산학기술성공학회논문지
Vol. 2, No. 2, pp. 81~89, 2001

The Simulation and Research of Information for Space Craft
(Autonomous Spacecraft Health Monitoring/Data Validation Control Systems)

H. Kim*, R. Jhonson, D. Zalewski**, Z. Qu**, S. T. Durrance**, and C. Ham****

요 약 우주 항공위성 시스템은 변하는 불확실한 우주항공 환경에(서) 운행되고 지상기지국으로부터의 원격통신 없이 장시간 동안 동작해야 할 자율적인 능력이 요구되고, 결함 없이 임무를 수행하여야 하며, 시스템에서 계측된 데이터의 신뢰성을 유지하기 위한 고장 상태 검출과 오류 수정 시스템을 확보하는 것이 중요하다. 본 논문에서는 확장 칼만 필터 기법을 적용한 동적모델 시뮬레이션 기법(High Fidelity, Dynamic Model-based Simulation)을 제안하였으며, 제안된 시스템은 비정상적인 데이터의 효과적인 검출과 대응이 가능해짐으로써 신뢰성 있는 우주항공위성시스템을 구축하도록 자동 상태 진단/데이터 시스템에 고장검출/오류수정 시스템을 적용하는 것이다.(Autonomous Spacecraft Health Monitoring/Data Validation Control System : ASHMDVCS).

Abstract Space systems are operating in a changing and uncertain space environment and are desired to have autonomous capability for long periods of time without frequent telecommunications from the ground station. At the same time, requirements for new 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 that they perform their mission flawlessly and also it is of extreme importance to have fault-tolerant sensor/actuator sub-systems for the purpose of validating science measurement data for the mission success. Technology innovations attendant on autonomous data validation and health monitoring are articulated for a growing class of autonomous operations of space systems. The greatest need is on focus research effort to the development of a new class of fault-tolerant space systems such as attitude actuators and sensors as well as validation of measurement data from scientific instruments. The characterization for the next step in evolving the existing control processes to an autonomous posture is to embed intelligence into actively control, modify parameters and select sensor/actuator subsystems based on statistical parameters of the measurement errors in real-time. This research focuses on the identification/demonstration of critical technology innovations that will be applied to Autonomous Spacecraft Health Monitoring/Data Validation Control Systems(ASHMDVCS).

Key Words : Autonomous spacecraft health monitoring/data validation control systems(ASHMDVCS), High fidelity dynamic model-based simulations(HFDMS), Electro-mechanical solenoid valves(EMSV)

1. INTRODUCTION

The objectives in describing the scope of this effort is to identify and demonstrate critical technology innovations that can be applied for the autonomous 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 subsystems by understanding and utilizing the science/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 Autonomous Spacecraft Health Monitoring/Data Validation Control System(ASHMDVCS).

The ASHMDVCS will provide the real-time signal detection, fault mode diagnostic identification, control

---

*Department of Electronic Engineering, Hankyong National University.
**Member of the FSI

본 논문은 NASA의 KSC, U.S.Airforces, The Boeing Co., University of Central Florida, Florida Institute Technology 등과 산학연계로 구성된 FSI의 Project의 일부로 연구가 진행되었으며, Ground Launch System에서 Autonomous 하기 위한 Spacecraft에 대해 System Parameter를 Realtime으로 Monitoring하고 Control하는 방법의 제안입니다.
(Tel: 031-670-5191)

and system parameter correction (if necessary) for the Spacecraft to autonomously operate in the space environment for long periods of time(years) without frequent telecommunications from the ground station. and/or "a fault-isolation capability".

This new innovation, using HFDMS approach will be advanced to implement a real-time monitoring and control methodology for the ASHMDVCS.

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 truth model, from which comparisons are made with the actual raw/conditioned data from measurement elements (i.e. Sensors and Actuators).

The insertion of this new concept of the ASHMDVCS 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 in real time[1].

Abnormal dynamic parameters are indicators of an out-of tolerance performance of the system, they can be a predictor of impending failures in those systems.

This feature adds a new dimension to existing control mechanizations that will greatly enhance the visibility of the "system state" which, in turn, increases the reliability of the test and evaluation process and autonomous operations over those currently in use.

This processing technique also promises the real-time detection of abnormal data flow conditions and the automatic identification of the specific areas(component/subsystem) causing the fault condition[2-4].

This attribute speeds up diagnostic analysis to near real-time and provides enough time to stabilize the system by parameter correction.

The design and development of current spacecraft systems were performed prior to the advent of such ideas as concurrent engineering, information modeling, real-time signal detection, robust and learning control and expert system mechanizations.

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, the ASHMDVCS are 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.

2. Objectives and Approaches of the ASHMDVCS

2.1. Challenges

The challenges that will be encountered in developing this autonomous control system can be summarized as designing 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 points 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 the next step in evolving the existing control processes to an 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 Sensor/

Actuator subsystems 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 the ACS methodology compatible to these autonomous systems, a set of objectives are identified to satisfy these projected needs with selected technology innovations.

Objectives that will describe the scope of this effort can be divided into

2.2. Sensing

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

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

C. 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.

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

E. 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).

2.3. Control

A. The control system should have fault isolation capability

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

C. Should possess advanced control algorithms combined with artificial intelligence techniques

The approach taken in the development of the ASHMDVCS are to employ the HFDMS methodology to conduct real-time autonomous operation of the ASHMDVCS.

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.

The Kalman estimation mechanizations(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 processes) will be used to

1. Optimize the "gain", K, in the "optimal observer".
2. Determine the health of the sensors and/or actuators.
3. Identify sensor/actuator "fault modes" and mechanize correction if possible.

When detection of an "abnormal flow" is triggered, designated diagnostic engines in expert systems will be convert to fault system mode which implemented for abnormally resolution and/or parameter correction.

3. Considerations and Learning for the ASHMDVCS

3.1. System Considerations

Autonomous operations of the ASHMDVCS with extreme reliability are of paramount importance in this development process. The factors of requirements necessary to achieve this goal are

a) Use of the HFDM Reference System Methodology.

b) Eliminate/reduce substantially the measurement noise.

c) Find optimal estimation of state variables and statistical parameters of "noise" by using the Kalman estimation.

d) Apply a real-time "error detection" system (Dynamic threshold).

e) Construct a Fault-mode file (expert system based).

f) Develop capability of correcting abnormal parameters ("state" and/or "sensor" and/or "actuator"), a control augmentation method.

A. Sensor Considerations

Factors that will be considered in the design and placement of the sensors for the ASHMDVCS are:

a) Reliability requirements for operating within large temperature ranges (190℃~190℃).

b) Redundant requirement for temperature, pressure, flow rate sensors (auto-weighting sensor strategy).

c) Self calibration mechanizations and the ability to modify sensor parameters.

d) Placement of sensors to measure the complete domain of "state variables".

e) Design response times of sensors to accommodate liquid-to-gas and gas-to-liquid phase changes.

The Kalman estimation process optimizes the state variables of the system by adjusting the "gain" based on the highest weighting going to the sensor/sensors with the lowest covariance or standard deviation.

The goal will strive to achieve a fault-tolerant sensor package.

B. Actuator Considerations

In order to achieve a fault-tolerant capability, the redundant actuators will be served by a common control network that will

a) Proportion their activation based on covariance values (both operating at all times).

b) Actuator non-linear models used for the HFDM implementation.

c) Maintain health monitoring by use of "dynamic threshold" methods.

d) Design response times of actuators to accommodate liquid-to-gas and gas-to-liquid phase changes.

e) Design ability to modify selective actuator parameters.

3.2. 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 a 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 sensor/actuator subsystems based on statistical parameters of the measurement errors in real-time (fault isolation system).

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

It is designed based on the 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 computing 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 ASHMDVCS 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.

A. 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 duration. 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 control systems. 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 techniques are powerful yet simple in design. The outcome of the design is a non-homogeneous nonlinear differential equation describing the controller [5-10].

The controller(solution of the differential equation) is calculated numerically via simulation code online(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.

4. EXPERIMENT AND SIMULATION

4.1. Electro-Mechanical Solenoid Valves (EMSV)

The example of using the IIFDMS methodologies to demonstrate a real-time detection technique is drawn from the analysis of EMSV.

The analysis focused on the highly non-linear the EMSV 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 the Kalman filter estimation mechanism (EKF) was used for data validation and computing the best estimate of the state(s).

4.2. Kalman Filter for Signal Conditioning

The use of the EKF is uniquely structured to condition raw data sequences in real-time[11 13].

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 Figure 1.

This Kalman filter process was applied to the model "response" example of the EMSV[14-15].

Figure 2. shows model reference state signals vs. measurement of the state signals (synthesized in this case).

Figure 3. shows model reference state signals vs. best estimate of the state signals (output of the filter)

Error profiles are respectively shown in Figure (4) and Figure (5).

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).

Figure 6. and Figure 7. shows measurement error covariance and estimation error covariance convergences.

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 the Kalman filter.

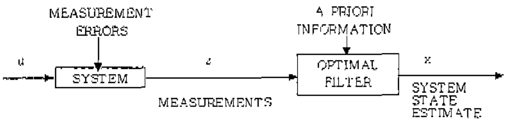

Figure 1. Data flow for filtering process.

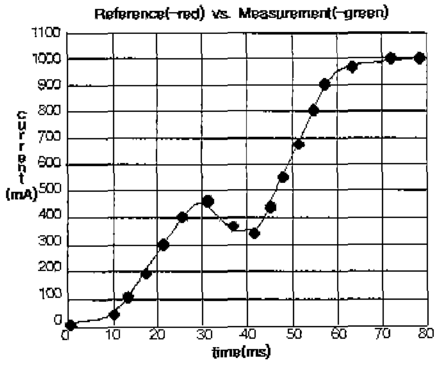

Figure 2. Reference(line) vs. measurement(dot).

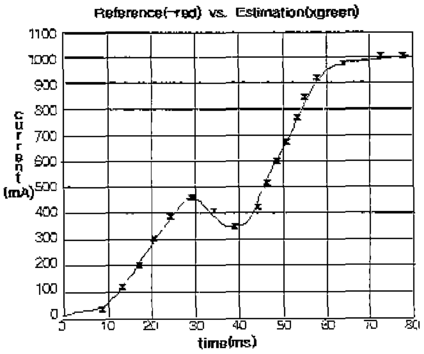

Figure 3. Reference(line) vs. estimate(x).

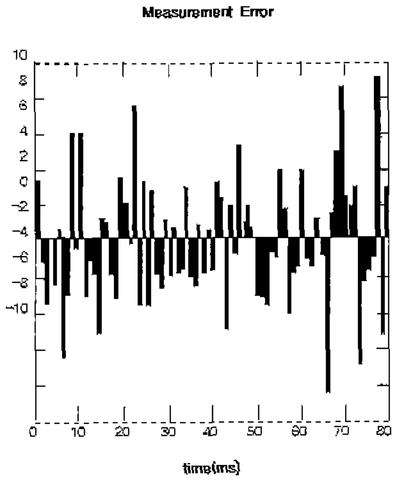

Figure 4. Measurement error.

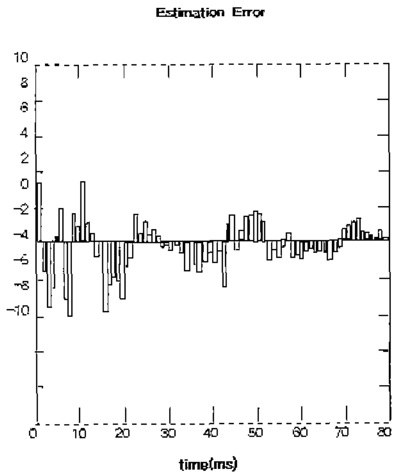

Figure 5. Estimation error.

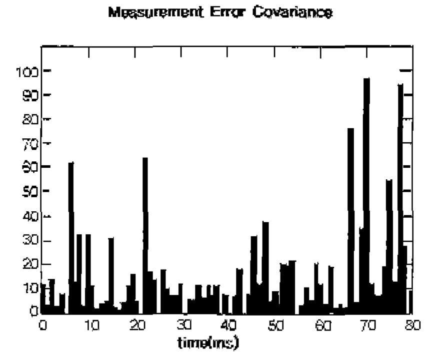

Figure 6. Measurement error covariance.

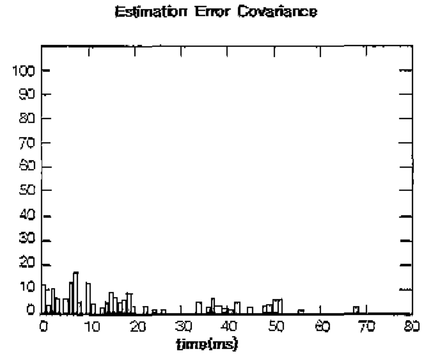

Figure 7. Estimation error covariance.

5. Facilities and Equipment

The University of Central Florida(UCF) has established a multi-university small Satellite and payload Development Laboratory(SDL) at the CCAS, Florida, to design, build, test and integrate space science, communication and earth observing experiments. The SDL will be operated under the auspices of the Florida Space Institute (FSI).

At the "center" of the FSI/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 Figure 8. the SGCS).

The cost share funding from The Boeing Company (TBC) will be providing focussed scholarships/fellowships in equipment/software for the Front End Processing Equipment.

The remaining hardware for the Front End Processing Equipment(FEPE) and the Command and Control System(CCS) will be funded by a matching grant from the UCF.

This FEPE and the CCS is shown in Figure(9).

The principal pieces of equipment to be used for this effort are

(a) Front end processors:
    1 each-ORIGIN 2000 (Silicon Graphics)
(b) High end workstations:
    2 each-OCTANE/SE, Dual CPU (Silicon Graphics)
    1 each-OCTANE/SE, Single CPU (Silicon Graphics)
    1 each-MODEL 320, Workstation, Single CPU (Silicon Graphics)

The equipment listed has been carefully selected to provide a compatible interface to the RF equipment of the SGCS and with the computer equipment already on hand. This initial hardware configuration will be used for the initial development of the real-time software for

(1) the abnormal signal detection system, (2) "best estimate" state identification responses and (3) fault mode diagnostic identification and correction controller design (autonomous control system).

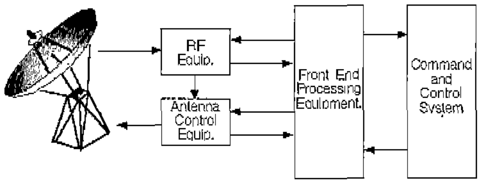

Figure 8. Satellite ground control station(SGCS).

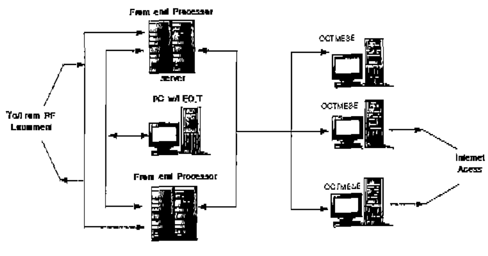

Figure 9. The Front End Processing Command and Control Systems(FEPFJCCS).

The inter-disciplinary equipment of the FEPE/CCS will be used for "Prototype" Development and "Research" objectives; they will be implemented with faculty, graduate and undergraduate students working and/or studying with the FSI (approximately 15). This involvement will satisfy the goal of the FSI, namely to provide hands on education to our students and to initiate the first phase of the Satellite Health Monitoring design and methodology. Under the Prototype Development experience projected for the SGCS, the students will obtain practice-based education on the application of orbital mechanics, real-time programming (C++, ADA, Wind-River) software configuration management, orbital operations and other command and control disciplines. The "research" objective will provide hands on environment for students in engineering to practice in the Satellite Health Monitoring and Autonomous Control System development process. These disciplines are Digital Signal Processing (DSP), Non-Linear Controller Design, Real-time Software Design, Estimation and Optimal Control, Instrumentation and Sensor Design and other Small Satellite and Launch Processing Design techniques.

The budget summary indicates that funds have been made available to purchase the major piece of equipment to develop the design and methodology for Satellite/Payload Health Monitoring and Data Validation. Facilities at the Cape Canaveral Air Station (CCAS), where the FSI/SDL is located as well as, at the UCF's nearby Research Park are currently available to locate the FEPE/CCS equipment to facilitate the effort.

6. Result and 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 the 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, the ASHMDVCS are 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 system to support autonomous operations.

REFERENCES

[1] B. Friedland, Control System Design, Mcgraw Hill, 1986.

[2] Roger W. Johnson, A New Methodology for Launch/Spacecraft Vehicle Ground Health Management, Monitoring and Test and Evaluation (White Paper), Institute for Simulation and Training, University of Central Florida, Apr., 29, 1994.

[3] Dr. Roger W. Johnson, A New Real-Time Detection Methodology for Automated Ground Health Monitoring (ACHM) Phase I, Report, University of Central Florida, Sep., 30, 1994.

[4] Dr. Roger Johnson, Sanjay Jayaram, Richard Hull, "A New Real-Time Detection /Diagnosis Methodology for Automated Manufacturing", Sixth International Conference on Robotics and Manufacturing-The International Association of Science and Technology for Development (IASTED), pp. 161~164, Jul., 26~29, 1998.

[5] Charles L. Phillips and Royce D. Harbor, Feedback Control, Systems, Second Edition,

Prentice Hall, 1991.

[6] R. D. Beach, et. Al., Fluid/Mechanical/Propulsion Smart Bit, GDSS-ERR-89-205 Report, General Dynamics, Dec., 1989.

[7] 김주웅, 김한웅, 이현관, 임준규, 엄기환, "웨브렛 다중신경회로망을 이용한 직접적응 제어방식연구", 한국 해양정보 통신학회 추계논문집, pp. 270~275, 1997.

[8] J. Kim, H. Kim, S. Jung, K. Yum "Intelligent Control Method of a PWM for LH", the 2nd IWAM97, pp. 553~558, Dec., 1997.

[9] 정경권, 김주웅, 정성부, 김한웅, 엄기환 "간단한 신경회로망 구조를 갖는 비선형 PID 제어기", 한국해양정보통신학회 춘계논문집, pp. 201~204, 1998.

[10] 권성훈, 이인재, 정지원, 김한웅, 엄기환, "신경회로망을 이용한 최적 제어 설계 방식" '98 대한전자공학회 하계종합학술대회 논문집, pp. 207~212, 1998.

[11] J. Kim, H. Kim, H. Lee, K. Yum, "The Multi Tracking Control Method Using the Modified Elman Neural Network", International Conference on Electronics, Information, and Communications (ICEIC'98), pp. II-439-442, Aug., 1998.

[12] Dr. Roger Johnson, Sanjay Jayaram, "Applications of Extended Kalman Filter at a Satellite Ground Control Station", Second IASTED International Conference on Control and Applications, pp. 124~127, Jul., 25~29, 1999.

[13] Arthur Gelb, Editor, Applied Optimal Estimation, The M.I.T Press, 1974.

[14] Robert Grover Brown, Patrick Y. C. Hwang, Introduction to Random Signals and Applied Kalman Filtering, Third Edition, John Wiley and Sons, Inc., 1997.

[15] John N. Little and Alan J. Laub, Control System Toolbox for Use with MATLAB, The Math Works Inc., Prentice-Hall, 1996.