CLOCK SYNCHRONIZATION OVERVIEW AND CHALLENGES IN AEROSPACE CONTROL SYSTEMS

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Abstract: *Aerospace systems are entering in the next generation of space exploration and the control systems become more complex and/or highly integrated. Alternative architectures to accurate time synchronization for measurement, navigation, communication, computation, command, control needs to being investigated. This paper presents a clock synchronization overview and the challenges in aerospace control systems. To do it, this paper discusses the some actual methods and technologies to achieve accurate clock synchronization and highlight the most challenges in aerospace control systems of these methods and technologies.*

Keywords: *clock synchronization, aerospace, control*

1 Introduction

The notion of time is fundamental to our existence and many familiar in our lives. We can reflect about past, present and future events, and still even argue about event in time domain. In according with Kopetz (1997), in many natural phenomena models, time is an independent variable who determines a sequence of state of the system. The main property of time is a monotonicity, which does indicate who time always moves forward. This property in a first point of view, it seems simple, but in complex and distributed systems this property becomes complicated because of physical properties of clocks.

Current systems such as satellites, aircrafts, automobiles, turbines, intelligent energy systems, wind power generators and traffic controls are becoming increasingly complex and/or highly integrated as prescribed by the SAE-ARP-4754 Standard. Such systems integrate computers and communications with real time distributed control systems among other key technologies. In these systems, the time requirements should be followed strictly and with great precision and accuracy, creating the need to work with high-precision clocks in a synchronized way to achieve a good time management.

The aerospace systems there are a lot of problem involving clock synchronization in measurement, navigation, computation, communication, command and control. For example, Eiwoegerer (2009) shows in your work a solution of navigation of satellites with an inertial measurement unit (IMU) integrated with GPS system. The IMU is a technology dependent of time and therefore the clock synchronization between an IMU and GPS must to be necessary. In the aeronautical systems, air traffic controls, because of strictly requirements, are becoming more efficient and the aircrafts can be landing and takeoff with a minimal difference in the time. This requirement makes the air traffic control system dependent of accurate clock synchronization. Therefore architectures, methods and technologies to accurate time synchronization for measurement, navigation, communication, computation, command, control needs to being investigated.

The purpose of this paper is to present and discuss the some actual methods and technologies to achieve accurate clock synchronization and highlight the most challenges to apply these methods and technologies in the aerospace control systems.

2 Basic Definitions/Concepts

2.1 Fault Modes of a Clock

A physical clock, and therefore logical clocks, has some imperfections. These imperfections can be caused by environmental changes such as variations in temperature and voltage, aging of crystal, in case of quartz clock, and some others reasons. Figure 1 show the mainly imperfections of clocks.

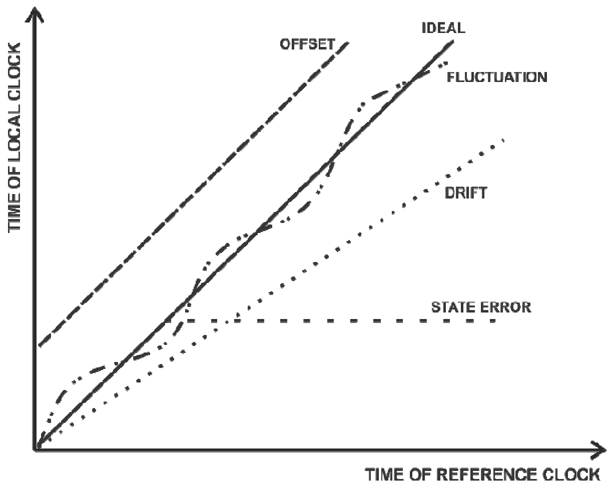

Figure 1. Clock errors.

These imperfections are known as drift, initial or instantaneously offset, fluctuation and state error:

- **Clock Drift:** Clock Drift is when a local clock has a frequency of oscillation greater or less than another local clock and/or a reference clock, i.e. the drift is the rate of change between the two clocks.
- **Offset:** There are two types of offset: the initial offset is when there is a difference between the initial times of local clocks and/or of a reference clock; instantaneous offset is the difference between the times of local clocks and/or of a reference clock at each moment.
- **Fluctuation:** The fluctuation or jitter is the uncertainty in the measurement of the clock.
- **State Error:** The State Error is when a local clock stops the measurement of the progression of time, i.e., the local clock stops on a fixed value. The State Error can be considered a Failure or a Fault.

These imperfections of clock are impossible to eliminate. Thus, there is a need to use fault tolerant methods to achieve the clock synchronization and to minimize the effects of these errors of a clock in the performance of measurement, navigation, computing, communication and control systems.

2.2 Family Solutions

There are a many different solutions for clock synchronization. Ramanathan *et. al.* (1990) shows the three different solutions of clock synchronization. Therewith, it is possible to divide these solutions in three main family solutions, how show Figure 2.

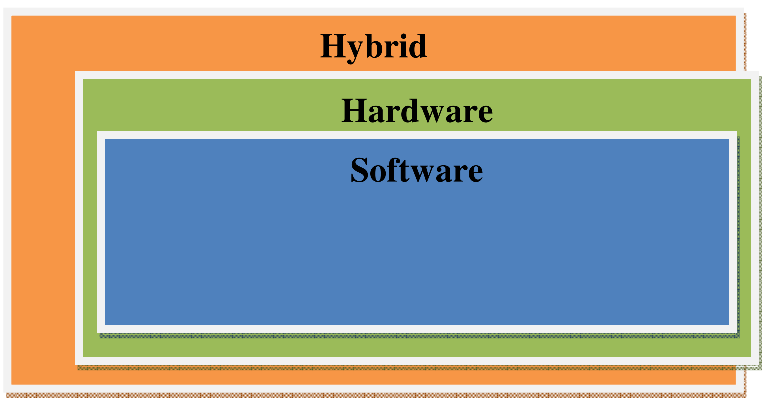

Figure 2. Family Solutions.

Hybrid solutions are joint solutions between hardware and software. Normally used when the great precision and accuracy is required at the clock synchronization. Hardware solutions are solutions at low level, applying the correction clock directly at the oscillator mechanism. Software solutions are the solutions applied at high level, applying the correction clock via software making the use of clock synchronization algorithms and some fault tolerant algorithms.
Table 1 summarizes the advantages and disadvantages of these three methods:

Table 1. Advantages and Disadvantages of Family Solutions.

Family	Cost	Precision	Advantages	Disadvantages
Hybrid	Very High	Very High	Very High Precision	Low Flexibility
Hardware	High	High	High Precision	Low Flexibility
Software	Low to Middle	Middle	High Flexibility	More Bandwidth consume

There are no the best solution in the Table 1. For each project, one family of solutions can be best that another and an analysis needs to be making before.

2.3 Clock Synchronization Architectures

There are a lot of methods for clock synchronization. These methods can be divided into family of solutions, how to saw before, and these methods follow the clock synchronization architectures. This paper presents two of these architectures. The most methods of clock synchronization are based in one of them.

2.3.1 Distributed Architecture

The distributed architecture does not use a master clock to synchronize the system. To achieve clock synchronization this architecture creates a global time. The global time is achieved by one mathematic equation that's involving a set of clocks.
This architecture is frequently used in a communication by databus, where the global time must be achieved for correction operation of network. Figure 3 show the one schematic of this architecture over a databus.

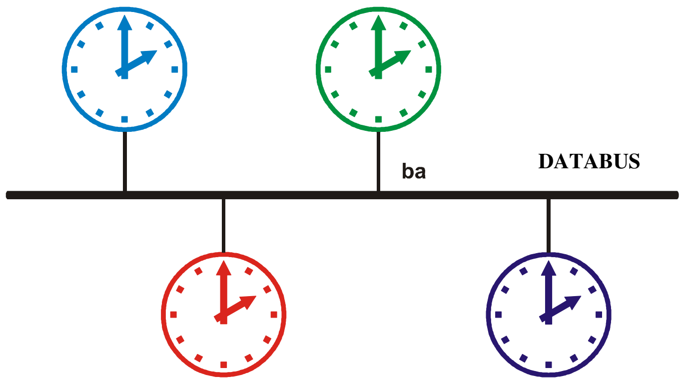

Figure 3. Distributed Architecture.

Figure 3 shows the four clocks and each local clock calculates your correction. These calculations by each clock make the convergence to a global time, i.e., all clocks converge to a same time into one precision.

This architecture has an advantage that it possible, without major challenges, applies byzantine fault tolerant clock synchronization method. If the clock synchronization algorithm is a byzantine fault tolerant the reliability of system increased. On the other hand, this architecture has a disadvantage who the increased the traffic of data and because of the fault tolerance there is a cost on the precision achieved between the set of clocks. Kopetz (1997) presents a table of cost on precision due to a use of byzantine fault tolerant in an average clock synchronization algorithm.

2.3.2 Centralized Architecture

The centralized architecture uses a master clock, i.e., the slave clocks received periodically a time of master clock and then the slave clock compare and adjust its time. Figure 4 show the schematic of this architecture.

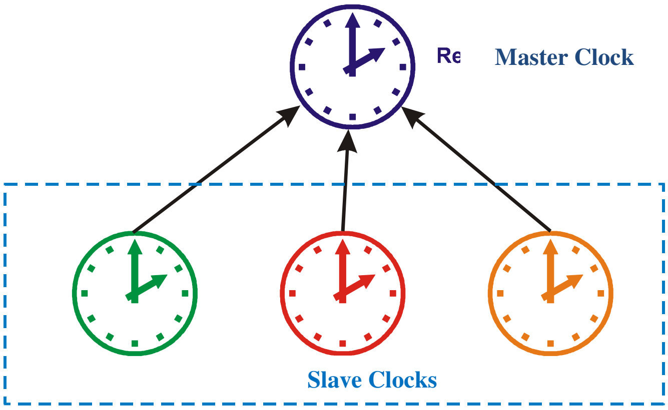

Figure 4. Centralized Architecture.

This architecture is widely use in many systems. There is an IEEE 1588 Standard initially used for clock synchronization over Ethernet protocol and now is migrating to another protocols and applications. This architecture is mostly applied in systems that make use of clock synchronization with GPS (Global Position System).
The master clock is usually with greater quality, as an atomic clock, an international standard time (UTC – International Time Coordinated or TAI – International Atomic Time) or in many cases the GPS who contains an atomic clock to establish a time base.
This architecture, besides not being tolerant for Byzantine errors, has the disadvantage of having a common point of failure, i.e., if the master clock fails, all slave clocks lose synchronization reference compromising the system. This disadvantage have been minimized with use of master clocks with greater quality, on the other hand the cost of system can be increased. With the efforts to minimize the problem of common point of failure, the reliability of this architecture has been increased over the years.

3 Methods Solutions

To establish a clock synchronization there are a lot of methods, even in hardware manner as in software manner. Each solution has your advantage and disadvantage. For each project one solution can be better that other. This paper show two clock synchronization algorithms and two methods via hardware for do that.

3.1 Clock Synchronization Algorithms

The clock synchronization algorithms that are based on mathematical logic, which basically define the operations that the system must perform to keep their clocks synchronized with time or within a pre-specified precision.

There is a range of clock synchronization algorithms. This paper shows two algorithms the FTM (Fault-Tolerant Midpoint) algorithm, known as Welch-Lynch, and clock synchronization by Kalman Filter.

3.1.1 FTM Algorithm

The FTM Algorithm, created by Lundelius *et.al.* (1984), is an byzantine fault tolerant algorithm with distributed architecture. To ensure that all nodes have a consistent view of time is needed to re-synchronization of clocks regularly (periodically). For this the algorithm follows a logical sequence. Each node applies this sequence with the aim of reaching a correction term. With this correction term, the deviations caused by the drift of the clocks are adjusted and so that all clocks are synchronized within a certain precision. Figure 5 show the flowchart of FTM algorithm applied a clock synchronization over databus.

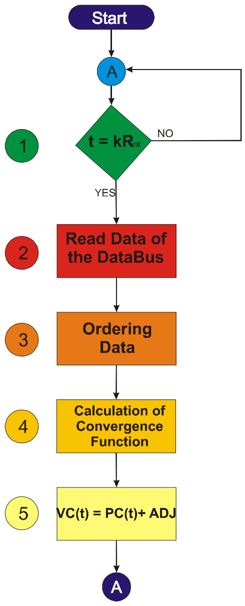

Figure 5. Flowchart of FTM Algorithm.

Number 1 in Figure 5 indicates a loop condition. This condition means that if the local clock time of the node is equal to the time of re-synchronization, then synchronization has to start somewhere. The period of re-synchronization is predetermined. Number 2 in Figure 5 indicates where one has to read data of the clocks, all clocks send a broadcast with the timestamp of its own clock. Number 3 in Figure 5 indicates the ordering of data. Each node sees only its row of the matrix with the timestamps values forming a vector of values A. This vector is sorted in ascending order. At Number 4 of Figure 5 the FTM algorithm calculates the convergence function, after ordering the data in ascending order. It discards the highest and lowest value of A; so, it is the arithmetic mean of the highest and lowest value of the remaining elements in the vector, according to Equation 1. At Number 5 of Figure 5 the algorithm calculates the adjustment function with the value of the convergence function (Olivera Junior *et. al.*, 2010).

$$cfn(A) = \frac{A[f+1] + A[n-f]}{2} \qquad (1)$$

Between two successive re-synchronization periods, the local clocks can derive from each other, but with adjusting for all clocks in the system all clocks converge to a limited deviation. This deviation is called a limited precision.
More information about the FTM algorithm can be found in Oliveira Junior, *et. al*, (2010), Dutertre (1998) and Lundelius*, et. al*, (1984).

3.1.2 Kalman Filter Algorithm

In according with Kuga (2005), the Kalman filter is a set of mathematical equations that provide an optimal solution for linear recursive linear estimation problems. Furthermore, the Kalman filter is an estimator that can incorporate dynamic noise in the dynamic model and measurement model. It is possible to apply the Kalman Filter for clock synchronization. The Kalman Filter can be implemented in a centralized architecture. Marques Filho *et. al* (2003) show the filter applied to minimize the effects of initial offset and drift of clock.
Equation 2 show the model defined by two state variables, instantaneously offset and drift, propose by Varnum (1983).

$$\begin{bmatrix} \dot{T} \\ \dot{D} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} T \\ D \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \quad (2)$$

Based on this model it is possible to use a Kalman Filter to synchronize clocks. This approach is not a byzantine fault tolerant and can be used mainly in centralized architecture, where has a presence of a master clock. The advantage is that the Kalman Filter provides an optimal solution for linear recursive linear estimation and easily to implement in clock synchronization problems. More information and results can be found in Oliveira Junior (2010).

3.2 Hardware

With the growth in demand for high speed communications links, data processing and systems on chip the clock synchronization via hardware has becomes more important in system engineering design. The clock synchronization via hardware are solutions that apply the correction in low level, i.e., in the physical level of clock oscillations circuits. The most known is a GPS approach. This paper show two techniques used in hardware clock synchronization approach, the GPS and PLL (Phase Locked Loop).

3.2.1 PLL

The PLL (Phase Locked Loop) techniques are useful for establishing coherent phase or time references, jitter reduction, skew suppression, frequency synthesis, and clock recovery in numerous systems such as communication, wireless systems, digital circuits, rotors, and others. In according with Kihara *et. al.* (2003), the basic blocks are a phase comparator, a filter, and a controlled oscillator. Even complex PLLs share this configuration. Moreover, since the PLL output is synchronized to the input signal, the characteristics of the input signal also influence PLL performance. Figure 6 shows the basic configuration of the PLL.

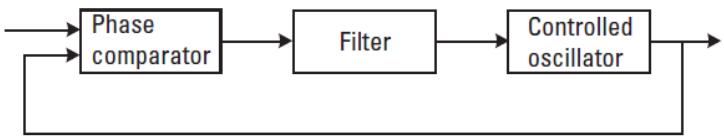

Figure 6. PLL Basic Configuration.
Source: *Kihara et.al (2003)*

Figure 7 shows an example of the digital phase synchronization process. Here, the output frequency of the controlled oscillator is initially lower than that of the input signal, and the phase difference changes over time, as shown in area (a) of Figure 7. The output frequency is driven higher than the input frequency, and the phase difference changes as shown in area (b) of Figure 7. If this control action is performed well, the output frequency of the controlled oscillator coincides with the frequency of the input signal. This holds the phase difference within the required range. Phase synchronization is achieved in area (c) of Figure 7. (Kihara *et.al* , 2003).

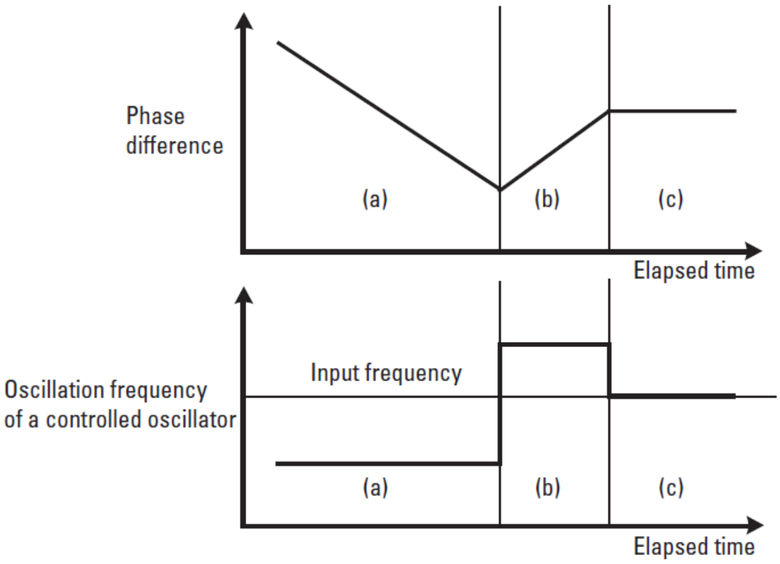

Figure 7. Phase difference and output frequency change over time during a phase synchronization process (digital control): (a) initial condition, (b) condition between the first and second digital controls, and (c) condition after the second control.
Source: *Kihara et.al (2003).*

3.2.2 GPS

The GPS (Global Positioning System) has become the world's principal supplier of accurate time. The GPS consists of a set of 24 satellites orbiting the Earth, each with an atomic clock synchronized together. With this is possible at any point on Earth at any instant of time, take measurements of position and time with good accuracy. Figure 8 shows an illustration of GPS constellation.

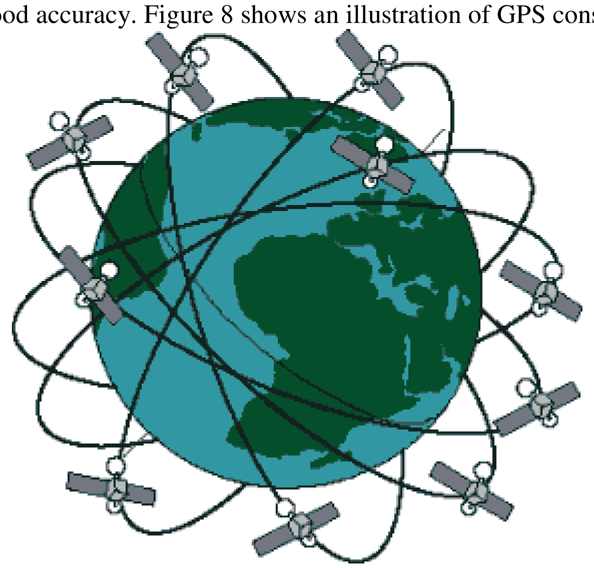

Figure 8. GPS Constellation.

In according with David *et. al.* (1997), there are three kinds of time available from GPS: GPS time, UTC as estimated and produced by the United States Naval Observatory, and the times from each free-running GPS satellite's atomic clock. The Master Control Station (MCS) at Falcon Air Force Base near Colorado Springs, Colorado gathers the GPS satellites' data from five monitor stations around the globe. A Kalman filter software program estimates the time error, frequency error, frequency drift and Keplerian orbit parameters for each of the satellites and its operating clock. This information is uploaded to each satellite so that it can be broadcasted in real time. This process provides GPS time consistency across the constellation to within a small number of nanoseconds and accurate position determination of the satellites to within a few meters. Because of this process, GPS cannot tolerate the introduction of leap seconds and your measurements of position and time are reliable to use in aerospace control systems.

4 Challenges in Aerospace Control Systems

Commonly in the aerospace control systems the challenges to achieve a good clock synchronization is high. The space environmental is harmful to clocks. Without taking into account the relativity effects, the environmental changes of space are very abrupt and these cause variations in temperature and voltage, aging of crystal, in case of quartz clock, more frequently that in terrestrial environmental. Because of this the effects of imperfections of clocks are more apparent. So, the methods and technologies to establish good time synchronization needs to be applied.
Below, we show some examples and challenges of aerospace systems:

- As a control systems are become complex and/or highly integrated, the numbers of actuators, sensors and distribute control tasks among several processors via communication channels are increasing and with that the requirements of time are becoming more strictly. The fault tolerant algorithms are sufficient to achieve a consistent view of time between nodes of network. But, the use of these algorithms has to be careful, especially when the number of nodes increases severely and can be cause delay in a loop and an increase of bandwidth, compromising the clock synchronization, communication and indirectly a control, we can show more information in Oliveira Junior et. al. (2010).
- The GPS technique is frequently used in navigation of low-Earth orbits satellites. This method of navigation is so important and effective, than has NASA studies to extend this technique to the whole solar system, how to show the Gifford *et. al.* (2004).
- The image data processing needs a correct timestamp of data to correct reconstruct before. With this, the satellites image systems need clock synchronization between some modules. For example, in a simple satellite imaging system we have a star sensor, a camera and the OBDH (On Board Data Handler). These modules need to be synchronized with each other for that the stamp of time in a data be done correctly.

There a lot of another challenges involving clock synchronization in the aerospace control systems. The examples cited before are to show that these challenges are increasing and some methods and technologies of clock synchronization need to be discussing, mainly in aerospace control systems and complex systems.

5 Conclusions

In the aerospace control systems, where specific timing requirements are present, the notion of time is fundamental to correct timing operation of the system. These possibilities motivated the discussion of the actual methods and technologies to clock synchronization.
This paper shows the family of solutions, architectures and methods for achieve time synchronization. There no better family, architecture or method. For each project one solution can be better that other, one method is more efficient, in sometimes one method has low-cost. There are a lot of possibilities. Thus, at the design time, the solution, architecture and method that meet the time requirements should be analyzed.

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