THIRTEENTH EUROPEAN ROTORCRAFT FORUM

5.6.

Paper No. 57

Aircraft Motion Sensor Integrity
for
Helicopter Automatic Flight Control

by

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September 8 ÷ 11, 1987

ARLES, Bouches du Rhône

FRANCE

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1. Summary

Stability and Autopilot augmentation signals provided by strap down inertial reference units can be configured in different ways to achieve the required integrity levels. Integrity is understood as the statistical measure of the availability of good aircraft motion data for flight control and autopilot purposes including the probability of the ability to differentiate between good and failed data[1].

The paper discusses parallel and skewed axis configuration integrity levels to be achieved with a system architecture consisting out of two strap down inertial reference units, one doppler velocity sensor, one magnetometer, one radar altimeter and an analytical TAS determination for the entire speed regime of a helicopter. The inertial instruments are two degree of freedom gyroscopes and single axis forced rebalanced accelerometers.

2. Introduction

The purpose of Automatic Flight Control Systems (AFCS) and Autopilot is mainly to assist the pilot by reducing the workload, improving the handling qualities and in the case of Control Configured Vehicles (CCV) providing the necessary stability to fly the aircraft at all. The pilot must fully rely upon the AFCS and the Autopilot and therefore the required level of integrity is based upon the mission requirements and the fact whether the aircraft can be flown manually or not[2].

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[1] singularities with significant probabilities of occurrence are to be taken into account as well

[2] a failure in the most critical pitch loop will lead to the loss of the aircraft

The paper given is mainly restricted to helicopter flight control requirements. Although the helicopter has very little aerodynamic damping in the low speed regime most of the existing rotorcrafts are not equipped with AFCS's and Autopilots.

Modern military helicopter however require AFCS's and Autopilots in order to allow the pilots to fulfil their primary military tasks in a hostile environment.

As the safety critical levels for AFCS and Autopilot signals are different the respective integrity level requirements are different whith the AFCS level being more critical than the Autopilot one.

The aircraft motion signals required for stability augmentation are as follows:

- ⊙ body roll rate p
- ⊙ body pitch rate q
- ⊙ body yaw rate r
- ⊙ pitch attitude rate

One of the advantages of the strap down technique is the direct measurement of the body angular rates. The pitch attitude rate will be required to improve pitch stability during manoevres as e.g. quick acceleration and deceleration. This parameter is achieved by proper transformation of the directly measured body related values[3]. In some cases the attitude angles are used for stability augmentation to achieve long term stability.

The automatic steering algorithm[4] which allows automatic steering to prestored way points can easily be processed in the sd-inertial reference unit. The flight control system will then receive the following signals:

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[3] attitude rates derived from vertical gyroscopes are calculated by differentiation and thus requiring appropriate filtering for noise reduction do not represent the same signal quality as attitude rates delivered from strap down inertial reference units particulary under dynamic conditions as e.g. a quick stop or similar

[4] the derivation of this new steering algorithm was supported by the german military procuring agency BWB and has been validated using the flight test data collected during company sponsored flight tests

- commanded body roll rate p_c
- commanded body pitch rate q_c
- commanded body yaw rate r_c
- commanded height profile

The commanded body angular rate/time profiles are calculated using parameters only as e.g. desired new heading ψ_{des} and lead angle derived from wind and groundspeed components which are already available in the navigation subsystem.

The automatic hover mode is supported by the following signals:

- radar altitude
- inertial altitude
- doppler vertical velocity
- inertial vertical velocity
- groundspeed components
- true airspeed components
- linear body acceleration components

The transition phases e.g. for SAR purposes can be composed out of the auto-steering and the auto-hover modes using all the data available for these modes.

One of the most critical situations one can have with safety critical systems and/or signals is a single point failure.

With commonly used doppler velocity sensors this situation occurs depending on the nature of the terrain flown over[5]. With decreasing signal to noise ratios on the calibrated beams the tracker will start searching for beams at higher incident angles and such provide large velocity errors.

As this is not an equipment failure but an insufficiency of the ground velocity determination principle[6] it can not be solved by

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[5] e.g. calm sea or desert

[6] the same problem occurs for back up navigation as well

simple redundancy.

At first one must be able to detect this false lock on with almost 100 % probability and secondly velocity components must be substituted by synergistic means.

3. Conventional Systems

These systems are mostly based on FAR 27/FAR 29 IFR requirements and therefore contain two vertical and two directional gyroscopes, with one DG slaved to a flux valve, two vertical accelerometers and a doppler velocity sensor at a minimum. The necessary parameters for stability augmentation and autopilot purposes[7] are then derived from the euler angles θ, ϕ and ψ.

It is quite obvious that a system with only two each of the safety critical parameters does not allow a proper judgement whether the equipments are working as specified or not.

In order to enhance the situation one might add a package of three rate gyroscopes. Figure 3-1 depicts such a system

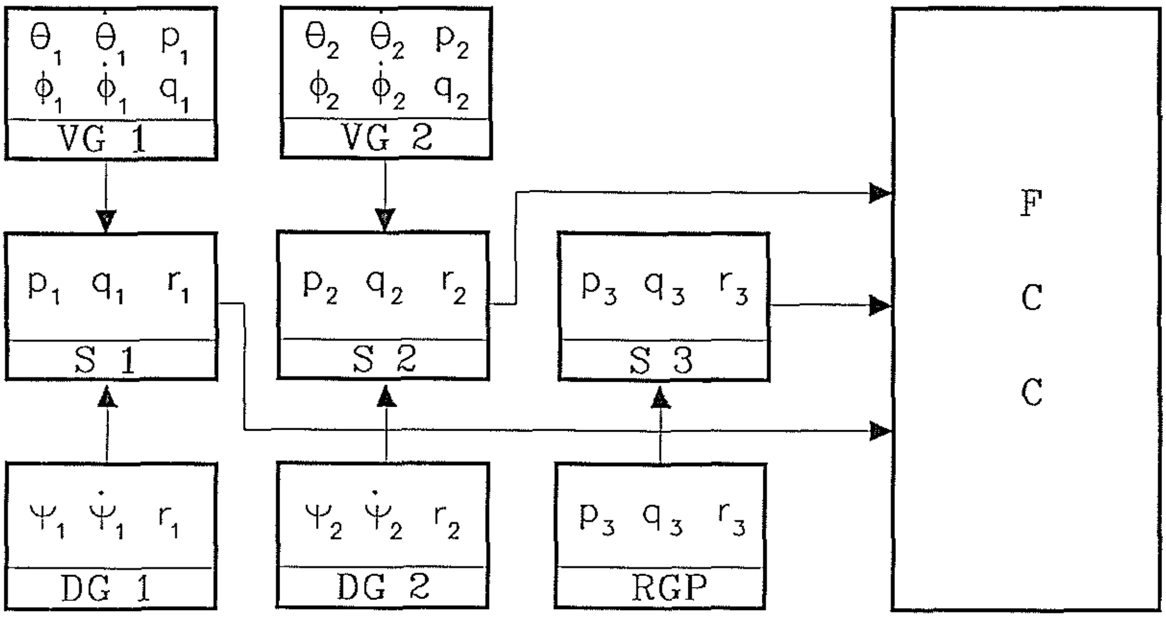

Figure 3-1 Conventional System

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[7] euler and body angular rates

Assuming to be able to perform a majority voting whenever n independent values of a critical parameter are available one can execute $\left\{\begin{matrix} n \\ 2 \end{matrix}\right\}$ difference equations allowing the isolation of n - 2 faulty signals with n = 3. Without extra BIT a detection and isolation of more than n - 2 faulty signals is impossible with this kind of system approach.

The stability augmentation parameters provided are

$$
\begin{array}{lcccc}
VG_1 & = & \begin{matrix} \theta_1 & \dot{\theta}_1 & p_1 \\ \phi_1 & \dot{\phi}_1 & q_1 \end{matrix} \\
VG_2 & = & \begin{matrix} \theta_2 & \dot{\theta}_2 & p_2 \\ \phi_2 & \dot{\phi}_2 & q_2 \end{matrix} \\
DG_1 & = & \begin{matrix} \psi_1 & \dot{\psi}_1 & r_1 \end{matrix} \\
DG_2 & = & \begin{matrix} \psi_2 & \dot{\psi}_2 & r_2 \end{matrix} \\
RGP & = & \begin{matrix} p_3 & q_3 & r_3 \end{matrix}
\end{array}
$$

Grouping the appropriate parameters into three sets the following cases are obvious[8]

case 1: all three parameter sets are within the range limited by the acceptable tolerance level $\pm\varepsilon_a$

case 2: two of the three parameter sets are within the limits of $\pm\varepsilon_a$, one is outside

case 3: one of the three parameter sets is within the limits of $\pm\varepsilon_a$, two are outside

case 4: one of the three parameter sets is within the limits of $\pm\varepsilon_a$, two are outside but the difference between the individual parameters of these two sets is $\leqq 2|\varepsilon_a|$

The cases 3 and 4 represent the critical situation of total loss of integrity of the stability augmentation parameters.

Analysing the architecture of fig. 3-1 furthermore one gets:

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[8] it is assumed that the three sets of parameters do have almost identical behaviour under static and dynamic flight conditions

⊙ the two vertical and the two directional gyroscopes are to be considered equivalent under all flight conditions

their outputs and their derivations and transformations can be used for comparison purposes in a voting scheme without difficulties

⊙ the outputs of the rate gyroscopes represent the appropriate body angular rates

the dynamic behaviour of these rate outputs is different from the 'equivalent' parameters computed from the euler angles by differentiation and transformation[9]

From the above it is obvious that the conventional simple scheme is not very well suited for automatic monitoring of system integrity. Due to the limited bandwith of conventional cockpit instruments however it provides enough information to the crew members to draw the necessary conclusions.

Simultaneously this concept does not provide very much synergistic capacity which in turn could be used to enhance system performance.

4. Two Strapdown IRU System

Strap down Inertial Reference Units are very well suited to provide AFCS and Navigation data simultaneously as they measure directly the aircraft motion in the body frame coordinate system. Furthermore a large increase in system reliability was achieved when strap down IRU's were first put in service[10].

Applying strap down technology to helicopter flight control allows the instantaneous use of directly measured motion parameters in combination with accurate attitude and navigation data at low weight and very high reliability. Simultaneously the motion parameters are available for fire control purposes as well.

Strapdown IRU's suited to meet the navigational requirement of

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[9] without noise and acceleration dependent errors one yields

$$p = \dot{\phi} - \dot{\psi} \sin\theta$$

$$q = \dot{\theta} \cos\phi + \dot{\psi} \cos\theta \sin\phi$$

$$r = - \dot{\theta} \sin\phi + \dot{\psi} \cos\theta \cos\phi$$

[10] the ARINC 705 Strapdown AHRS LTR-81 has already demonstrated more than 10000 h MTBF within more than 500000 equipment flying hours

modern combat and transport helicopters can be built using either Dry Tuned or Ring Laser or Fiber Optic Gyroscopes. Within this group of applicable gyro technology the DTG (Dry Tuned Gyroscope) is the only TDF (Two Degree of Freedom) one.

Two IRU's per ship set with two DTG's each can be arranged in different configurations e.g a parallel or a skewed gyroscope measuring axis configuration one.

4.1. Parallel Axis Configuration

In a parallel axis configuration one gets eight axis to measure aircraft angular rates[11]. This hardware configuration allows therefore triplex redundancy for two aircraft axis and dual redundancy for the remaining third axis with respect . to the angular rates required for stability augmentation.

Possible parallel axis configurations are shown in figure 4-1 and 4-2[12].

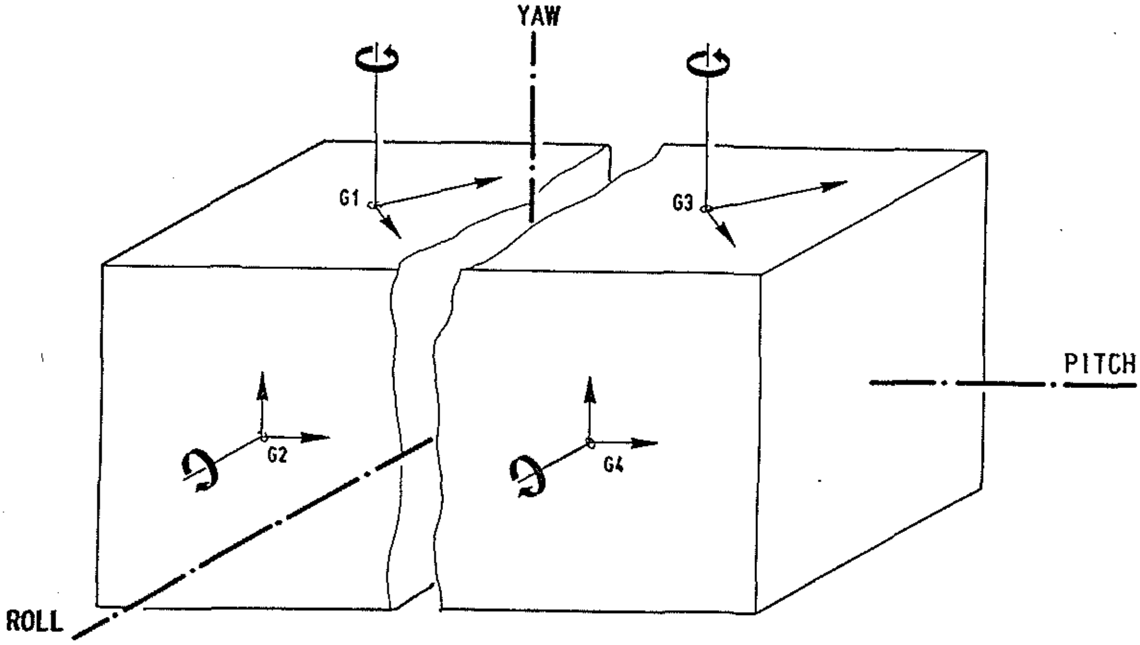

Figure 4-1 Parallel Axis Configuration I

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[11] with the other single degree of freedom inertial instruments only three axis per system can be achieved and thus only dual redundancy is possible in a parallel axis configuration.

[12] assuming perpendicularity between the gyro spin axis of each IRU

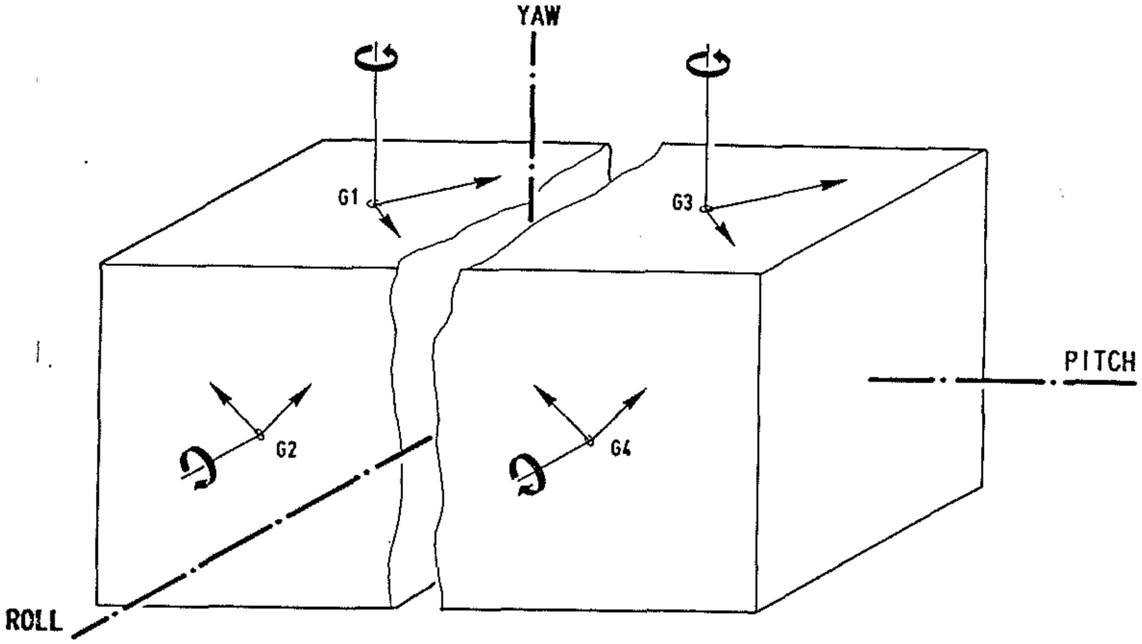

Figure 4-2 Parallel Axis Configuration II

The two parallel axis configurations shown are organized to be realized utilizing two identical SD-IRU's[13] and appropriate connector pin programming[14] thus giving the rotorcraft manufacturer maximum installation flexibility in the avionic suite. The two boxes can be spaced to reduce the vulnerability without degrading the accuracy. The noise generated by rotorcraft vibration and bending may influence the voter-monitor architecture implemented in the Flight Control Computer (FCC). The customer enjoys minimum acquisition, logistic and life cycle expenditure.

The only deficiency of this design using totally four DTG's is the lack of one gyro axis to achieve a full three axis triplex redundant configuration. It is our opinion that this is not a severe disadvantage but if required artificial redundancy could be added for the remaining third axis[15].

The two SD-IRU Parallel Axis Diagram of figure 4-3 depicts the signals generated in each of the two SD-IRU's to be delivered to the FCC.

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[13] same part number

[14] LITEF patent application

[15] based on the data collected during more than 100 h of flight test developing the LITEF analytical air data system for helicopters (LAASH)

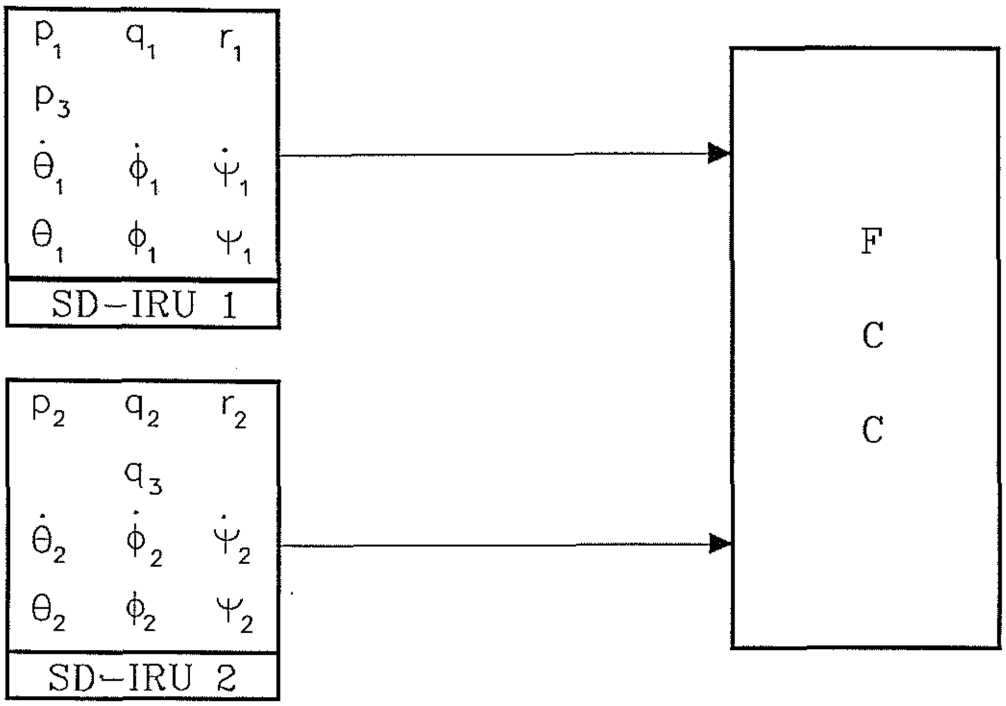

Figure 4-3 Two SD-IRU Parallel Axis Diagram

In the parallel axis configuration consisting out of two SD-IRU's one does not have to compare signals of different dynamic behavior as in the case of conventional systems e.g the one described in chapter 3. Therefore the voting limits can be adjusted in accordance with the unavoidable noise and the tolerable signal tolerances only.

Simultaneously the SD-IRU's provide directly measured angular rates in the body frame coordinates thus reducing data latency compared with conventional system architectures.

In addition strap down system have demonstrated much higher reliability than conventional systems and an advanced system concept based on two SD-IRU's provides full duplex navigation capability.

In order to calculate the availability of flight critical signals one has to consider component failures as well as dormant failures.

Dormant failures are all failures which can not be detected during preflight and/or inflight BIT but by means of an acceptance test (AT). The dormant failure rate is λ_{dorm} and Δt_{AT} the time between subsequent acceptance tests.

The integrity achieved without dormant failure modes is the architectural integrity with the architectural failure rate λ_{arch}.

The critical events which would lead to loss of integrity of the angular rate outputs (p and q) are as follows:

1. 2 out of 3 appropriate gyro axis fail
2. 1 out of 3 appropriate gyro axis fail and a singularity occurs
3. 2 out of 3 appropriate channels fail[16]

First one has to quantify the probability of the occurrence of a singularity, assuming 1 of 3 gyros has failed. In order to do this one must assume that all failure levels, $\pm\varepsilon_a$, are equally probable and a certain voter-monitor function is implemented in the FCC. With reference to figure 4-4 it is seen that the probability of the occurrence of a singularity is one out of three.

$$p_s = \frac{1}{3}$$

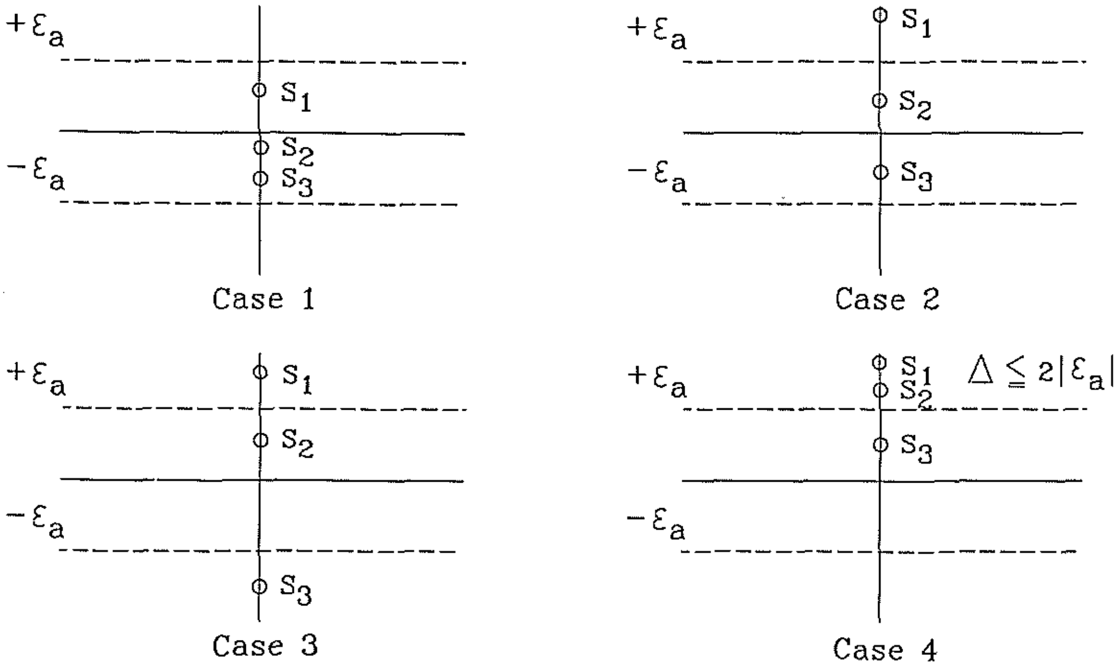

Figure 4-4 Three Independent Parameters

In order to calculate the reliability we use

$$R_T = 1 - Q^n \text{ with } n = 3$$

The effective failure rate yields

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[16] a channel is defined as all functions needed to provide angular rate outputs except for the gyro and its electronics

$$\lambda_{eff} = \lambda_{arch} + \lambda_{dorm} \frac{\Delta t_{AT}}{t}$$

with t being the mission time.

4.2. Skewed Axis Configuration

Strapdown technology utilizes amongst others gyroscopes which senses the vehicle angular motion in the body frame coordinates. In order to do this it is sufficient to have at least three angular rate sensing devices with their sensing axis distributed spatially such that neither two or three sensing axis are in parallel. The only reason to have the sensing axis orthogonal to each other is the great simplification and sometimes the omission of transformation algorithmen.

If one would like to have two independent SD-IRU's to navigate one needs collectively four DTG's or six single degree of freedom gyroscopes[17].

As already mentioned before the four gyros could be arranged such that the measuring axis are skewed against each other. With four gyros an obvious configuration is shown in figure 4-5.

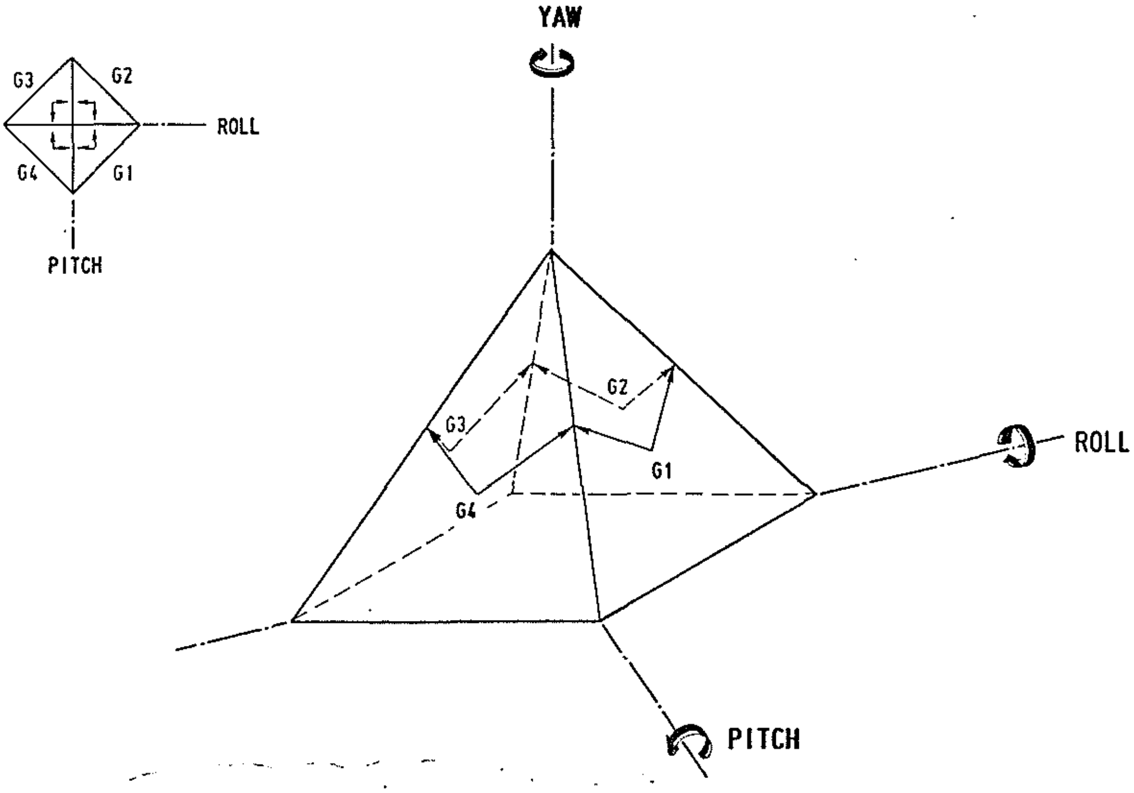

Figure 4-5 Skewed Axis Configuration

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[17] e.g. ring laser (RLG) or fiber optic gyros (FOG)

Fore the sake of more and better visibility and understanding figure 4-6 depicts the unfolded skewed axis configuration.

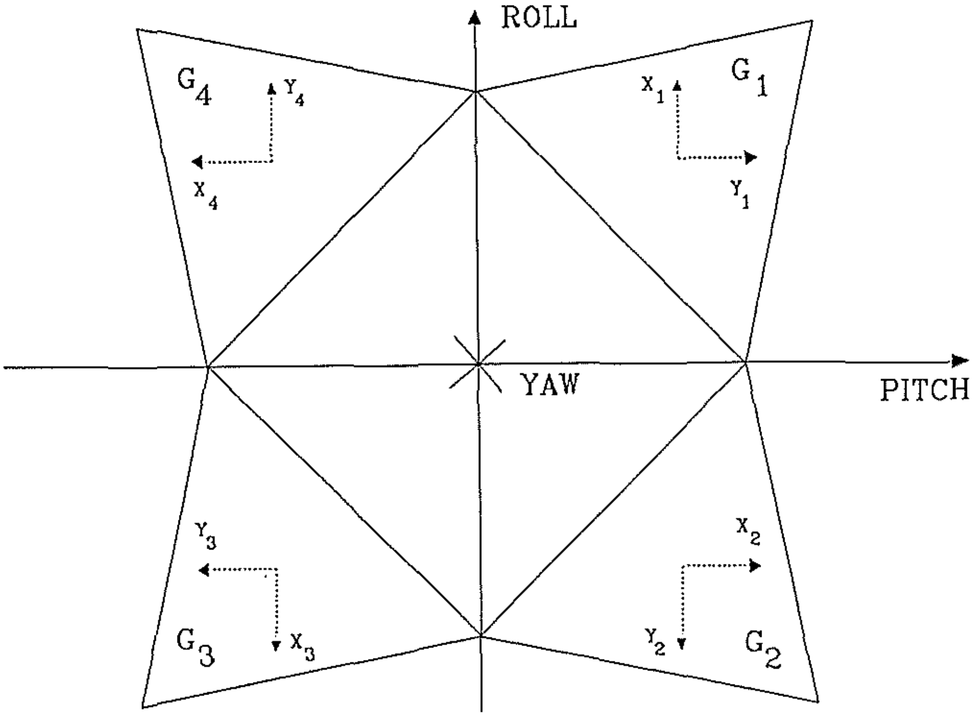

Figure 4-6 Skewed Axis Configuration Unfolded

The configuration described can be split along the roll or the pitch axis into two halves to be housed in two identical boxes with appropriate connector pin programming enjoying the same advantages as mentioned before discussing the parallel axis configurations.

Transforming the gyro axis into the principle rotorcraft axis (roll, pitch and yaw) one can see that there is a contribution of p, q and r in every gyro axis[18] thus providing a higher integrity level than any parallel axis configuration utilizing the same number of DTG's.

Each one of the two boxes senses sufficient aircraft motion information to function as an independent SD-IRU with respect to navigation.

As the skewed axis configuration shown does not have the disadvantage of the parallel axis configuration to provide triplex redundancy for two principle aircraft axis only the skewed axis configuration is superior to the parallel axis configuration with respect to flight critical angular rate information using the

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[18] no gyro spin axis is pointing along one of the principle rotorcraft axis

same number of gyros.

4.3. Comparison of System Architectures

The three architectures described in this paper are compared and the main features are summarized.

The relevant architectures are:

- ⊙ Conventional Systems
- ⊙ Two SD-IRU's Parallel Axis Configuration
- ⊙ Two SD-IRU's Skewed Axis Configuration

4.3.1. Conventional Systems

Combining two vertical and two directional gyros with a three axis rate gyro package one yields:

- ⊙ Three independent rate information per principle aircraft axis
- ⊙ Only one of the three sets of signals provided contains body rates directly measured
- ⊙ Two of the three sets of signals contain body rates derived from attitude angles by differentiation, filtering and transformation thus introducing additional data latency
- ⊙ In combination with a doppler radar and a magnetic sensing device duplex navigation capability can be mechanized but the achievable navigation performance does not comply with the requirements of modern combat and transport helicopters

If one would replace one set of vertical and directional gyros by an SD-IRU one would get:

- ⊙ Three independent rate information per principle aircraft axis
- ⊙ Two of the three sets of signals provided contains body rates directly measured

- One of the three sets of signals contain body rates derived from attitude angles by differentiation, filtering and transformation thus introducing additional data latency

- Together with a doppler radar and a magnetic sensing device only simplex navigation performance in accordance with the requirements of modern combat and transport helicopter is available

In both cases the three available rate signals are of different dynamic behaviour thus requiring either a larger voter-monitor tolerance band than it would be required if all rate signals would have the data latency of the rate gyro package or if the tolerance band would be appropriate to the rate gyro package there would be no longer triplex redundancy under dynamic conditions.

4.3.2. Two SD-IRU's Parallel Axis Configuration

In this configuration one yields:

- Three independent rate information for two principle aircraft axis (e.g. p and q)

- Two independent rate information for the remaining aircraft axis

- All rate signals are directly measured in the body frame coordinate system and thus of the same data latency

- The voter-monitor tolerance band can be optimally designed even for high dynamic conditions

- Together with a doppler radar and a magnetic sensing device duplex navigation performance in accordance with the requirements of modern combat and transport helicopter is available

4.3.3. Two SD-IRU's Skewed Axis Configuration

In this configuration utilizing four TDF gyros one yields:

- Isolation of two faulty gyros with the additional detection of one

- Together with a doppler radar and a magnetic sensing device duplex navigation performance in accordance with the requirements of modern combat and transport helicopter is available

4.3.4.

Table 4-1 provides an overview of the different features of the system architectures described.

Architecture => Function ⇓	Conventional System (1 SD-IRU + 1 DG + 1 VG + 1 RGP)	Two SD-IRU Parallel	Two SD-IRU Skewed
Detection	detection only dynamically limited	detection only	detection of 1 gyro
Isolation	none	none	isolation of 2 gyros
Navigation (Performance suited for modern military helicopters)	simplex	duplex	duplex

Table 4-1 System Architecture Comparison

Bearing in mind that weight is a very important factor for helicopters it is possible to enjoy the enhanced integrity of parallel or skewed axis SD-IRU[19] system architectures without trading weight versus integrity.

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[19] utilizing TDF gyroscopes

5. Concluding Remarks

The comparison of the different system architectures described yields:

- ⊙ Utilizing strap down technology does enhance system integrity for flight safety critical parameters and provides simultaneously the navigation accuracy required for modern combat and transport helicopters
- ⊙ The increase of system integrity and navigation accuracy can be achieved without trading integrity and navigation accuracy versus weight
- ⊙ It should be mentioned further that SD-Technology has already demonstrated an unexpected tremendous progress in reliability enhancement