Smart Power Management for an Onboard Wireless Sensors and Actuators Network

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The employment of wireless links for spacecraft onboard data communication is a new and challenging research topic. This new technology can be conveniently used for attitude determination and control sensors and actuators. Still, providing energy efficient data collection is of paramount importance to such an onboard wireless sensors and actuators network (OWSAN). This paper proposes a power management scheme based on estimation of the sensor measurements with a Kalman Filter. The power manager schedules the sleep periods on the node to lower the energy consumption of the wireless transmitter and the sensor. The simulation results show that there is a significant change in the energy consumption level of an onboard ADCS sensor.

Nomenclature

ADCS = Attitude Determination and Control System
LEO = Low Earth Orbit
OBC = On-Board Computer
OWSAN = Onboard Wireless Sensors and Actuators Network
WSN = Wireless Sensors Network
WSAN = Wireless Sensors and Actuators Network

I. Introduction

MINIATURIZATION of spacecraft modules driven by applying novel technologies and advanced electronic design enabled more efficient and autonomous onboard sensors and actuators. For example, application of onboard wireless communication between spacecraft subsystems allows overall mass reduction and increased power efficiency while improving the flexibility of the spacecraft design, integration and testing. Statistics show that 6 to 10 percent of the mass of a spacecraft is due to wires and electrical interfaces[1]. Furthermore, enabling wireless communication can address other issues of wired communication such as: failures of wires and connectors, high cost of late design changes, time overhead for allocating routes and shields, undesired ground loops, and etc. The employment of wireless communication technology onboard spacecraft is still in early demonstration phase due to its technical challenges.

In our previous work we discussed major research challenges concerning this new technology and we showed that restricted onboard power budget is one of the major challenges to overcome[2]. We also defined a set of typical requirements in respect to the wireless data handling system for microsatellites and concluded that not every onboard subsystem is an appropriate candidate for being equipped with a wireless transmitter. Our evaluation showed that sensors of attitude determination and control system (ADCS) are potential candidates to be equipped with a low power wireless data transmission technology such as ZigBee. This is due to low to medium data rate of

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Table 1. Comparing OWSAN with WSAN and wireless ad-hoc network

	WSAN	Wireless ad-hoc network	OWSAN
Number of nodes	100s to 1000s	10 to 100	Typically less than 10
Deployment	Densely	Relatively sparsely	Closely
Failure	Prone to failure	Not prone to failure	Not prone to failure
Communication	Broadcast	Point to point	Point to point
Topology	Dynamic	Almost steady	Steady
Node ID	Local	Global	Local
Data correlation	Low – medium	None-low	High
Energy availability	Limited and Not rechargeable	rechargeable	Limited but rechargeable

measurements of ADCS sensors (typically 50kbps - 1Mbps) and not very harsh requirements on data robustness. Such a network of onboard ADCS sensors can form a type of onboard wireless sensors and actuators network (OWSAN). Some prototypes of wireless ADCS sensors are already designed and tested. For example wireless digital sun sensor designed by TNO [3] and EADS micro pack wireless temperature transducers [4] can be noted. In this type of devices, sensors are usually integrated with a battery, a power harvesting solution and a wireless transmitter module. The power harvester ideally extracts the power from the surrounding environment. Ambient heat, sunlight or Earth's albedo light, and electric current induced by movement of spacecraft through Earth's magnetic field are some potential energy sources. Wireless transmitter introduces an extra energy consumer overhead on the equipment. A sensor node can only operate as long as its battery maintains electrical power. Therefore electronic design, communication protocol, circuits and sensing must be energy efficient. In addition, a power management scheme can reduce the energy consumption and may improve the life time of ADCS sensors. Different power management techniques have been proposed to reduce the energy consumption in battery powered devices [5,6,7]. Some of the techniques rely on approximate querying which exploit the natural tradeoffs between energy consumption and data accuracy [8,9]. The technique basically relies on the applications specific error bound which are disseminated to each sensor node along with the query. A measurement is sent to the base station if the change of two consecutive sensor values exceeds a user-defined error bound. There are also other approaches which exploit sleep scheduling but they mostly lack the explicit interaction with the application layer modules [10,11].

We believe that the application constraints play a great role in designing a more efficient power management mechanism specifically for sensors of spacecraft ADCS because the sensor measurements are correlated and can be accurately estimated. The problem is to maintain the performance of ADCS without degrading the availability. In this work we limit ourselves to a set of ADCS sensors and design a power manager for a wireless magnetometer. We build a hybrid model of the sensor and transmitter and use a Kalman Filter to predict the sensor measurements. This prediction and periodical sensor measurements are used to decide about the operation mode of a node (active or sleep). This estimation is used to run the transmitter only when the measurements are required. This sleep scheduling can greatly decrease the energy consumption.

In this paper first we characterize OWSAN as a separate class of wireless networks. Then in section III we introduce hybrid automata model of an OWSAN node. Next, a power management algorithm is introduced which is based on a Kalman Filter and a decision maker. Finally, in section IV, the results of simulations of this scheme are presented and compared with a case where no power manager is used.

II. Onboard Wireless Sensors Actuator Networks

The spacecraft wireless sensors and actuators of attitude determination and control system can form a network of nodes. We introduce such network as onboard wireless Sensors and actuators network (OWSAN). By taking a closer look to the properties of OWSAN interesting characteristics can be identified which distinguishes it from available WSAN and wireless ad-hoc networks. Table 1, summarizes the characteristics of OWSAN and compares it with WSAN and wireless ad-hoc networks. The key characteristics of OWSAN can be enlisted as follows:

- In OWSAN usually the number of nodes is very limited even when redundant components are considered. The nodes are placed in close proximity and the locations are known. Therefore dynamic data routing and localization are not issues;

- Unlike WSAN, the nodes are usually not prone to failure because the designed reliability for space applications is usually very high;
- The nodes usually transmit the measurement data (with or without pre-processing) to a central processing unit which may use the sensor data to manage the actuators. Therefore the type of the communication is point-to-point and not broadcast;
- The nodes have fixed local IDs on the spacecraft;
- The modes are not physically moving so the configuration of the network is not dynamically changing over time;
- The flowing data in OWSAN is highly correlated because the sensors are used to measure the attitude of the satellite which evolves with a very slow dynamics and is highly predictable. This correlation is very useful in reconstructing the lost data and increasing the fault tolerant aspects of OWSAN;
- The interest is toward making the nodes completely wireless. Therefore the nodes must be equipped with a local battery and possibly a local energy harvester. Thus the sensors and actuators will have limited energy available. Nevertheless, some of the nodes such as the Sun Sensor can be equipped with a power harvester. Also, close proximity of the sensors brings the possibility of sharing a power harvester between two or more sensors.

The available power on each node should be shared between the sensor (or actuator) and the data transmitter. The question here is how to use the available power in an intelligent way to extend the life-time and maintain the performance of ADCS. Later we try to model a typical OWSAN node and derive a simple power management scheme.

III. Modeling

An OWSAN may be made of a few sensors and actuators which compose the network nodes. Each node may be equipped with a sensor, a local energy harvester, a rechargeable battery and a wireless transmitter such as a ZigBee module. ZigBee is particularly very interesting for this purpose because it is a short-range and low power communication standard [2]. In this work only the sensors of ADCS are considered as the nodes of OWSAN and the power manager is designed for one of them. The model is focused on one node which is equipped with a transmitter and battery. Also, to simplify the problem, the energy harvester is not accounted.

A. Problem Statement

In a nominal mode when availability of power is not a problem, the wireless transmitter may communicate the measurements in fixed periods. The energy consumption of a ZigBee transmitter is very low in sleep mode. Thus, the transmitter should be kept in sleep mode as long as possible to conserve the available energy. Here we define three operation modes for an OWSAN node:

- Mode 1 (q_1): The sensor is running and the transmitter is active;
- Mode 2 (q_2): The sensor and the transmitter are asleep;
- Mode 3 (q_3): The sensor and the transmitter are both switched off because there is no more energy available in the node.

It should be noted that Mode 2 may have two variations based on the type of the sensor: sensor is switched off and transmitter is asleep, or sensor and transmitter are both asleep. This may depend on the electronic design of the sensor or the boot up time. In this paper we consider these variations together as Mode 2, without loss of generality. Mode 3 is not interesting in the power manager design because it is a dead-end.

Depending on the necessity and frequency of receiving each measurement, a sensor may visit mode 1 and 2 frequently. The energy consumption of the node will be different in each of these operation modes. The problem here is to decide about the frequency of switching between Mode 1 and Mode 2 for each node and maintain the required attitude determination precision. A smart power manager algorithm for ADCS is envisioned as an adequate solution for this problem. Deciding about the best mode of operation for each node can be a function of several

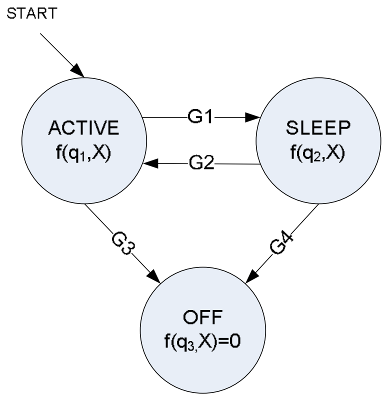

Figure 1. State transition diagram for power management of a general OWSAN node

variables such as: the available energy level at each node, and ADCS precision requirements imposed by the mission operator, etc. Such structures can be modeled as a hybrid system.

B. Hybrid Automata

The mathematical model which can be used for modeling different operation modes of a node is hybrid automata. In a hybrid system, hybrid automata can be used to model both discrete and continuous dynamics of a system. As it is shown in Figure 1, the transitions between states (q_1, q_2 and q_3) are the discrete transitions, while the continuous dynamics are included in each state. Certain conditions which can be viewed as discrete events (G_1, G_2, G_3 and G_4) constitute the transitions, causing the system to move from one state to another. A hybrid automaton can be described as[12]

$$H = (Q, X, f, Init, D, E, G, Res)$$

where

- Q is finite set of discrete variables representing the discrete dynamics of H therefore $Q = \{q_1, q_2, q_3\}$;
- X is the finite set of continuous variables, thus it is the energy level in the node;
- f is vector field, defining the continuous flow in each discrete node. So we have

  $$f(q_1, X) = f_{sa}(t) + f_{ta}(t)$$
  $$f(q_2, X) = f_{ss}(t) + f_{ts}(t)$$
  $$f(q_3, X) = 0$$

  with $f_{sa}(t)$ and $f_{ta}(t)$ as the energy consumption models of sensor and the transmitter in active mode consequently, $f_{ss}(t)$ and $f_{ts}(t)$ as the energy consumptions of sensor and transmitter in sleep mode;
- $Init$ is the set of initial conditions in each state;
- D is the domain and defines where the continuous dynamics are valid which is the operational range of the node's battery;
- E is set of edges and defines the possible transitions. From Figure 1 it is clear that $E = \{(q_1, q_2), (q_2, q_1), (q_1, q_3), (q_2, q_3)\}$;
- G is the set of guard conditions which define when a transition can occur;
- Res is reset map.

Design of the power manager is equivalent to find a set of guard conditions. Here we introduce a simple power manager scheme which tries to keep a node in mode 2 as long as the ADCS precision requirements are met.

IV. Power Manager

We design the power manager based on approximating ADCS sensor measurements. A lot of research has been done on developing efficient and reliable prediction-based power management techniques for the WSN applications[14,15,16]. In most of them the trajectory of the sensor measurements are estimated by exploiting the correlation between the measurements. In most of these works, sensors are locally tuning their sampling rates without a knowledge of the overall system and its dynamics. In this paper we use a similar approach but we put the power manager in the base station of the network which is ADCS processing unit. Thus we can use extra information from the correlation of other sensors and the dynamics of spacecraft attitude. The power manager uses the attitude determination algorithm of ADCS so its implementation will be very light-weight. The sensor node will be asked to send the data only when the difference between the predicted measurement value and the real one exceeds a threshold.. We use a Kalman Filter[13] along with the model of the attitude dynamics and the sensor measurements. In this approach it is not necessary to run a Kalman Filter per sensor. Here we briefly introduce the basics of Kalman Filtering to show how its properties are used for decision making. The discrete spacecraft attitude process and sensor observation models in the state space can be written as:

$$x_k = F_k x_{k-1} + B_k u_{k-1} + w_k$$

$$y_k = H_k x_k + v_k$$

where F_k is the system dynamics matrix, B_k is the control distribution matrix, y_k is the measurement vector, H_k is the measurement matrix and w_k and v_k are successively white Gaussian system process and measurement noises. The Kalman Filter for this given state space model will be given by the following steps:

State prediction:

$$\tilde{x}_{k/k-1} = F_k \hat{x}_{k-1/k-1} + B_k u_{k-1}$$

Covariance prediction:

$$P_{k/k-1} = F_k P_{k-1/k-1} F_k^T + Q_k$$

Residuals:

$$\tilde{e}_k = y_k - H_k \tilde{x}_{k/k-1}$$

Kalman gain:

$$K_k = P_{k/k-1} H_k^T (H_k P_{k/k-1} H_k^T + R_k)^{-1}$$

State estimation:

$$\hat{x}_{k/k} = \tilde{x}_{k/k-1} + K_k \tilde{e}_k$$

Covariance estimation:

$$P_{k/k} = (I - K_k H_k) P_{k/k-1}$$

Here $\tilde{x}_{k/k-1}$ is the predicted state vector, $P_{k/k-1}$ is the predicted covariance matrix, $\tilde{e}_k$ represents the vector of sensor measurement residuals, K_k is the optimal Kalman gain, $\hat{x}_{k/k}$ is the estimated state vector after correction with the measurement information and $P_{k/k}$ is the estimated covariance matrix for step k. Thus each prediction-correction step in the algorithm calculates the value of the covariance matrix and the Kalman gain. Our approach is based on the comparison of real and estimated values of the sensor measurements. When the predicted measurements are not close to the real sensor measurements, the Kalman gain changes according to the differentiation in the covariance matrix of the measurement residuals. The residual reflects the discrepancy between the predicted measurement ($H_k \tilde{x}_{k/k-1}$) and the actual measurement (y_k). A residual of zero means that the two are in complete agreement and an increasing difference between predicted measurement values and real values shows that state estimation error is increasing and the attitude determination is diverging from the optimal attitude results. It is sufficient for the power manager to check the residual periodically and compare it to a threshold. If the error is above a defined threshold the sensor should visit Mode 1 and it starts sending the measurements with the nominal attitude determination rate. The relation between residuals and the overall attitude determination error is nonlinear and is not mathematically feasible to find an analytical relation for this threshold. Thus, statistical approaches can be used to find a suitable threshold by conducting simulations[17]. Next section describes our simulation setup and results.

V. Simulation

Simulations are realized with a dedicated MATLAB/SIMULINK toolbox which is developed for the purpose of this research. This toolbox facilitates development and design of ADCS for LEO spacecraft and includes, among others, models of orbit propagator, disturbances, Earth gravity field, Earth magnetic field, sensors, actuators and solar panels. The SIMULINK model of the power manager and attitude determination system are made and added to this toolbox.

Our simulation scenario is based on BIRD spacecraft orbit characteristics[18]. The minimum required ADCS precision is set to 0.5 degree (absolute error). The simulation is run for 1000 seconds while the spacecraft is not in eclipse and is freely tumbling. In this work we consider a set of a 3-axis gyroscope, 3-axis magnetometer and six sun sensors (one sun sensor on each side of the cube) for attitude determination. The models of the sensors are generic. The energy consumption model of a standard low power ZigBee transmitter module such as Texas Instrument CC2530 is considered as the transmitter to define the operation modes. In the active mode it consumes average 25mA but the current consumption in sleep mode is only 1uA.

The power management scheme is designed for the magnetometer. The operation modes are defined as follows:

- Mode 1: the magnetometer node provides measurements every 2 seconds. This sampling rate is chosen directly based on the dynamics of the spacecraft.
- Mode 2: the magnetometer is in "low sampling rate" mode. It provides one measurement data every 20 seconds.

Two different scenarios were simulated and compared. The first one is not using any power manager and the magnetometer is always in Mode 1. In the second one the power manager is observing the residuals and making decisions.

A. Scenario 1

In the first scenario no power management is used and the results of this scenario are used as the benchmark. Besides, the residuals of the magnetometer are evaluated to find the thresholds for power manager for later usage. Figure 2 shows the results of the attitude determination simulation. It is shown that the determination algorithm starts converging and satisfies the precision requirement after 333 seconds. Figure 2 shows that the correspondent residuals of magnetometer converge to zero. It never practically reaches zero because there is always noise and uncertainty involved in the measurements. At about T=353s, the error of the Kalman Filter reaches 0.4 degree. This

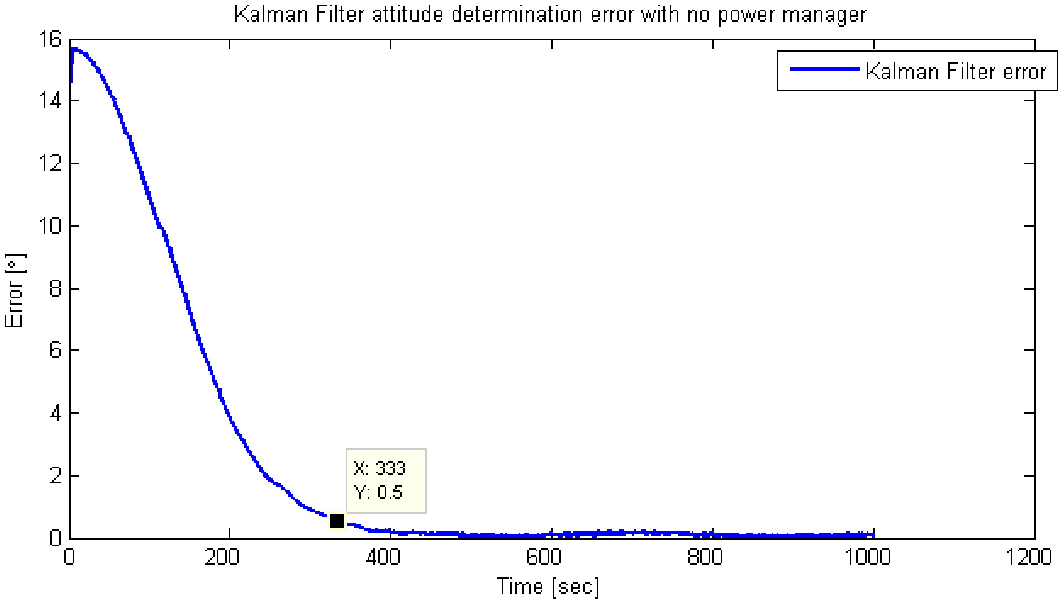

Figure 2. The error of the spacecraft attitude determination while all sensors are used and no power manager is active.

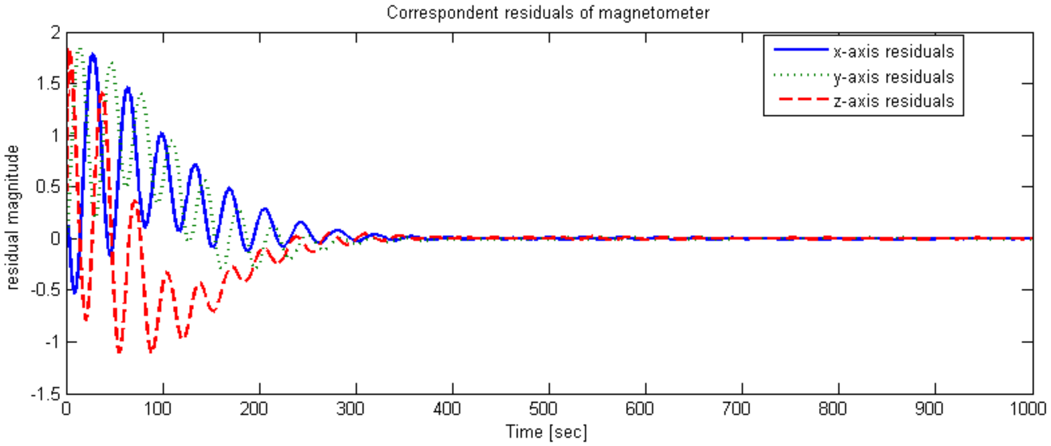

Figure 3. Correspondent residuals of magnetometer while no power manager is active. It can be seen that the residuals converge to zero. This means that measurement predictions can be used instead of real sensor measurements in order to conserve energy.

error drops to 0.3 degree after T=364s. The correspondent magnitude of the sensor residuals at these two readings can be used as the high and low thresholds for the power manger (γ_h and γ_l). We design the power manager such that it switches the magnetometer to mode 2 as soon as the magnitude of the measurement residuals goes below γ_l . The node will be switched back to mode 1 when the residuals grow and hit threshold γ_h.

B. Scenario 2

In the second scenario the power manager in included in simulation. The power manager reduces the sampling rate to one sample per 20 seconds while the residuals magnitude is small. Later the node's sampling frequency can be switched back to nominal rate when the residuals exceeds γ_2 threshold. The simulation is done for the same orbit and 1000 seconds of free tumbling. The initial conditions on the Kalman Filter are changed to show the functionality of the power manager. Figure 4 shows the result of power manager decision maker. This figure depicts that the power manager has switched the magnetometer to mode 2 at T=311 seconds and the residuals have never exceeded the upper threshold during the simulation time. This means that the magnetometer has been kept in mode 2 for the remaining 689 seconds of the simulation. During these 689 seconds, the power manager needs to receive a few measurements to monitor the development of the residuals (1 sample per 20 seconds). But the amount of this information is significantly less than the measurements number in the nominal mode. In sleep mode only the ZigBee transmitter is consuming energy which is negligible comparing to the active mode (1uA comparing to 25mA). Figure 5 shows the attitude determination results with this sensor scheduling scheme. The error of attitude determination is still meeting the required value.

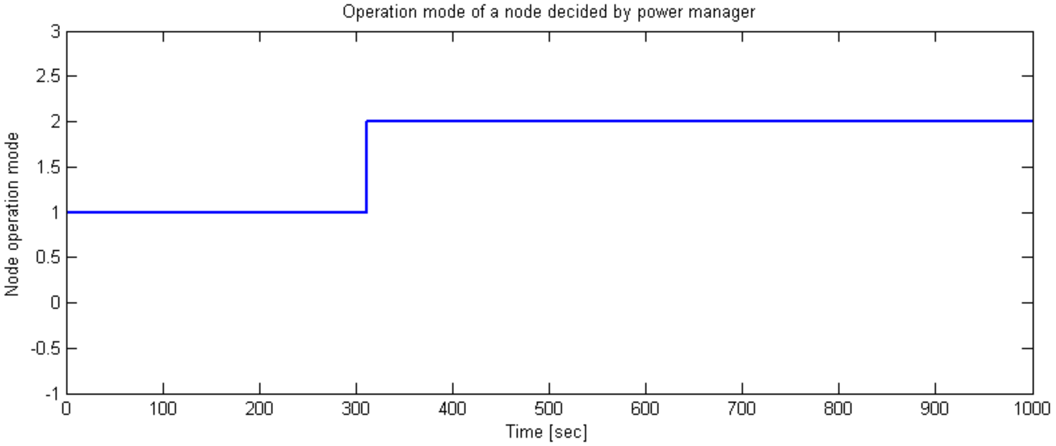

Figure 4. The operation mode of the magnetometer is changed by the power manager to mode 2 at T=311 seconds.

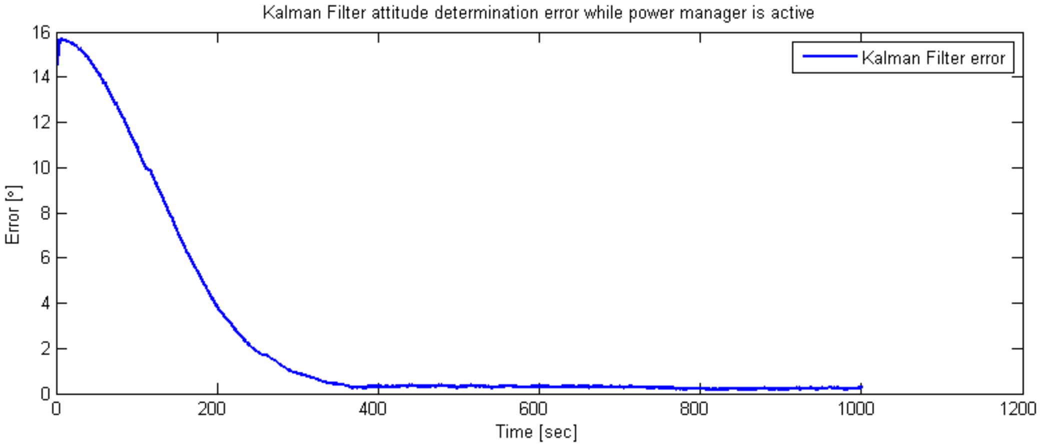

Figure 5. Error of attitude determination while the power manager is active. The power manager has reduced the magnetometer sampling rate by 10 times at T=311. Attitude determination error is maintained below 0.5 degree.

The energy consumption of the ZigBee module in sleep mode is negligible comparing to its active mode. For comparing the results of the simulations, we assume that it takes 50 milliseconds for the magnetometer to make a sample and transmit it to the base station. Thus during 1000 seconds simulation period the magnetometer has been active for 25 seconds in the first scenario. But, in scenario 2, the power manager has reduced this time to about 9.5 seconds. This means that the magnetometer has used about 68% less energy when the power manager was activated. However, the attitude determination precision was maintained as promised.

VI. Conclusion

In this paper first we focused on energy consumption problem of a typical sensor node of an onboard wireless sensors and actuators network (OWSAN). We introduced a general hybrid automata model of an OWSAN node. Then, a simple but effective power management algorithm based on Kalman Filtering was used. It was shown that this power manager can be effectively integrated with onboard attitude determination algorithm and runs its decision maker. We showed that the decision maker can be designed by using the prediction of the sensor measurements and comparing them with periodical measurement from the sensors. Our simulation showed that in case of free tumbling of a spacecraft the power manager can reduce the energy consumption of the magnetometer by 68% while maintains the attitude determination precision of the spacecraft.

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References

[1] Amini, R., Aalbers, G., Hamann, R., Jongkind, W., and Beerthuizen, P.G. “New Generatins of Spacecraft Data Handling Systems: Less Harness, More Reliability,” *57th International Astronautical Conference.* Valencia, 2006.

[2] Amini, R., Gill, E., and Gaydadjiev, G. “The Challenges of Intra-Spacecraft Wireless Data Interfacing,” *58th International Astronautical Congress.* Hyder-Abad, 2007.

[3] de Boom, C., Leijtens, J., Duivenbode, L., and van der Heiden, N., “Micro Digital Sun Sensor: System in a Package,” *Internation Conference on MEMS, NANO and Smart Systems.* 2004. 322-328.

[4] Eckerly, S., Schalk, J., Coumar, O.,and Haira, K. “The EADS Micropack,” *5th Round Table on Micro/Nano Technologies.* Noordwijk: ESA-ESTEC, 2005.

[5] Chung, E.Y., Benini, L., and Micheli, G.D., “Dynamic Power Management Using Adaptive Learning Tree,” *ICCAD Conference*, 1999, pp. 274-279.

[6]Zuquim, A.L.A.P., Vieira, L.F.M., Vieira, M.A., Vieira, A.B., Carvalho, H.S., Nacif, J.A., Coelho, C.N., Jr., da Silva, D.C., Jr., Fernandes, A.O., Loureiro, A.A.F., "Efficient power management in real-time embedded systems," *IEEE ETFA Conference*, Vol 1., 2003, pp. 496-505.

[7]Sinha, A., and Chandrakasan, A., "Dynamic Power Management in Wireless Sensor Networks," *IEEE Design & Test of Computers,* Vol. 18, 2001, pp. 62-74.

[8]Han, Q., Mehrotra, S.,and Venkatasubramanian, N., "Energy Efficient Data Collection in Distributed Sensor Environments," *24th International Conference on Distributed Computing Systems*. Tokyo, Japan, 2004.

[9] Silberstein, A., Braynard, R., and Yang, J., "Constraint Chaining: On Energy-Efficient Continuous Monitoring in Sensor Networks," *2006 ACM SIGMOD International Conference on Management of Data.* Chicago, Illinois, 2006.

[10]A. Keshavarzian, A., Lee, H., and Venkatraman, L., "Wakeup Scheduling in Wireless Sensor Networks," *7th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, Florence, Italy, 2006.

[11]Santini, S., and Romer, K., "An Adaptive Strategy for Quality-Based Data Reduction in Wireless Sensor Networks," *Third International Conference on Networked Sensing Systems*, Chicago, Illinois, USA, 2006.

[12]Matveev, A. S., Savkin, A. V., *Qualitative Theory of Hybrid Dynamical Systems*, 1st ed., Birkhauser, York, 2000, Chapter 2

[13]Grewal, M. S., Andrews, A. P. , *Kalman Filtering*, 1st ed., Prentice-Hall, 1993, Chapter 4

[14]Jain, A., A., and Chang, E. Y., "Adaptive Sampling for Sensor Networks," *First Workshop on Data Management for Sensor Networks (DMSN 2004): in conjunction with VLDB 2004.* Toronto, Canada, 2004.

[15]Jain, A., Chang, E. Y., and Wang, Y. F., "Adaptive stream resource management using Kalman Filters," *ACM SIGMOD/PODS conference (SIGMOD '04).* Paris, France, 2004.

[16]Tang, M., Jinli, C., "An Energy-Efficient Data-Driven Power Management for Wireless Sensor Networks," *DMSN'08 Conference, New Zealand, 2008*

[17]Hajiev, C., Soken, H. E., "Adaptive Kalman Filter with the Filter Gain Correction Applied to UAV Flight Dynamics," *17th Mediterranean Conference on Control and Automation Conference*, 2009, pp 892-897

[18]Lorenz, E., Borwald, W., Briess, K., Kayal, H., Schneller, M., and Wuensten, H., "Resumes of the BIRD mission," *4S Symposium: Small Satellites, Systems and Services (ESA SP-571)*, 2004, pp. 31.1.