

AN ALGORITHM FOR SATELLITE COLLISION AVOIDANCE AND ITS POSSIBLE EXTENSION TO AN AIRCRAFT COLLISION AVOIDANCE SCENARIO

Álvaro de Albuquerque Arraes
Empresa Brasileira de Aeronáutica S/A – Embraer, São José dos Campos, Brazil
National Institute for Space Research (INPE), São José dos Campos, Brazil
alvaro.arraes@gmail.com

Marcelo Lopes de Oliveira e Souza
National Institute for Space Research (INPE), São José dos Campos, Brazil

Abstract. *In this on going work we present the development of a satellite collision avoidance algorithm for satellite formation in the event of one satellite malfunction. We examine the aspects of collision prediction and avoidance through reconfiguration of the satellite cluster. After that we intend to extend the algorithm to an airport scenario in the event of aircraft emergency landing, the control tower authority being considered as the controller for aircraft flight path reconfiguration. The preliminary tests will show the usefulness of the algorithm. This is an excellent example of engineering required to promote the interaction between universities and enterprises in the future.*

Keywords: *collision avoidance, satellite formation, collision prediction, aircraft emergency landing.*

1. INTRODUCTION

The issue of collision avoidance is present in both space and aeronautical scenarios. In either one, a collision usually has tragic consequences, meaning heavy material losses in both scenarios and life losses in the aeronautical scenario.

The purpose of this on going work is to try to evaluate the evolution of the uncertainty in the estimated navigation data (position and velocity) in a satellite cluster scenario when these data are not reported anymore.

The knowledge about position and velocity of the satellites depend on information obtained from sensors embedded in the satellites or in terrestrial stations. This information, however, contains uncertainties due to the following reasons (Matney et alii, 2003):

- Intrinsic uncertainty in the measurement of position and velocity.
- Uncertainty in the propagation of the future position, due to Earth's gravitational harmonics and solar/lunar perturbations.
- For objects at lower-altitude orbits, uncertainty in the future atmospheric drag.
- Imprecisions in the control accelerations.

The main idea is to estimate position and velocity according to the last valid acquired data by means of Kalman filtering; and to propagate the uncertainty of these values. As a result, the trajectory can be visualized as the movement of a volume that grows as it moves forward. In this situation, the collision between two satellites will be considered as the interception of the resulting volumes at any time.

In the event of collision prediction, reconfiguration of the satellite cluster must be employed to avoid the disaster. The time necessary for the collision avoidance maneuvers must be accounted for. The problem is then reduced to estimating position and volume of the uncertainty volume of the satellites and all nearby objects some time in the future, which must be greater than the reconfiguration time.

Considering that the algorithm is intended to be useful in real time conditions, the evaluation of the collisions must be done in a straightforward way, i.e., all the estimation process must be deterministic. For this reason, in order to reduce complexity involved in calculating the intersection between the uncertainty volumes, the form of the uncertainty volume will be simplified to a box.

The extension of the algorithm to the aeronautical scenario will also be discussed.

1.1. Space Scenario

In the space scenario, there has been increasing interest in the use of small cooperative **satellite formations** instead of one bigger platform. A satellite formation is a kind of **satellite constellation**, being composed of a number of small satellites, keeping controlled relative distances an operating as to behave as one big virtual satellite (Gao et al., 2003). In this way, it is possible to synthesize a much larger aperture than it is possible to achieve with a single satellite. In addition to this, there are some other advantages (Koon et al., 2001):

- Better performance in Earth observation.
- Small satellites are less expensive, making it possible to have redundancy.

- The cluster may be expanded by adding new satellites.
- The cluster may be reconfigured to perform new mission objectives.
- The cluster may be expanded to include new sensors.
- In the event of one satellite malfunction, the cluster may be reconfigured to compensate for it.

In an environment where the satellites work relatively close to one another, the ability to predict collisions and to prevent them is necessary.

Moreover, the increasing number of space debris make it necessary to catalog and update debris positions in order to reconfigure satellites to avoid colliding with them.

1.2. Aeronautical Scenario

In the aeronautical scenario, the number of airports has not grown so fast as to accommodate the increase in the number of aircrafts and routes. This situation overcrowds the most used airports and routes, making it harder for the control towers to manage. The possibility to predict the possibility of collision could help to lighten the burden, specially in a situation of emergency (Athenes et al., 2002).

2. SYSTEM DESCRIPTION

2.1. Simulation Architecture.

2.1.1. Relative motion simulation

The motion simulation comprises the following modules:

- Kalman Filter
- Scenario initialization
- Dynamic Model simulation
- Track generator

2.1.2. Collision predictor simulation

The simulation architecture comprises the following modules:

- A Kalman Filter
- A covariance matrix propagation module
- A box intersection estimation module

2.2. Dynamic Model

The **dynamic model** to be used in this research shall describe the relative motion between two satellites. Two candidate models are studied: the C-W equations (Clohessy and Wiltshire, 1960) and the ROEM (Gao et alii, 2003).

The C-W equations have been used by many recent papers about satellite formation flying. It is an approximate equation and has some issues regarding increasing errors when the distance from the satellites is big (Gao et alii, 2003). Nevertheless, for situations when the distance between the satellites in the formation is not big, it may be an adequate choice.

The ROEM (Relative Orbital Element Method) is presented by (Gao et alii, 2003). It is proposed as an alternative to the C-W equations to overcome the limitations of the first model: the algebraic approximations used to obtain the C-W equations are not always acceptable, resulting in physical inconsistencies (absurd results) in some situations.

2.2.1. C-W Equations

. The purpose of the model is to describe the relative position between two satellites. One of the satellites is called the main satellite and the position of the second satellite (following satellite) is mapped into the fixed coordinates of the main satellite.

The C-W equation models the relative position for satellites in circular orbit (Clohessy and Wiltshire, 1960), according to:

$$\ddot{x} - 3n^2 x - 2n\dot{y} = f_x \tag{1}$$

$$\ddot{y} + 2n\dot{x} = f_y \tag{2}$$

$$\ddot{z} + n^2 z = f_z \tag{3}$$

where $n = (\mu / R^3)^{1/2}$ is the angular velocity of the main satellite around the Earth, f_x, f_y, f_z are the relative impulses (accelerations) between the two satellites. When f_x, f_y and f_z are zero, the C-W equations have the analytic solution (Kuga et alii, 2005):

$$\begin{bmatrix} x(t) \\ y(t) \\ \dot{x}(t) \\ \dot{y}(t) \end{bmatrix} = \begin{bmatrix} 4-3\cos(nt) & 0 & \frac{\sin(nt)}{n} & \frac{2(1-\cos(nt))}{n} \\ 6(\sin(nt)-nt) & 1 & \frac{2(-1+\cos(nt))}{n} & \frac{4\sin(nt)}{n} - 3t \\ 3n\sin(nt) & 0 & \cos(nt) & 2\sin(nt) \\ 6n(-1+\cos(nt)) & 0 & -2\sin(nt) & -3+4\cos(nt) \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \\ \dot{x}_0 \\ \dot{y}_0 \end{bmatrix} \tag{4}$$

2.2.2. ROEM Equations

The 6 orbital elements used to describe the movement of a satellite are (Pilchowski et al, 1981):

- Ascension of the ascending node **Ω**;
- Inclination angle of orbital plane **i**;
- Argument of the perigee **ω**;
- Semi-major axis **a**;
- Eccentricity **e**;
- Time of perigee passage $\mathbf{t_p}$**;**

The motion of a satellite is presented in its orbital plane in Fig. 1. ***O*** is the mass center; ***S*** is the mass center of the satellite; P is the perigee.

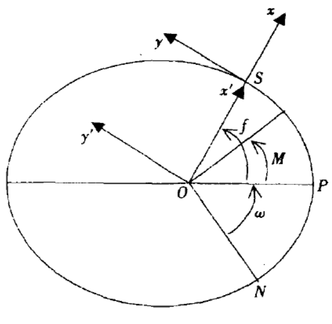

Figure 1: Motion of satellite in orbital plane.

The relative position between the main satellite and the following satellite can be shown in Fig. 2.

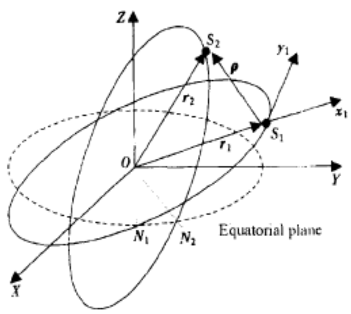

Figure 2: Relative motion between 2 satellites.

The relative position between the satellites can be stated by (Gao et alii, 2003):

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{a_2(1-e_2^2)}{1+e_2\cos f_2}\begin{bmatrix} \cos\Delta\theta - \Delta\Omega\cos i_1 \sin\Delta\theta \\ \sin\Delta\theta + \Delta\Omega\cos i_1 \cos\Delta\theta \\ -\Delta\Omega\sin i_1 \cos\theta_2 + \Delta i \sin\theta_2 \end{bmatrix} - \frac{a_1(1-e_1^2)}{1+e_1\cos f_1}\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

where $\Delta\Omega = \Omega_2 - \Omega_1$, where Ω_2 belongs to the second satellite and Ω_1 belongs to the first; equivalently to the other orbital elements.

3. DISCUSSION OF THE METHOD

3.1. Propagation of Trajectory

The propagation of trajectory is done with Kalman filtering, according to the following equations explained in Kuga et alli (2005):

$$x_{k+1} = \varphi_{k+1,k}\ x_k + \Gamma_k\ \omega_k \tag{6}$$

where x is the state to be estimated, is the state transition matrix, Γ is the matrix that relates dynamic noise to the state, and ω is the dynamic noise vector modeled by white noise, defined by:

$$\omega_k = N(0, Q_k) \tag{7}$$

Propagation:

$$\overline{x}_k = \varphi_{k,k-1}\ \hat{x}_{k-1} \tag{8}$$

$$\overline{P}_k = \varphi_{k,k-1}\ \hat{P}_{k-1}\ \varphi^t_{k,k-1} + \Gamma_k\ Q_k\ \Gamma^t_k \tag{9}$$

where $\overline{x}_k$ and $\overline{P}_k$ represent the state and covariance propagated to time k.

Updating:

New data due to observation model:

$$y_k = H_k\ x_k + v_k \tag{10}$$

where H is the matrix that relates the state to the measurement data and v is the measurement noise modeled by white noise, defined by $v_k = N(0, R_k)$.

3.2. Collision model

The collision model is based on the intersection of cubic boxes circunscribed to the vehicles modelled as ellipsoids whose semi-axes are the standard deviations obtained from the covariance matrix diagonal. The collision criteria is when the intersection volume becomes grater than 5% of the total volume.

4. TESTS

As preliminary tests we have compared our relative motion simulation with the results presented by Kuga et alii, (2005) and:

1) Compared our results of errors in the estimated relative position presented in Figure 3 using the C-W equations with the results of Kuga et alli (2005) presented in Figure 4 using the same equations, as follows:

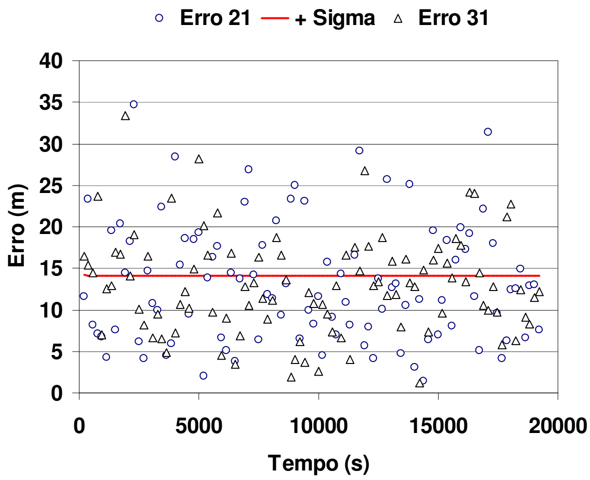

Figure 3. Errors in the estimated relative position (obtained results)

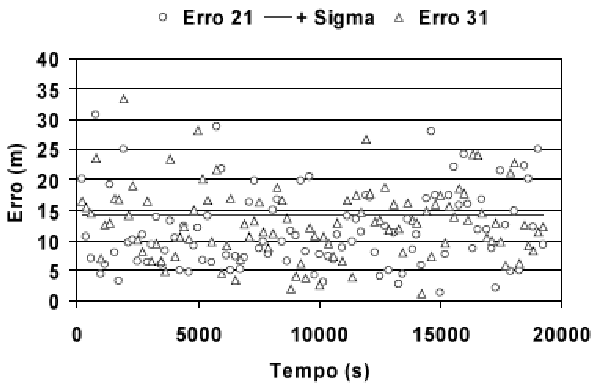

Figure 4. Errors in the estimated relative position (by Kuga)

2) Compared our results in estimated relative velocity presented in Fig. 5 ng the C-W equations with the results of Kuga et alli (2005) presented in Fig. 6 using the same equations, as follows:

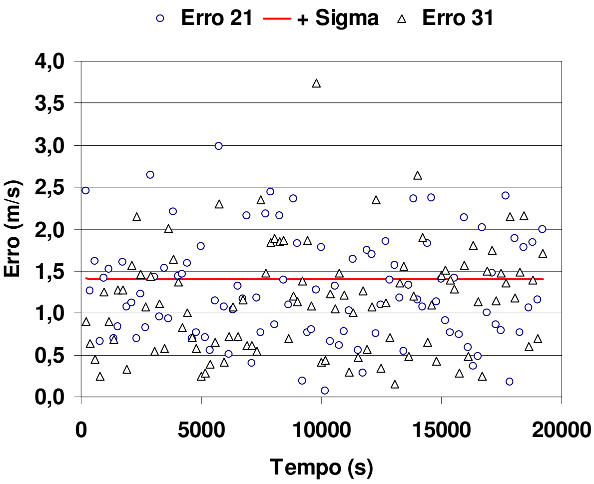

Figure 5. Errors in the estimated relative velocity (obtained results)

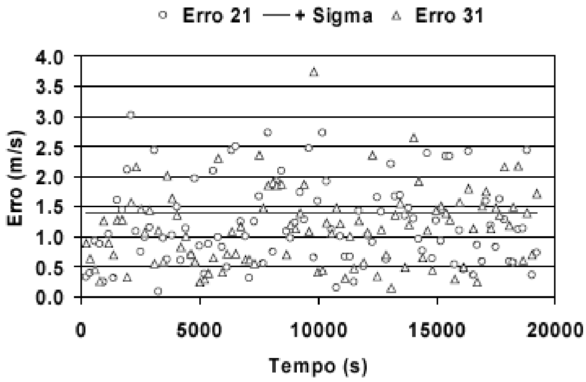

Figure 6. Errors in the estimated relative velocity (by Kuga)

For the time being, we used the results of the work of Kuga to validate our own results by repeating the simulation conditions. The result is not exactly equal for the simulations uses random number generation, but the obtained behavior is very similar.

Since this is an on going work, in the near future we intend:
1) to repeat such tests with the ROEM model;
2) to program the intersection of boxes routine;
3) to extend the algorithm to an airport scenario in the event of aircraft emergency landing, the control tower authority being considered as the controller for aircraft flight path reconfiguration.

and show them at the presentation of this work during the conference.

5. CONCLUSIONS

The present work is still being developed. The tests executed up to now intended to show the correctness of the implemented algorithms.
We expect the next preliminary tests will show the usefulness of the algorithm.

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7. RESPONSIBILITY NOTICE

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