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Volume I

MULTIPLE IMU SYSTEM DEVELOPMENT

by

Martin Landey and Richard McKern

December 1974

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The Charles Stark Draper Laboratory, Inc.
Cambridge, Massachusetts 02139

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ACKNOWLEDGEMENT

This report outlines the contract history and development process accomplished for "Space Shuttle Avionics—A Redundant IMU On-Board Checkout and Redundancy Management System". The work was performed for NASA/George C. Marshall Space Flight Center under contract NAS8-27624.

Major contributions to this program were made by Harrold Brown, Billie Doran, Charles E. Lee and Lewis Cook, all of NASA/MSFC, and Joan Dudley and C.D. White, of Sperry/Space Support Division. Those at CSDL who played an important role in the project include Richard McKern, Richard Blaha, David Brown, David Dove, Martin Landey, Duncan Sprague, David Swanson, Kenneth Vincent and Roy Whittredge.

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The publication of this report does not constitute approval by the National Aeronautics and Space Administration of the findings and conclusions it contains. It is published only for the exchange and stimulation of ideas.

ABSTRACT

A review of the contract is presented. Analytical work and digital simulations defining system requirements are described. A review of possible multiple system configuration improvements is also given. The report concludes with a summary of program achievements.

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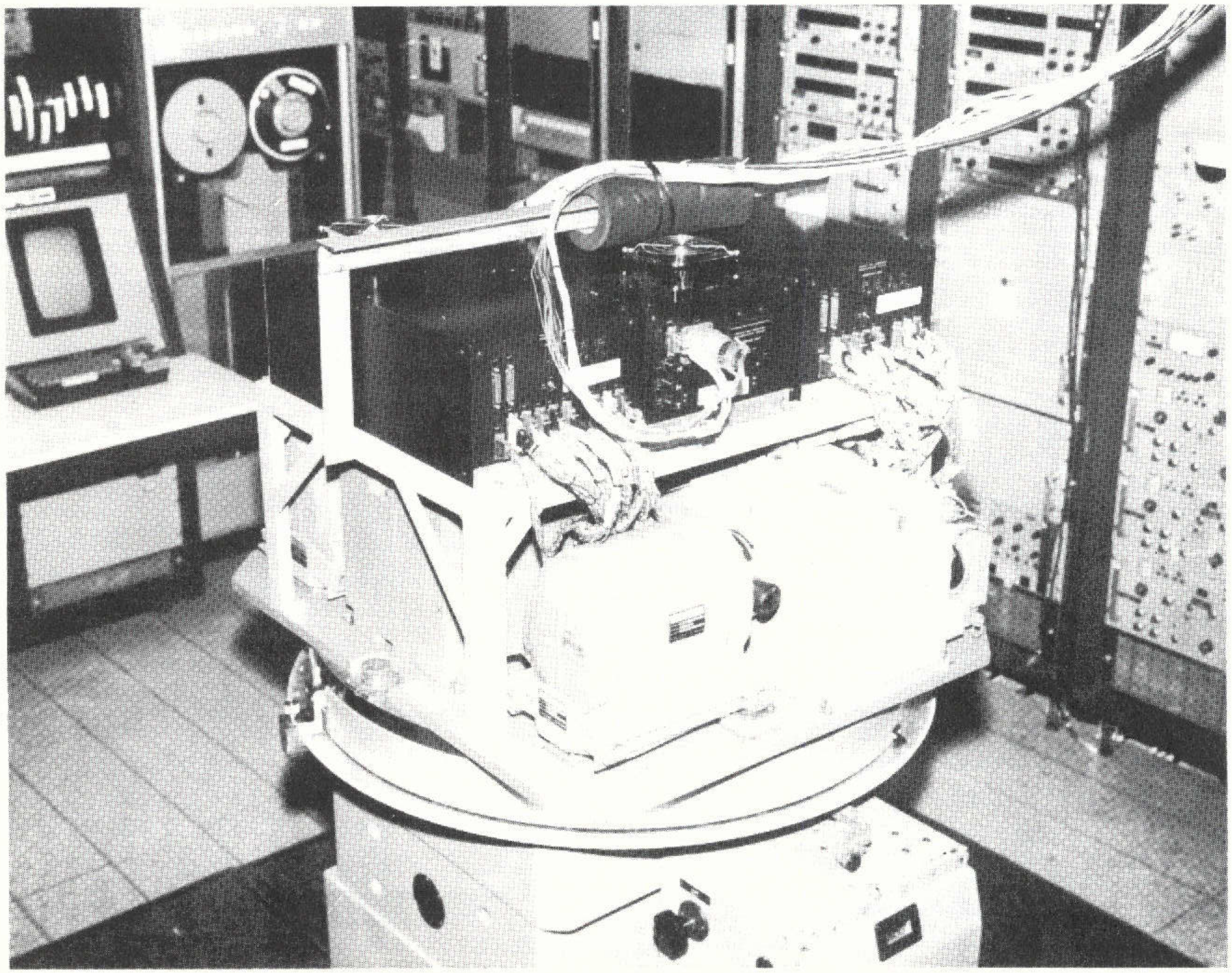

Redundant KT-70 System at NASA/MSFC

1. INTRODUCTION

This document forms part of the final report on the Space Shuttle Avionics Multiple IMU System, NASA/MSFC Contract NAS8-27624.

The contract was originally awarded to the Charles Stark Draper Laboratory on July 7, 1971. The initial twelve month effort was devoted to the study and definition of failure detection and isolation (FDI) requirements for a multiple gimballed system. It also addressed prelaunch requirements for calibration, ground alignment and gyrocompassing as well as an inertial navigator. Under this task, a preliminary test plan was formulated around the demonstration of FDI development using three redundant KT-70 IMUs and a single 4π-CP2 computer. An interim report covering this work phase (R-733, Space Shuttle Avionics A Redundant IMU On-Board Checkout and Redundancy Management System) was published in September, 1972.

This contract was amended in June, 1972, to add several additional tasks. Detailed electronic design of all system units was to be accomplished. These interface units would be assembled and their designs verified. An integrated, redundnat IMU system would be demonstrated and delivered to NASA/MSFC. Software for this system was also specified. Deliverable software included ground alignment and gyrocompassing, an inertial navigator, and a full range of FDI programs (Tape 1, FDINAV). A multi IMU calibration program was also required (Tape 2, IMUCAL).

This final report is organized into four volumes which will present in detail all activity under the extension of the original contract. This extension required both hardware interface and software coding design for a laboratory demonstration of this redundant IMU system using three KT-70 IMUs and a single 4π-CP2 computer.

The four volumes describe analytical and developmental activities, hardware design, software design, and a system test plan. Each volume is described briefly below.

Volume I—Multiple IMU System Development

A review of the contract is presented. Analytical work and digital simulations defining system requirements are fully described. Failure detection and isolation algorithms are presented and new technology achievements described.

Volume II—Multiple IMU System Hardware Interface Design

Design of each system component is described. Emphasis is placed on functional requirements unique in this system, including data bus communication, data bus transmitters and receivers, and ternary-to-binary torquing decision logic. Mechanization drawings are presented.

Volume III—Multiple IMU System Software Design and Coding

Design of system software is explained: both individual routines and their interplay are described. Executive routines, ground alignment, gyrocompassing, navigation and calibration routines are presented and described using flowcharts. Failure detection and isolation algorithms and system reconfiguration procedures are also presented and described with flowcharts.

Volume IV—Multiple IMU System Test Plan

Operating procedures for this redundant system are described. A test plan is developed with two objectives. First, performance of the hardware and software delivered is demonstrated. Second, applicability of multiple IMU systems to the space shuttle mission is shown through detailed experiments with FDI algorithms and other multiple IMU software: gyrocompassing, calibration, and navigation. Gimbal flip is examined in light of its possible detrimental effects on FDI and navigation.

1.1 Introduction to Volume I

This volume of the project final report is an outline of system development. Software and hardware development are described, with emphasis on new technology appearing in this program. Application of the delivered system as a test tool for shuttle avionics concepts is also outlined. The report is concluded with a summary of program accomplishments.

2. SYSTEM DEVELOPMENT

The Charles Stark Draper Laboratory has recently concluded a three year program in which a redundant gimballed inertial system was analyzed, designed and built for the NASA/George C. Marshall Space Flight Center. The history of this program is divided into two phases. The first is an analytical effort, to define requirements and mechanization methods for a redundant inertial system. The second is a design phase, in which the detailed design and construction of hardware and software was carried out.

It will be evident that this effort evolved in parallel with the emerging space shuttle vehicle avionics baseline. The effort has constantly had this goal: to develop a system which would be used as a test bed for shuttle concepts. In fact, the shuttle baseline did evolve to require IMUs and general purpose computers generically similar to those used in this system, although those were independent decisions. This program has exerted acknowledged influence on the baseline, however, in several areas. The optimal skew geometry developed under this contract has been baselined. Failure detection and identification studies performed under this contract have had effect on the shuttle FDI requirements.

2.1 History of the Contract

The work described in this report has been performed under contract NAS8-27624 with NASA/MSFC. This contract was let in July, 1971 (phase I), comprising two tasks. These are definition of an autonomous redundancy management scheme, including failure detection and identification techniques, and definition of an experimental program to verify the system described.

The contract was amended in June, 1972 (phase II), incorporating responsibility for design and delivery of a redundant gimballed inertial system employing off the shelf IMUs and computer equipment. This system was delivered to NASA/MSFC in January, 1974.

A follow-on to this work, extending the contract to September, 1974, encompassed additional software development. The user was provided with optional single or multiple navigators, and with a choice among several data selection algorithms.

2.1.1 Phase I Studies

The contract awarded to the Draper Laboratory of M.I.T. in July, 1971 set forth in the statement of work the study objectives summarized in the following sentences:

> "To define an onboard checkout, failure detection, isolation and redundancy management scheme for a redundant IMU system that meets a fail operational/fail operational/fail safe (FO/FO/FS) criterion. In addition, an experimental program that will implement the onboard checkout, failure detection, isolation and redundancy management scheme will be defined."

The approach taken to study the failure detection and isolation (FDI) accuracy requirements was to use actual shuttle mission trajectory simulations with defined terminal accuracy requirements. Acceptable threshold requirements for evaluation of FDI implementations were then defined by showing the accuracy requirements of individual system coefficients in each trajectory phase and observing error propagation characteristics in position and velocity. By use of actual trajectory phases and required IMU characteristics to meet terminal accuracy requirements, threshold requirements for the multiple system FDI were obtained. This formed the basis of all FDI sensitivity-to-requirements evaluations.

FDI algorithms were subjected to continual simulation and review, and were changed significantly over the course of the contract. Details of this history and reasons for selection of the algorithms coded are given in Chapter 3, SOFTWARE DEVELOPMENT.

It was the intent in this work to establish a method of FDI which is compatible with the off-the-shelf IMU, which could be demonstrated in the laboratory and which satisfied baseline accuracy requirements derived for the shuttle mission.

A second area of interest involved redundant IMU system prelaunch checkout procedures. Investigations were made in this study to show how best to use the multiple system information as an indication of individual IMU parameter verification within expected levels of performance. Initially, interplatform alignment was verified using measured gimbal angles. With alignment acceptable, powered flight FDI was employed as an aid in judging an individual IMU's performance.

The second task involved defining a test program for a strawman redundant system, which was directed to utilize equipment available at NASA/MSFC. The test plan for a multiple IMU system at NASA/MSFC was defined directly for three production Kearfott KT-70 IMUs and their supporting electronics, mated to an IBM 4π-CP2 computer. The computerized test facility available at NASA/MSFC, known as SSCMS (Strapdown System Control and Monitor Station), would be used in monitoring system performance. The test plan presented included single IMU calibration and gimbal flip evaluations, multiple IMU gyrocompassing, land navigation and powered as well as unpowered flight FDI demonstrations. This plan was presented in an interim report, Space Shuttle Avionics——A Redundant IMU On-board Checkout and Redundancy Management System, CSDL report R-733, September, 1972.

2.1.2 Phase II Efforts

The contract amendment authorized CSDL to design and build the system proposed as a strawman in earlier work. The bulk of this report is concerned with documenting that work.

Volume II, Multiple IMU System Hardware Interface Design, describes the delivered hardware. Significant features are explained in Chapter 3 of this volume. Volume III, Multiple IMU System Software Design and Coding, describes the software delivered with the system. Highlights are described in Chapter 4 of this volume. Volume IV, Multiple IMU System Test Plan, is concerned with presenting test procedures and evaluation techniques for the system.

2.1.3 Follow-on Efforts

The follow-on task under this contract involved developing three data selection algorithms and coding them for use as either pre-navigation or post-navigation filters. These were simple vector averaging, mid-vector selection and the so-called Kaufman Filter. (Vector formulation of the Kaufman Filter was first derived for this work.)

The user is given a choice among these filters to provide $\overline{\Delta V}$ for the system navigator. (In the initial release, only averaging was available.) Alternatively, the user can elect multiple navigators, each driven by a separate IMU, with post selection among state vectors using the same data selection algorithms. This work is described in section 4.4.

2.2 Overview of the Developed System

CSDL has delivered a system employing three KT-70 IMUs controlled by and providing data to a single 4π-CP2 computer. A bidirectional 10 MHz serial data line is employed for all information transfers (commands and data demands). A separate line is used for the gyro pulse torquing clock common to all IMUs.

This system has been designed to interface with NASA/MSFC's Strapdown System Control and Monitor Station, using both analog and digital links. The SSCMS is used both for data storage and retrieval purposes and for monitoring the system in real time.

System software, at delivery time, included ground alignment and gyrocompassing, an inertial land navigator, failure detection and identification and redundancy management (failure isolation by reconfiguration). A multiple IMU calibration program was prepared by fitting Sperry Space Support Division's single KT-70 calibration program into this system's executive structure.

Since delivery, navigation capabilities have been extended to comprise either a choice among three pre-navigation selection filters or three independent navigators. The multiple selection filter/navigator software (Release 2 of FDINAV) is implemented to respond to FDI decisions so that reconfiguration is identical with that in Release 1.

A detailed test plan has been prepared by CSDL, designed to show the applicability of the redundant IMU system to the shuttle problem. This plan includes evaluation of multiple IMU gyrocompassing and navigation. Its primary thrust, however, involves study of FDI algorithms. It is intended, moreover, that the system function as a test bed for shuttle software concepts, as discussed below.

2.3 Application of This Work to SSV

It has been mentioned that work done under this contract has contributed materially to the emerging shuttle hardware and software baselines. Several examples are cited here.

1. The optimal skew geometry for triply redundant IMUs was derived for this system. System FO/FS criteria could be met only with skewed platforms permitting autonomous instrument FDI at the two IMU level.

CSDL's derivation of skew orientations with

$$T_1^2 = T_2^3 = T_3^1$$

simultaneously yielded optimal skew geometry for FDI purposes and minimal coding in that transformations were alike. This geometry has since been specified for the three shuttle IMUs.

2. FDI studies performed under this contract have consistently contributed to the field as it emerged to meet shuttle requirements. It must be borne in mind that this project started quite early in the development of redundant IMU systems. FDI analysis performed for it, providing self-contained failure identification and fault-down logic, was a pioneering effort.

3. A more specific example is the use of statistical rather than deterministic FDI algorithms. Statistical FDI was developed initially at CSDL for use in redundant strapdown systems. Its use in a redundant gimballed system was first proposed in this work. While it was not used in the delivered software, development continued and it is now proposed as the IMU FDI method for operational shuttle vehicles.

This hardware does not meet shuttle baselines in several regards. However, it is sufficiently like the shuttle inertial hardware to permit use as a test bed until shuttle hardware is operational. It is likely that no better approximation to the redundant flight hardware will be available in 1975. Suggestions for use of this system as a test tool appear as Chapter 5.

2.4 Publications Under This Contract

CSDL activity under this contract has been documented both in CSDL formal publications and in the open literature. There follows a list of publications specifically derived from this project. Technology, particularly in FDI and redundancy management, has been transferred to other shuttle related activities at CSDL, and has appeared in publications funded by those contracts.

CSDL reports are:

1. Richard McKern et.al., Space Shuttle Avionics—A Redundant IMU On-board Checkout and Redundancy Management System, CSDL R-733, September, 1972.

2. Martin Landey and Richard McKern, Multiple IMU System Development, CSDL R-798 Volume I, December, 1974.

3. Martin Landey and David Brown, Multiple IMU System Hardware Interface Design, CSDL R-798 Volume II, December, 1974.

4. Kenneth Vincent, Jr. and Roy Whittredge, Multiple IMU System Software Design and Coding, CSDL R-798 Volume III, April, 1974.

5. Landey, Vincent and Whittredge, Multiple IMU System Test Plan, CSDL R-798 Volume IV, October, 1974.

In the open literature:

1. David Dove and Richard McKern, Redundancy Management of Multiple Inertial Systems For Space Shuttle, ION Conference, Orlando, March, 1972. (Also published as CSDL E-2652, April, 1972.)

2. Dove and McKern, Failure Management of Multiple Gimbal Inertial Systems, AGARD Guidance and Control Panel 15th Symposium, Florence, Italy, October, 1972. (Also published as CSDL R-726, August, 1972.)

3. Harrold Brown, David Dove and Richard McKern, Failure Detection and Isolation of Redundant Inertial Systems For Space Shuttle, Fifth IFAC Symposium on "Automatic Control in Space," Genoa, Italy, June, 1973.

4. Richard McKern and Howard Musoff, Redundancy Management of Inertial Systems, AIAA 73-852, AIAA Guidance and Control Conference, Key Biscayne, August, 1973.

3. HARDWARE DEVELOPMENT

Design of this system was, of course, an evolutionary process. A review of program milestones and major design decisions is presented here as an aid to understanding the design priciples behind the delivered system.

3.1 Hardware Design Decisions

A strawman system had been defined under Phase I of this contract (see CSDL R-733, this program's interim report). Implementing this strawman in usable form made up the on-going design effort.

Several major decisions were represented by the strawman itself. Early work in Phase I had considered four off-the-shelf aircraft IMUs for use in this system. Specification of the Kearfott IMU was made in August, 1971. At this time, decisions were also taken that the strawman would be designed using an IBM 4π-CP2 computer and its ancillary equipment then available at NASA/MSFC. Three IMUs would be employed. Further, the system could make use of MSFC's SSCMS for control and monitoring if desired.

With the IMU and computer specified, their interface could be studied in detail. One early decision was that direct computer control of gyro pulse torquing was impractical in view of the large I/O requirements. Instead, the computer would issue only net torque commands in ternary form with dedicated logic at the IMU interface performing ternary-to-binary conversion and issuing each pulse command.

Consideration of table slip rings (at the suggested test facility) showed them impractical for the total power requirements of three IMUs. In consequence, it was decided that the system's power and data bus lines should use "overhead" cables. The proposed test plans would be modified to take account of the table motion limitations imposed by such cabling.

In February, 1972, attention was turned to external control and monitoring. Two options appeared to be the use of a Kearfott KT-70 test console, modified for redundant system use, or use of the SSCMS. It was decided that the SSCMS would be the better choice, in view of its built-in data processing, storage and display facilities. Further, the test table proposed for use by this system was mechanized for rate control by the SSCMS's HP2116B computer.

The question of S/D converters was explored. Would each IMU interface require one per axis, or could a single convertor be multiplexed to serve all axes? The deciding factor was the complexity of interpolation logic required with a single convertor—without interpolation data staleness would be greater than acceptable limits for FDI.

Preliminary designs for the data bus were also completed in February. The system would use a bus design approximating the McDonnell Douglas Corporation Phase B shuttle data bus design. The bus would employ biphase manchester coding at 1MHz. No cross-strapping would be allowed at the peripheral device (that is, the IMU interface unit). All messages would be initiated by the computer, which implied that no hardware interrupts could be used. A maximum polling rate of 50/s was set, from which the computer minor cycle time of 20ms was determined.

By June, 1972, the decision to use "overhead" cabling was firm, freeing table slip rings for parallel monitoring of the inertial system by the HP2116B computer. One factor in this decision was a contractual requirement that a parallel operation and monitoring capability exist. A proposal to use Kearfott GSE for this purpose (pluggable but not parallel) was turned down by MSFC. CSDL continued to examined this problem, and determined that it would be impossible for two source of command (i.e., two operating computers) to coexist. Therefore, a significant hardware impact would be required for command switchover, involving changing virtually all input lines by relays. Further, about 120 buffer amplifiers would be required. In August, 1972, CSDL proposed dropping the parallel monitoring capability. The slip rings were reassigned to use for analog test points in the system.

Preliminary design of the processor interface unit (PIU) was completed in June, 1972. The design involved making all data bus communications transparent to the 4π-CP2. The digital link to the HP2116B, although a parallel rather than serial bus, was deemed an equivalent data bus address as far as the computer was concerned, saving building a direct computer-to-computer interface. The PIU was functionally a finite state machine, with hardware functions for parallel to serial and serial to parallel conversion, data routing and timing.

As the design evolved, decisions were made to build the bus to the NASA/MSFC Type II Data Bus Terminal specification. Bus speed was increased to 10MHz. It also was decided to use return-to-zero alternate-mark-inversion coding compatable with this specification.

Expected use of the HP2116B and SSCMS in supporting testing of the redundant system was formalized in a meeting at NASA/MSFC. MSFC took responsibility for all HP2116B coding involving real time data monitoring and storage, data display and offline calculations. The HP2116B also was to exercise control over the test table, and to control SSCMS monitoring of system analog test points.

Design of the IMU interface unit (IU) was progressing in parallel with other tasks. Although logical design was incomplete, specification of S/D convertors and wirewrap back planes were made, allowing mechanical design. Each IU was provided with 5 vdc and ±15 vdc power supplies, eliminating the need for the baselined table mounted interconnect box. Power, in other words, would be carried separately to each IU, with distribution accomplished in the GSE power panel.

One major change was made to the existing PIU design—the three data buses were logically treated as being on one data bus transmitter rather than three separate transmitters. This change allowed a single command to be sent to all IMUs, and the requirement for a separate system sync line was dropped.

A design review of the PIU and IU was held at NASA/MSFC in December, 1972. Approval was granted and construction was begun.

Final design of the power distribution panel (PDB) was completed in February, 1973. Data bus transmitter and receiver designs were approved in March.

System analog test point listings were firm in April and slip ring assignments were made in May. Hardware design of the system was considered complete in March, 1973.

3.2 Hardware Construction History

With design approval in December, 1972, purchase orders were issued for long lead time items: connectors, S/D convertors, back planes and the system master oscillator.

Mechanical and electrical assembly of the PIU and one IU began the next month. PDB assembly started in February. Bus transmitters and receivers were assembled in March and April.

Both the PIU and PDB were built and subjected to bench testing in April. IU #1 was first tested in May. Assembly of IUs #2 and 3 then followed.

Single string system integration, using a GFE IMU and its Adaptor Power Supply, was accomplished in July. System software testing followed with the IMU controlled by the 4π-CP2 in August.

IUs #2 and 3 were cycled through the system in October and November with verification complete in December.

A formal system selloff demonstration was held at CSDL in January, 1974 and the redundant system was delivered to NASA/MSFC at the end of that month.

3.3 Post Acceptance Modifications

Two modifications have been made to the delivered hardware.

As originally designed, power was applied to all IMUs by a single switch at the PDB. NASA/MSFC requested a modification permitting switching of power to individual strings. This change was made by adding switches in the excitation line to each string's power output relay in the PDB.

A more important problem which appeared during system testing was a large apparent gyro bias instability, typically $0.1^{\circ}/hr$ or twenty times the expected uncertainty. Analysis traced this uncertainty to use of a free-running multi-vibrator in the IU for the gyro pulse torquing (GYPTO) clock. Uncertainty was introduced through inability to set multi-vibrator frequency precisely at 400 Hz. CSDL proposed and developed a solution in which a 400Hz clock line was added to the data bus. In effect, the sync line was reinstated in the system. This violated the original data bus specification, but yielded a system with tolerable gyro uncertainties.

3.4 Hardware Overview

A full description of the system is deferred to Volume II of this report. A summary of significant hardware features is appropriate here, however.

This system is characterized by the control of three IMUs by a single computer. Operationally, this allows collaborative FDI and redundancy management not possible among multiple single string systems.

This mechanization is achieved using a processor interface unit consisting of a sequential machine to carry out complex command and data retrieval tasks on a single command from the computer. Control is exercised over a serial data bus similar in concept to the shuttle vehicle bus now specified. Bus transmitters and recievers were designed specifically toward this end.

The overall system, then, consists of redundant off-the-shelf IMUs and an off-the-shelf computer. Interfaces have been designed to couple them into an integrated system capable of serving as a laboratory test facility for verification of shuttle hardware/software concepts.

4. SOFTWARE DEVELOPMENT

Development and integration of software for the redundant IMU system was initially limited in scope by an intention to adapt existing coding to this usage. That is, ground alignment, gyrocompassing, navigation and calibration were to be based on single KT-70/4π-CP2 coding performed for NASA/MSFC by Sperry Space Support Division. In fact, only the calibration program was used.

Whether existing programs were employed or not, there was a need for a system executive, failure detection and isolation routines, redundancy management, and integration of the hardware and software through appropriate interfaces. These tasks, as anticipated, required the major part of time spent on software at CSDL, despite decisions not to use Sperry coding.

The software task was extended beyond system verification and delivery by a contract modification calling for multiple navigator options. These options were incorporated in software Release 2, delivered in September 1974.

4.1 Summary of Delivered Software

Software was delivered in the form of two "tapes". Tape 1, FDINAV, contained all coding except the calibration program. Tape 2, IMUCAL, consisted of a multiple IMU calibration routine and the executive and I/O routines. Two tapes were required as program lengths exceeded space available in the computer. The 4π-CP2 with its auxiliary memory has 32K 16 bit words of core. Tape 1 requires about 31K words, and Tape 2 22K.

Tape 1 consists of support programs, application programs and schedulers. Support programs are the executive, typewriter operating system, IMU parameter compensation and downlink processor. Schedulers are written for initialization, alignment/gyrocompassing and navigation/FDI modes. The application programs are ground alignment, gyrocompassing, navigation and the various FDI routines.

Tape 2 comprises the calibration program and portions of the support programs.

Detailed presentations of these programs appear in Volume III, Multiple IMU System Software Design and Coding, of this report.

4.2 Multiple System FDI Formulation

The fundamental emphasis used in investigating the FDI problem was to introduce into simulations the best estimates of detection and identification thresholds connected with Shuttle flight phases. This permitted an evaluation which was addressed directly at the Shuttle problem and resulted in implementations which could be evaluated directly in terms of coverage and probability of success within performance requirements. Another aspect which was evaluated concerned the implementation of the complete redundancy management mechanization which integrated FDI with available BITE, and investigated the closed loop effects of multiple data selection filters and multiple navigators. This permitted evaluation of several crosstrapped system configurations. These simulations can be used to show how actual hardware characteristics influence the configuration signal-to-noise levels. They permit a more realistic look at specific configurations in terms of attainable coverage and missed and false alarm probabilities under various levels of IMU degradation.

CSDL's earliest work in FDI was concerned with the dodecahedron strapdown configuration (SIRU), begun in 1968. In this problem, the redundant gyroscope and accelerometer configurations can be completely divorced and separate formulations can be implemented using compensated instrument data in the body frame. A judgement about each instrument loop is made through a set of parity equations using individual data sources geometrically coordinatized to obtain common frame comparisons. The comparison basis could be the formulation of a simple averages, a least squares fit or a complete maximum likelihood estimator. In SIRU, the basis of error detection uses data transformations through fixed geometry for common frame solution of parity equations. The equivalent gimbal system parity equation development must recognize that no clean separation of instrument axis redundancy is possible. That is, redundant accelerometer outputs include not only accelerometer errors. Gyro error effects and stable member alignment geometry uncertainty infringe on the common frame voting process. Although various methods exist to untangle individual error sources the voting process is inherently more complex and ultimately capable of less resolution.

As proposed early in 1971, the basic problems are to track the individual IMU stable member alignment with respect to all other IMUs, and to establish the validity of the IMU velocity outputs. The attitude screening step can be degraded but never bypassed completely. It could be limited, for example, to screening to the attitude delivery requirements of the flight control system. Fundamentally, it establishes each IMU's stable member attitude with respect to another stable member using an Euler angle sequence of gimbal angles. The accelerometer FDI is then a known geometry problem solved using parity equations. An alternative which was investigated establishes the relative stable member orientations by observing the accelerometers' incremental velocity vectors. The incremental velocity vector magnitude differences, platform to platform, represent accelerometer error sources. The velocity vector cross-product yields relative attitude errors. The advantages of this method are that the gimbal chain Euler sequence with its associated uncertainties is bypassed in producing the attitude divergence and that the accelerometer output data is finely quantized in existing off-the-shelf aircraft inertial hardware. A shortcoming of the approach is that the attitude error sensitivity is variable, being maximum perpendicular to the vehicle input acceleration with no sensitivity to attitude errors about the input acceleration. The other fundamental problem in this approach appears at the two IMU level. Accelerometer scale factor and bias errors influence both incremental velocity vector magnitude and direction. Thus, it is difficult to discriminate between attitude and velocity error sources. This work has at various times been suggested to aid FDI initialization for azimuth alignment containment at launch, but has not been pursued further for Shuttle application.

A closed loop implementation was also investigated which uses gimbal angle Euler sequences to establish each stable member relative to another. The average stable member position is then established and all individual stable members are torqued via a closed gyro loop to keep all IMUs actively coaligned. This results in a forced mechanical alignment of stable members to permit accelerometer voting directly in a mechanically established common reference frame. The system, then, is monitored for performance by tracking the gyro torquing required. This establishes the attitude divergence. This solution basically offers no better resolution then tracking the small angle errors in software, but it does simplify the software required for a velocity-based FDI as well as the requirements for generating incremental inertial velocity for navigation. This approach appears fruitful for use in a local level system.

Separate algorithms have been selected and coded for this system based on attitude and velcotiy information at both the three colinear and two skewed IMU level.

With colinear IMUs, an error vector is derived for each IMU (velocity or rotation vector). The sum of component magnitudes, axis by axis, is compared with a constant detection threshold. If that is exceeded, isolation is attempted by comparing individual components with a constant isolation threshold.

With skewed IMUs, an error vector is defined for each IMU. The velocity error vector is given by an IMU's measured $\overline{\Delta V}$ minus the other IMU's $\overline{\Delta V}$ transformed into its own frame. The attitude error vector is derived from the stable member to stable member quaternion constructed from the gimbal angles. Detection is based upon comparison of the vector's magnitude with a constant threshold. Isolation is done by comparing the maximum component of the unit error vector with a second constant threshold.

The delivered FDI and redundancy management software (documented in Volume III) includes most of the tracking test type FDI configuration now baselined for the Shuttle Approach and Landing Test (ALT) software. It could easily be modified to include the present FDI baseline using sequential probability ratio testing (SPRT) for Operational Flight Testing (OFT).

4.3 Software Development Process

As with the hardware, a baseline statement of system software requirements existed from phase I. The process of implementing the baseline is described below.

4.3.1 Use of Existing Software

Initial plans for this system's software were based on use of existing coding developed for NASA/MSFC's single KT-70/4π-CP2 system. This software included a local level land navigator, ground alignment and gyrocompassing routines, and a calibration program. Only the calibration program was actually used in the redundant IMU system.

Replacement of the local level navigator with an inertial navigator was an early step. This change was due to FDI requirements based upon gimbal angles: the torquing process required to maintain local level disallowed attitude FDI algorithms then under consideration. In consequence, a pure inertial land navigator was developed for this system.

The gyrocompass delivered as GFE proved inadequate for an inertial system, although it was well suited for its intended use in a local level system. The routine leveled the platform but was not north seeking. Instead, azimuth offset was estimated and was compensated by the navigator. CSDL chose to derive and code alignment and north-seeking gyrocompass algorithms rather than modify this existing coding.

4.3.2 Design Timeline

Requirements for system support software (exclusive of IMU compensation) were set by definition of the data bus interface. The preliminary definition was issued in June, 1972.

System timing estimates were also made in June, based upon software developed for other systems. The executive overall design was completed in July. Detailed design (flow charts) was prepared in August. The typewriter I/O program to support test activities could then be designed. That activity occupied September through November. In December, 1972, the system executive and typewriter I/O package were assembled using an MSFC-supplied 360 cross assembler.

With the executive design firm, the HP2116B interface could be defined. CSDL met with NASA/MSFC personnel in October, 1972, to complete this definition. It was established that the 4π-CP2 would act as master in all computer/computer exchanges. Display and storage requirements were set. CSDL agreed to provide a 50 pps sync signal to the HP2116B so that table angle readings could be synchronized with gimbal angles on the downlink. Scanning of the analog test points was also discussed and defined.

System applications programming proceeded in a parallel effort. With use of existing coding eliminated, CSDL designed ground alignment, gyrocompass and inertial navigation routines. Based on analytical work and simulations performed over the previous year, four FDI algorithms were chosen. These provided for failure detection among three colinear IMUs (with separate algorithms based on velocity and attitude data) and between two skewed IMUs (again with separate algorithms using velocity and attitude information). Colinear IMU FDI algorithms were coded in December, 1972. Other application programs were coded and verified over the next two months, except for skewed IMU FDI. That coding was completed in July, 1973.

The GFE multiple position calibration program was delivered to CSDL in April, 1973. In June, additional positions were added to the sequence by MSFC to determine gyroscope g-sensitive drift terms. CSDL integrated its IMUCAL (Tape 2) in August.

As hardware integration was accomplished, system software was excercised in increasing amounts. 4π-CP2/PIU communication was demonstrated in September, 1973. Communication with and control of the IMU was achieved in October. Debugging of the application programs continued through system selloff and delivery (January, 1974).

Multiple string operation using Tape 1 occured in February, 1974.

4.4 Post Delivery Modifications

Four modifications have been made to Tape 1 since delivery. These corrected possible problem areas, incorrect navigation constants and incorrect levelling equations. Greater detail is given here than in the preceeding discussion because these modifications stand as corrections to the software described in Volume III of this report.

One problem area involved an overflow condition. This condition would occur during ground alignment if gyro bias compensation terms exceeded 0.23°/hr. Correction involved rescaling data items used in fixed point arithmetic. The other possible problem area involved false gimbal rate hard failure indications on startup. This problem was eliminated by defining a new initialization flag set only on the first pass following SYN, and RUN, commands.

Changes to navigation constants involved interpretation of available NASA/MSFC constants in terms of astronomic rather than geocentric latitude.

The delivered version of Tape 1 contained incorrect equations for levelling the platform during slew (in the ground alignment sequence). Corrected equations were derived and incorporated.

4.5 Software Developed Under the Follow-on Contract

The follow-on contract encompassed additional software tasks. Navigation, which had been based on the average $\overline{\Delta V}$ of the three IMUs, was expanded to include several options. A single navigator could be used, as in the initial release, with a choice among three pre-navigation selection filters. Alternatively, the user could command multiple string navigation (each IMU driving its own navigator), with the three selection algorithms available for post-navigation use. The three filters were average $\overline{\Delta V}$, midvector $\overline{\Delta V}$ and the Kaufman $\overline{\Delta V}$ (least squares fit to form a resultant vector).

Data down link lists were altered to accept this new information. (NASA/MSFC updated display and storage formats to incorporate the additional data.) Requisite changes were made to the NAVFDI scheduler. No changes were required in the FDI algorithms.

One other change involved altering the gyro compassing scheduler to terminate alignment on receipt of a discrete from a PIU switch, rather than according to a fixed preprogrammed time interval. This change permitted more detailed study of gyrocompass stability through varying settleout time allowances.

5. APPLICATION OF THIS SYSTEM AS A TEST TOOL

CSDL has prepared a detailed system test plan (Volume IV of this report) designed to demonstrate capabilities of the delivered hardware. Emphasis is placed on FDI and redundancy management testing, the areas of new technology in the system software. Testing also involves evaluation of multiple IMU gyrocompassing, navigation and calibration.

Beyond the contractual test plan, CSDL sees application of this system as a primary test tool for both the space shuttle vehicle and to formulate aircraft inertial system redundancy concepts.

It has been said that the IMU, data bus and computer used in the laboratory system are similar to those specified for the shuttle. No multiple string system built to the shuttle hardware baseline will be ready before 1976, leaving this system as a principal test bed for shuttle FDI and redundancy management software development.

This redundant system is also well suited for use in aircraft inertial system research and development. Most present inertial systems involve three independent strings, cross-strapped only manually by crew decisions. Clearly, the next step in aircraft system development will involve design of associative systems allowing autonomous fault detection and redundancy management both for navigation and for autopilot control. By virtue of the use of an off-the-shelf aircraft computer and IMUs, this system is similar to the evolving design, and can function as a primary test object, allowing great capability to formulate cross-strapping philosophies for flight and automatic landing research.

Discussion of each of these application areas follows. Each section emphasizes both use of existing software and additional software which could be formulated.

5.1 System as a Test Tool for Shuttle Concepts

Although this system is similar to the shuttle inertial hardware, it is not identical. Coding developed for the shuttle cannot be used without rewriting it in 4π-CP2 assembly language. Yet this system can be used for experimentation with algorithms suggested for the shuttle. Suggestions are presented here for work with FDI and attitude determination. Examination of accelerometer bias attitude sensitivity is also explored. The system is generally applicable for engineering evaluation in FDI, calibration, initial alignment and navigation.

5.1.1 Failure Detection and Isolation

The present FDI coding does not reflect all of the latest shuttle software requirements. Testing done with it is of value in establishing sensitivities, which can be used to give understanding to existing simulations.

FDI which is now specified for the shuttle, however, appears to be fully compatible with this existing structure. Initial shuttle testing in ALT will employ IMU FDI limited in scope, based primarily on the "tracking tests" which are presently implemented.

For operational flight vehicles, statistical FDI (SPRT) developed at CSDL is specified. SPRT has been used successfully in redundant strapdown systems. For gimballed systems, however, work with it has been limited to simulations. Coding shuttle algorithms for test with the existing multiple IMU systems would provide a beneficial test tool well before operational shuttle coding is started.

5.1.2 Attitude Determination

The shuttle IMU will be used to determine vehicle attitude, as required for the digital autopilot. Several algorithms are under active consideration.

While the attitude chain in the shuttle IMU differs significantly from the KT-70 chain, these algorithms work only with the computed gimbal angle. Therefore, this system again can serve as a test bed for proposed shuttle software.

5.1.3 Navigation

Navigation is another area in which this system can be of use in the shuttle program. It is possible to design a navigator for this system which matches the shuttle software requirements. This coding would have the versatility required for navigator testing, and could with little effort be kept up to date with changing equation sets.

In this area, empirical work could be done with various selection filter formulations, with recovery from failures, and with navigator sensitivity to redundancy management actions.

5.1.4 KT-70 Accelerometer Bias Attitude Sensitivity

Kearfott reports an accelerometer bias sensitivity to attitude in the shuttle IMU (a member of the KT-70 family). It is necessary to determine the magnitude of this problem, and whether it can be alleviated. If not, it will be necessary to devise techniques for calibrating and compensating for this effect. The present multiple IMU system could be used for this testing without having to change the calibration program significantly. Compensation routines would require only analysis and some recoding.

5.1.5 Additional Software

Other software which might be coded for this system includes calibration of misalignment and skewed IMU initial alignment.

There is probably little value in extending the calibration program, as shuttle IMU calibration is well advanced. If this system is to be used outside the laboratory, however, intra-and inter-IMU misalignments would have to be calibrated and compensated.

Extension of classical ground alignment and gyrocompassing to deal with skewed IMUs, as in the shuttle application, does not require new technology. However, no other facility for testing this coding presently exists.

5.2 System as a Test Tool for Aircraft Concepts

The laboratory demonstration system is well suited for aircraft applications work. With future requirements of aircraft inertial hardware maturing rapidly, this configuration appears to be the next logical step in system design. Requirements which are forseen include fault tolerance, increasing dependence on inertial hardware by digital autopilots and fly-by-wire systems using significantly improved terminal area navigation aids for automatic guidance to the runway.

The underlying assumption in each of these areas is that fault tolerance through autonomous fault detection and redundancy management can increase reliability to the point where automatic control is acceptable. This is a goal which must be met by similar systems in the shuttle.

Specific aircraft directed work which could be done with the existing system includes deriving and coding a local level navigator, developing an aided-inertial navigator, and designing an FDI formulation for use with local level systems.

5.2.1 Local Level Navigator

Presently, only a pure inertial navigator is coded for this system. Aircraft applications usually require a local level design. Suitable software compatible with this computer exists and has been tested to permit exploring aided navigation areas. It can be used to determine the additional level of fault identification attainable with skewed IMUs, as well as how to mechanize a system for this application.

5.2.2 Aided-Inertial Navigator

The laboratory system has no provision for navaid integration. Whether or not radio aids are added to the hardware, an aided-inertial navigator could be coded for testing. Dummy inputs would be used. Aircraft systems, in general, depend on radio aids for long term stability, and such systems are well understood. Of more interest at a developmental level are terminal area requirements with emphasis on short term preformance and screening capabilities.

5.2.3 FDI for Local Level Systems

FDI has been explored almost entirely in the context of pure inertial systems. There does not appear to be any theoretical prohibition of FDI in local level systems, but significant work remains to be done. CSDL has suggested that an active closed loop stable member coalignment torquing algorithm can be implemented in such a configuration, but has not carried the analysis into a simulation stage. If a local level navigator were implemented, this system would provide a test vehicle for aircraft directed FDI studies.

5.3 Summary

CSDL believes that the system described in this report can prove a useful test tool over the next few years. In two areas, shuttle and aircraft systems, it stands alone among existing hardware in approaching the design goals of a redundant system. For shuttle, therefore, it can be used for testing until other laboratory systems are on-line, and thus permit actual laboratory experience before final software flight requirements must be attained.

6. SUMMARY OF PROGRAM ACCOMPLISHMENTS

The redundant gimballed inertial system designed and delivered by CSDL required significant advances in inertial technology. Contributions to the art appear at all levels.

The design philosophy in this program emphasizes redundant rather than simply multiple IMUs. That is, the system is designed to permit autonomous collaborative fault detection and identification, and fault correction through reconfiguration. This system is, in this light, the first practical redundant gimballed IMU system. It represents an extension of technology previously used only in redundant strapdown sensor systems.

This program's effects are felt in two ways. First, this work has consistently paced and influenced the evolving space shuttle vehicle GN&C baseline design. Second, the hardware and software produced have pointed toward the next generation aircraft inertial navigation equipment.

With respect to the shuttle baseline, this program has provided a continually maturing test bed in implementing the required capabilities in FDI and redundancy management. Algorithms have been considered and simulated primarily with a view of establishing applicability for the shuttle. Hardware development toward this system has also influenced the evolving baseline.

Demonstration has been made of a practial redundant gimballed IMU system. Use of off-the-shelf aircraft IMUs controlled by a single flight computer using a simple data bus is shown to be an attainable step for aircraft inertial systems, increasing both their reliability and applicability for digital fly-by-wire aircraft control systems usage.

In summary, the program reported here has played a germinal role in both the space shuttle program and in possible advanced avionics studies.

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