Study for the Information Operations for Long Unattended Periods of Time at the Space System

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Abstract

The space systems are being operated in a uncertain space environment and are desired to have autonomous capability for long periods of time without frequent telecommunications with the ground station.At the same time, requirements for new set of satellite system set of projects/systems calling for "autonomous" operations for long unattended periods of time are emerging. Since, by the nature of space systems, it is desired to perform its mission flawlessly and also it is of extreme importance to have fault-tolerant sensors and actuators for the purpose of validating science measurement data for the mission success. This studies focused on the identification/demonstration of critical technology innovations that will be applied to the Validation Control System.

Key word : Spacecraft Monitoring Validation Control System(SMVCS), High Fidelity Dynamic Model-based Simulation(HFDMS), Electro-Mechanical Solenoid Valve (EMSV), Autonomous Control System(ACS).

Introduction

The objectives of this effort is to identify and to demonstrate critical technology innovations that can be applied for the process with increased reliability and parameter correction to support autonomous operations. Using a High Fidelity, Dynamic Model-based Simulation (HFDMS), a real-time health monitoring and data validation system will be developed for detecting an "abnormal signal flow" in the sensors and actuators by understanding and utilizing the science data and health monitoring measurement data collected. As the result, this methodology can achieve rapid identification of non-expected data flow. This research focuses on the identification/demonstration of critical technology innovations that will be applied to the Spacecraft Monitoring Validation Control System(SMVCS).

The unique element of this process control technique is the use of high fidelity, computer generated dynamic models to replicate the behavior of the actual systems.

It will provide a dynamic simulation capability that becomes the reference model, from which comparisons are made with the actual raw/conditioned data from measurement elements.

The insertion of this new concept of SMVCS into spacecraft monitoring and control systems will provide a real-time intelligent, command and control system that has the capability to monitor and observe transient behavior, along with the dynamic parameters of the systems being tested. Current capabilities cannot measure the dynamic behavior of the system

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in real-time can not be measured.

The measurement and actuator elements must now be analyzed to understand how the increased "reliability" and "parameter correction" requirements can be implemented into the systems to support autonomous operations.

Approaches

Challenges

The challenges that will be encountered in developing this autonomous control system can be summarized as design and developing nonlinear and time-variant adaptive control for implementation in uncertain space environment, to incorporate a substantial degree of built-in intelligence and robustness with advanced control algorithms or their combinations with artificial intelligence techniques may need to be integrated into a final configuration.

Hence, the final configuration of the autonomous control system should be a combination of advanced algorithms with built in artificial intelligence.

The greatest need in technology innovations point toward autonomous control; this focuses current research efforts towards the development of a new class of fault-tolerant sensors and actuators so that projected system reliability requirements can be met. The characterization for he next step in evolving the existing control processes to a autonomous posture is to embed this new technical innovation, that make a high fidelity, model-based simulation [2] possible into an Autonomous Control System(ACS).

This thrust will embed intelligence into the computer to actively control, modify parameters and select sensors and actuators based on statistical parameters of the measurement errors in real-time. Taking into consideration the state-of technology, the current status of existing and emerging control implementations and the requirements necessary to design the automated, real-time ACS methodology compatible to these autonomous systems, a set of objectives are identified to satisfy these projected needs with selected technology innovations.

The objectives that will describe the scope of this effort can be divided into sensing and control:

Sensing

◦ Identify and demonstrate critical technology innovations to be applied for the autonomous process.

◦ Fomulate and apply the new selected innovations using a HFDMS approach to implement a real-time monitoring system for automatic detection system for detecting an "abnormal signal flow" in SMVCS.

◦ Formulate and apply another innovative concept to separate "sensor" from "system" errors and to automatically implement those sensors and actuators with the smallest error co-variances.

◦ Describe a methodology for rapid identification of non-expected data flow and/or "a fault-isolation capability".

◦ From comparisons to a "fault-mode file", parameter variations of sensor, actuator or system state will be generated and demonstrated. Two resulting files are generated:

a. Sensor "variance" parameters (all sensors active)

b. Redundant actuator command ratios (all actuators active will share command input requirements).

Control

◦ The control system should have fault isolation capability

◦ It should compensate the system parameters and degrading system variables (compensate mild fault modes and extend performance envelopes)

◦ Should possess advanced control algorithms combined with artificial intelligence techniques

The approach taken in the development of the SMVCS is to employ a HFDMS methodology to conduct real-time autonomous operation of the SMVCS. This new innovation of using high fidelity models (i.e. those that include the characteristic differential equation, along with their dynamic parameters) to replicate the nominal behavior of the actual system, results in a dynamic simulation that becomes the reference/truth model, from which comparisons are made with actual raw (or conditioned) data from sensor elements. An extended Kalman Filter (EKF) will be used to reduce raw measurement error before correlation between simulated and actual responses are generated. These correlations, in turn, will form the salient factor in formulating an automatic detection system. The statistical parameters of the noise (i.e. which are generated as a by-product of the Kalman process) will be used to:

◦ Optimize the "gain", K, in the "optimal observer".

◦ Determine the health of the sensors and/or actuators.

◦ Identify sensor/actuator "fault modes" and mechanize correction if possible.

if detection of an "abnormal flow" is triggered, an automatic hand over to a designated diagnostic expert system fault mode file will be implemented for anomaly resolution and/or parameter correction.

Design and Learning

Design Autonomous Control System

There have been advanced efforts in recent times in the field of understanding/validation of the science data collected, to develop better analysis tools and to implement the science data into the best possible use. Hence, there is the greatest needs for research efforts in the area of validation of measurement data from scientific instruments. The characterization for the future in evolving the existing control procedures into a autonomous posture is to embed intelligence to actively control,

modify parameters as a basis to select sensors and actuators based on statistical parameters of the measurement errors in real-time.

The embedded intelligence system will be developed based on a dynamic model-based simulation methodology.

It is designed based on Kalman filter estimation and an advanced control algorithm combined with artificial intelligence techniques such as neural-fuzzy control. So, the real-time analysis can detect changing system parameters and degrading system variables brought about by the environmental changes that the system encounters so that the autonomous control system can compensate mild fault modes and extend performance envelopes.

This on-line monitoring and autonomous control capability is essential in this critical application to improve the system's reliability and to minimize catastrophic failure of overall system.

The analysis tools includes developing advanced algorithms to facilitate on-board com -puting capability and real-time estimator for health monitoring, implementing artificial intelligence techniques and learning control capabilities for guaranteed performance and global stability and finally developing artificial intelligence technique algorithms for reconfiguration capabilities.

Thus the SMVCS will embed the spacecraft with fault detection and isolation techniques including a model-based reasoning system. Development of algorithms for on-board spacecraft autonomy along with optimization of the control system will form the core issue of this research effort. Finally demonstration of implementing these algorithms and embedded sensors and electronics will be performed.

Learning Robust Control

Learning control is a class of control systems that update the control input iteratively in order to enhance the transient performance of systems that are repeatedly executed over a fixed finite time ion. This control can enhance the transient performance of the system under control from trial to trial without the exact knowledge of the system.

Using the periodicity of the system dynamics, it can learn the unknown periodic time functions of the system to compensate its state-independent uncertainties.

The proposed learning control also provides robustness to the designed control system. This assures global stability and guaranteed performance.

Neural-Fuzzy Control is another class of control systems that has a great potential since it is capable to compensate for the uncertain nonlinear dynamics using the programming capability of human's heuristic knowledge. One of the biggest advantages of using this control system is the fact that there is no requirement of exact system knowledge. It is also possible to implement built-in intelligence into the system that can possess reconfiguration capability to uncertain environment changes.

Dynamic Robust Control :Real-Time Controller design technique is powerful yet simple in design. The outcome of the design is a non-homogeneous nonlinear differential equation describing the controller.

The controller, solution of the differential equation, is calculated numerically via simulation code on-line(in real-time) since the form of the differential equation can be quite lengthy and/or complex.

The significance of this development is that controllers, using this technique, can adjust to changing system parameters brought about by the environmental changes that the system encounters.

This implies that mild fault modes could be compensated for and "performance envelopes" could be extended. The advantage of this technique is the fact that it has real-time operation capability.

Experiments

Electro-Mechanical Solenoid Valve (EMSV)

The example of using the HFDMS methodologes to demonstrate a real-time detection technique is drawn from the analysis of a EMSV. The analysis focussed on the highly non-linear Electro-Mechanical Solenoid Valve and the detection of abnormal parameters in that valve.

Normally, the modeling of a physical system like the EMSV is accomplished by the summation of torque and/or forces on the mass to be actuated with the result of the generation of differential equations that characterize the transient and steady state response of the system. This model then becomes the "reference" or "truth-model" from which comparisons are made to actual raw data profiles. In the case of the EMSV, the physical modeling parameters were not available.

Therefore the alternative procedure of adaptive identification was used to obtain the reference profile/signature. Later on an extended Kalman Filter (EKF) was used for data validation and computing the best estimate of the state(s).

Kalman Filter for Signal Conditioning

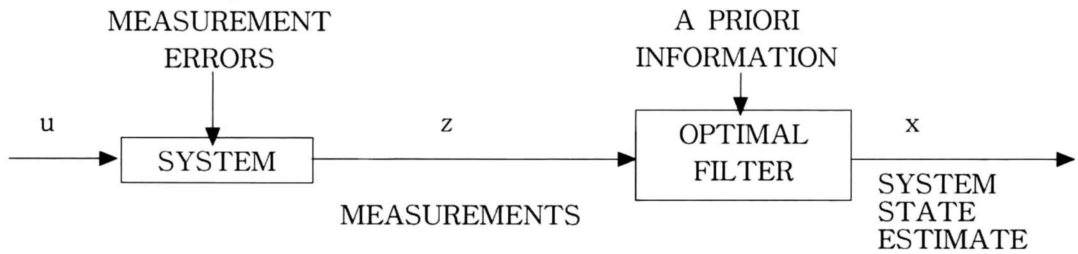

Fig. 1. Data Flow for filtering Process

The use of the EKF is uniquely structured to condition raw data sequences in real-time. In practice, these are several different cases that can be handled by the recursive procedure.

Case (i): The state variables can be measured directly; the object would be to filter the noise from the raw measurement before comparison to the nominal model (fault detection would be the motivation here).

Case (ii): The state variable can be measured directly. If several sensors are used to measure the same variable, automatic weighing, based on statistical parameters of the sensors are applied by the EKF to generate the "best estimate" of that state variable.

Case (iii): The state variable is impossible to measure directly. This case can be implemented by finding the "best estimate" of those states by using measured data that can be related by a known functional relationship to the desired state variables.

The block diagram of the Kalman filter process is shown in Fig. 1.

This Kalman filter process was applied to the model "response" example of the EMSV. It shows (Fig. 2 and Fig. 3).

the model reference state vs the measurement of the state (synthesized in this case) and the model reference state vs. the best estimate of the state (output of the filter).

is shown in Fig. 2 and Fig. 3. The error profiles are respectively shown in Fig. 4 and Fig. 5.

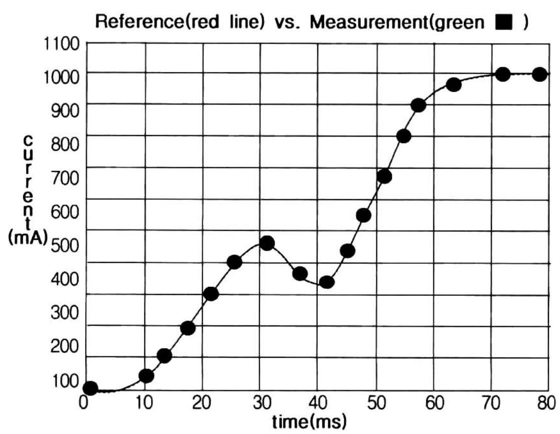

Fig. 2. Reference(line) vs. Measurement(dot)

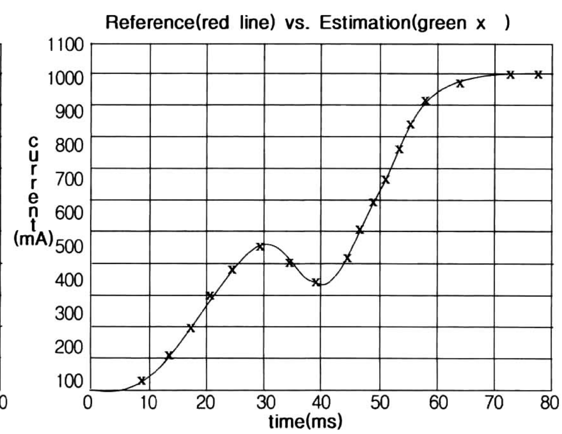

Fig. 3. Reference(line) vs. Estimate(x)

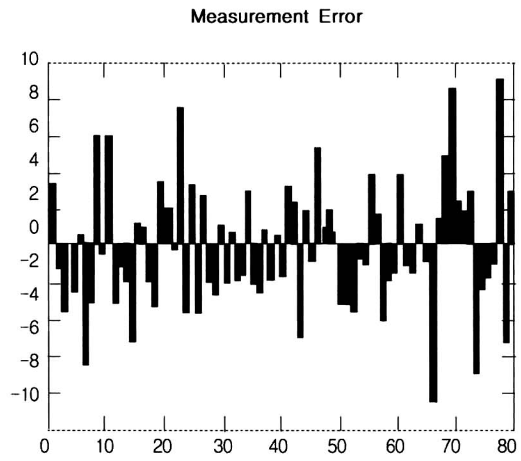

Fig. 4. Measurement Error

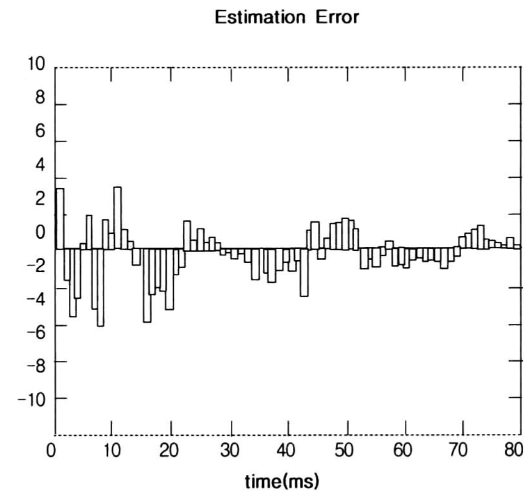

Fig. 5. Estimation Error

Notice the estimation errors are significantly lower and converge. Again, the noise reduction is significant and bound the estimated error between ±4mA (0.4% of measurement).

A measure of the distribution of measurement and estimation errors of the state is captured in the Error Covariance plots as shown in Fig. 6 and Fig. 7.

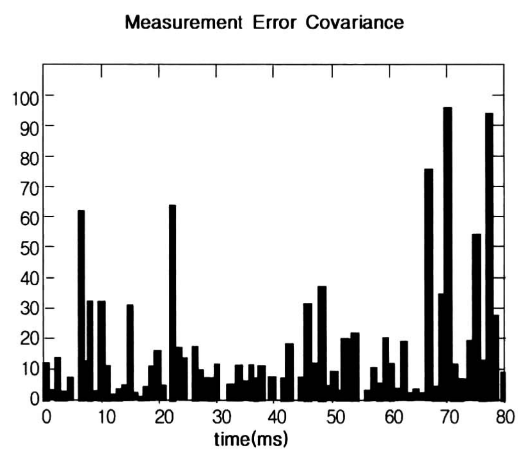

Fig. 6. Measurement Error Covariance

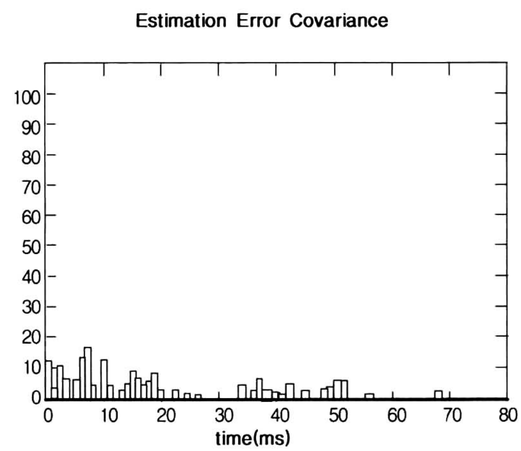

Fig. 7. Estimation Error Covariance

To mark of reduction, in estimation error covariance can be seen between the covariance of the raw measurement errors and the covariance of the estimation errors. This result was expected and caused by the implementation of Kalman filter.

Equipment

The system has established a multi-university small Satellite and payload Development Laboratory(SDL), to design, build, test and integrate space science, communication and earth observing experiments. The SDL will be operated under the auspices of the system.

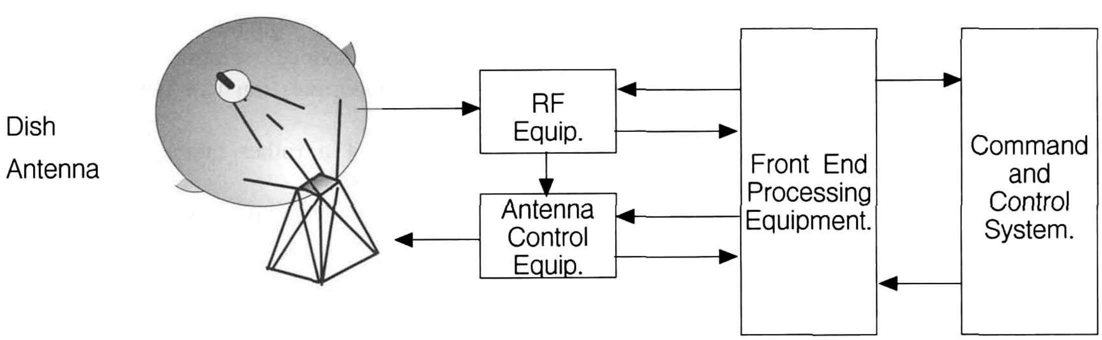

Fig. 8. Satellite Ground Control Station(SGCS)

At the "center" of the SDL development is the Satellite Ground Control Station (SGCS); it stands as a crucial element in the development plan for the SDL. The SGCS is composed of a ten meter (diameter) dish-antenna , supporting base structure, RF equipment, an antenna control system, front end processing equipment and a command and control system (see Fig. 8 SGCS).

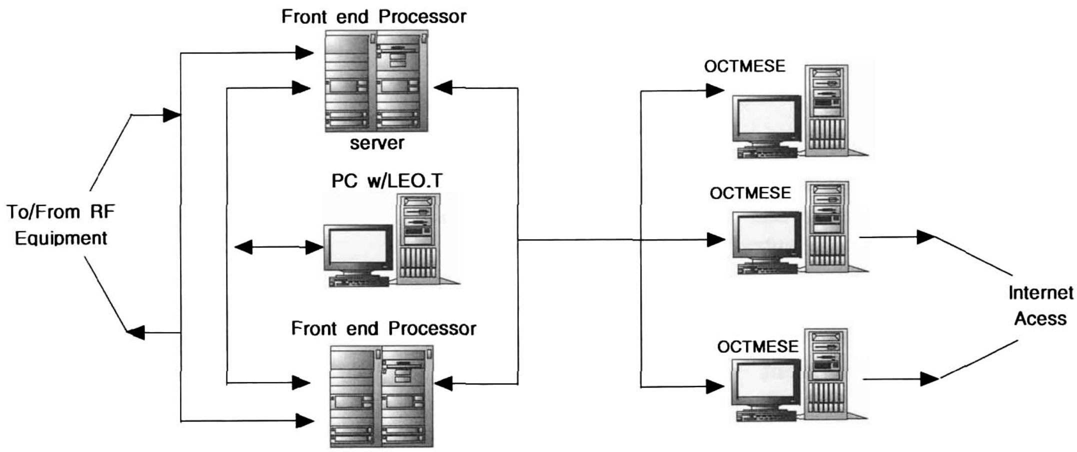

Fig. 9. Front End Processing - Command and Control System

The remaining hardware for the Front End Processing Equipment(FEPE) and che Command and Control System(CCS) will be funded by a matching grant from the UCF. This FEPE and CCS is shown in Fig. 9.

Conclusions

A marked reduction, in turn, can be seen between the covariance of the raw measurement errors and the covariance of the estimation errors. This result was expected and caused by the implementation of Kalman filter.

A Kalman filter application to the EMSV has therefore shown, the kind of data conditioning desired for a "real-time detection" mechanization. It will essentially reduce the noise components of the raw data significantly and virtually eliminate false detection indications. This approach of comparing the model transient response signature to the "best estimate" signature (derived from raw data stream) to detect abnormal transient behavior is the next step.

Consequently, any information flow is largely the result of a rather disjoint bottoms-up integration, rather than the result of a planned, top-down approach.

At the same time, requirements for new set of projects/systems calling for "autonomous" operations for long unattended periods of time are emerging.

With the digital computer speed now fast enough to support real-time computation, an SMVCS is potentially a reality. The measurement and actuator elements must now be analyzed to understand how the increased "reliability" and "parameter correction" requirements can be implemented into the systems to support autonomous operations.

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