynamics and Control: A Practical Engineering Approach*: Cambridge University Press, 2000.

[10] W. W. S. Wei, *Time Series Analysis: Univariate and Multivariate Methods.* Redwood City, California: Addison-Wesley., 1990.

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