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INTEGRATION OF INERTIAL SENSORS IN HELICOPTERS

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ABSTRACT

The demand for saving weight, volume and especially cost requires new design concepts for avionic systems. In future, highly integrated systems will replace the conventional systems with specific "stand-alone" equipment for each system function.

The paper presents a concept for the integration of "inertial functions" - flight control, sight-stabilization, navigation - of a helicopter. A configuration with a minimum number of dislocated inertial sensors is proposed. The system functions are accomplished on system level by integration and multiple use of the sensor signals. It will be proven that the navigation functions, attitude and heading can be derived from the flight control and stabilization hardware so that the usually required separate attitude and heading reference system for the navigation is saved. Moreover, the proposed concept provides as an additional function the autonomous initial alignment to north.

INTRODUCTION

The interest in cost-effective solutions for civil and military avionic systems increases more and more.

One step in this direction is the integration of avionic equipment for different functions of the system /1/, /2/. In modern avionic systems this is possible on the base of fast data transfer and computer systems. This paper especially deals with the "inertial functions" (functions which depend on inertial sensors) of helicopters.

In conventional avionic systems the different "inertial functions" are implemented in specific or "stand-alone" equipment. In the example of Fig. 1, the flight control subsystem consists of two sensor-units, a sensor-electronic, a computer and a control/display unit. The other "inertial functions": sight-stabilization and navigation are based on specific hardware, too.

FUNCTIONS	HARDWARE: SENSORS		HARDWARE: SENSOR-ELECTRONICS		HARDWARE: COMPUTERS	HARDWARE: CONTROL/DISPLAY
FLIGHT CONTROL	S_{11}	S_{12}	E_1		C_1	C/D_1
SIGHT STABILIZATION	S_2		E_2			C/D_2
OPTRONIC STABILIZATION	S_{31}		E_3		C_3	C/D_3
NAVIGATION	S_{41}	S_{42}	E_{41}	E_{42}	C_4	C/D_4

Figure 1 Conventional Realization of "Inertial" Functions: Specific Equipment for each Function (schematic).

On the contrary, Figure 2 shows an example, where the individual components are integrated and contribute to several "inertial functions". The navigation, for instance, requires no specific hardware. Over all a remarkable saving of hardware compared to Fig. 1 is noticed.

	HARDWARE								
	SENSORS			SENSOR-ELECTRONICS			COMPUTERS		CONTROL DISPLAY
FUNCTIONS	S_1	S_2	S_3	E_1	E_2	E_3	C_1	C_2	C/D
FLIGHT CONTROL	X			X			X		X
SIGHT STABILIZATION		X			X			X	X
OPTRONICS STABILIZAT.			X			X		X	X
NAVIGATION	X	X	X	X	X	X	X		X

Fig. 2 Future Realization of "Inertial Functions on System-Level by Integration of Sensors and Electronics (schematic).

The different functions in this concept are obtained on system level. Very important in this case is the question which sensor has to be installed where in the aircraft and what sensor-performance is required.

In the subsequent paragraphs a concept for flight control, stabilization and navigation of helicopters is proposed which is based on the described principle.

INERTIAL SENSORS AND SENSOR-CONFIGURATIONS IN HELICOPTERS

The avionic system of modern helicopters, particularly for military applications, has the following "inertial functions":

- Automatic flight control (necessary for low-level and nap of the earth flights as well as hover manoeuvres)
- Navigation (attitude and heading-reference for Doppler navigation)
- Stabilization (sight-, optronics-, weapon-stabilization).

The function "Stabilization" is represented by a stabilized two-axis (azimuth and elevation) platform for optronic sight stabilization.

Realization of these functions is possible by a multitude sensor-configuration. Three different but characteristic sensor-configurations among these are compared in Fig. 3 and 4. It should be mentioned that redundancy problems are not included in the following investigations.

The conventional Configuration 1 (Fig. 3) with "stand-alone" equipment for flight control, navigation and stabilization utilizes conventional rate or rate-integrating gyros. A vertical and a directional gyro determine attitude and heading. Three single axis accelerometers are applied for the flight control. Two resolvers measure the platform angles.

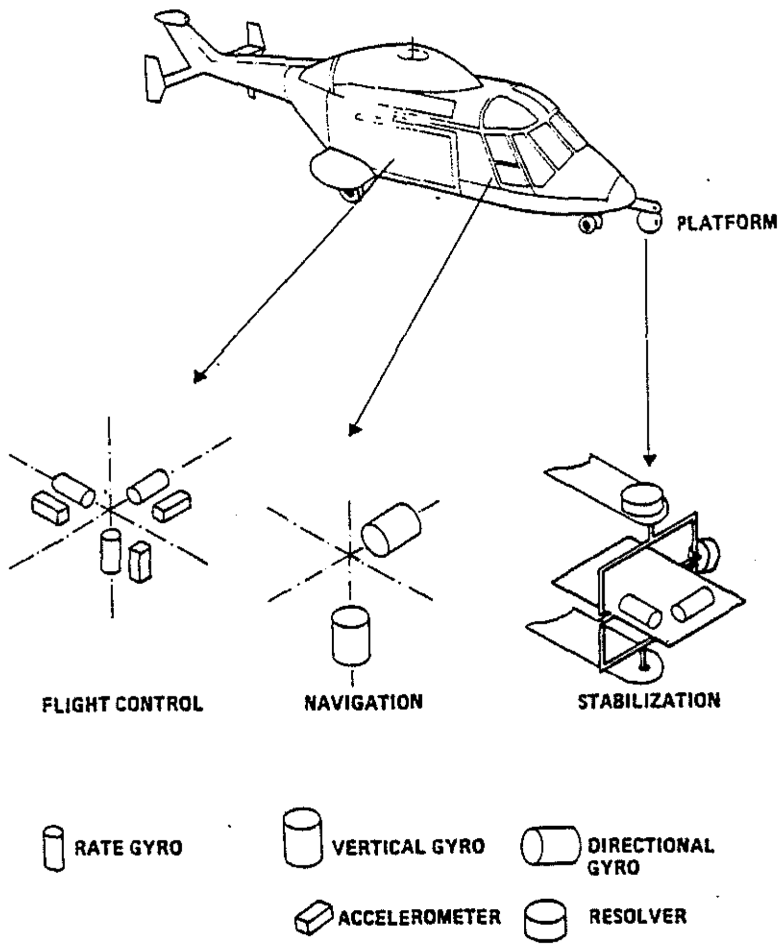

Fig. 3 Conventional Configuration of Inertial Sensors in Helicopters (Configuration 1).

Configuration 2 is a modern solution, shown in Fig. 4. Flight control and navigation are realized by one strapdown sensor-unit which consists of two two-axis dry-tuned-gyros (DTG) and three single-axis accelerometers. According to standardization requirements the stabilization gyro of the platform is also a two-axis DTG of the same type. The resolvers correspond to configuration 1.

Configuration 3 is a new proposal with a minimum number of inertial sensors. Only the stabilization is a "stand-alone" function. Flight control and navigation are the result of the integration of all available sensors. The sensors correspond to those of Configuration 2 except the x-z-gyro of the strap-down system, which is omitted and the x- and y- accelerometers which are mounted on the outer platform gimbal. The latter is required for initial alignment to true north (see below).

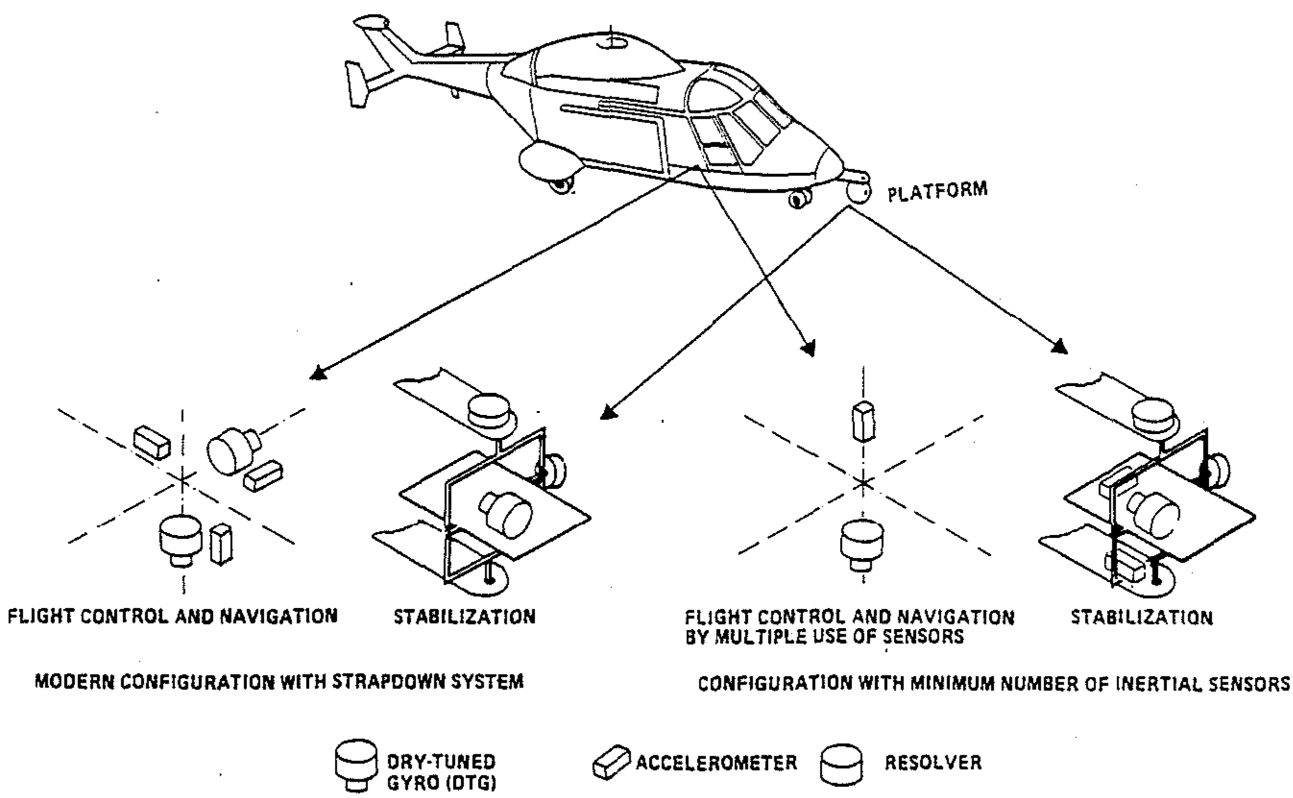

Fig. 4 Configuration of Inertial Sensors in a Helicopter.

Table 1 gives a summary of the required sensors for the three configurations. The number of sensor axes, which is approximately proportional to cost, decreases noticeably from configuration one to three.

FUNCTION	CONFIGURATIONS		
	1 (CONVENTIONAL)	2 (STRAPDOWN SYSTEM)	3 MINIMUM NUMBER OF SENSORS
FLIGHT CONTROL	3 SINGLE-AXIS GYROS (RATE/RATE-INTEGRATING, 15–30°/h DRIFT) 3 SINGLE-AXIS ACCELEROMETERS	2 TWO-AXIS DRY-TUNED-STRAPDOWN GYROS (1°/h DRIFT) 3 SINGLE-AXIS ACCELEROMETERS	1 TWO-AXIS DRY-TUNED STRAPDOWN GYROS (1°/h DRIFT) 3 SINGLE-AXIS ACCELEROMETERS
STABILIZATION	2 SINGLE-AXIS GYROS (RATE/RATE-INTEGRATING, 15–30°/h DRIFT)	2 SINGLE-AXIS GYROS (RATE/RATE-INTEGRATING, 15–30°/h DRIFT)	1 TWO-AXIS DRY-TUNED STRAPDOWN GYRO (1°/h DRIFT)
NAVIGATION	2 TWO-AXIS ATTITUDE GYROS (SLAVED TO VERTICAL AND MAG. NORTH)	————	————
NUMBER OF MEASUREMENT AXES	9 (GYROS) 3 (ACCELEROMETERS)	6 (GYROS) 3 (ACCELEROMETERS)	4 (GYROS) 3 (ACCELEROMETERS)

Table 1 Inertial Sensors for the Different Configurations.

The first and second configuration have been mechanized and tested extensively with the expected results. The following investigation is therefore concentrating on the highly integrated third concept. The theoretical proof that this configuration fulfills the requirements too is now given in the following sections.

ATTITUDE AND HEADING REFERENCE

The functions of Table 1 require sensor signals and data, which are listed in Table 2. The appropriate reference systems are defined in Figure 5.

FUNCTION	MEASUREMENTS		
	BODY FIXED ANGULAR RATES	ANGLES	ACCELERATIONS
FLIGHT CONTROL	p_H, q_H, r_H	(ψ, θ, ϕ)	a_x, a_y, a_z
STABILIZATION	q_p, r_p	α, δ	
NAVIGATION		ψ, θ, ϕ	

Table 2 Required Measurements for "Inertial" Functions

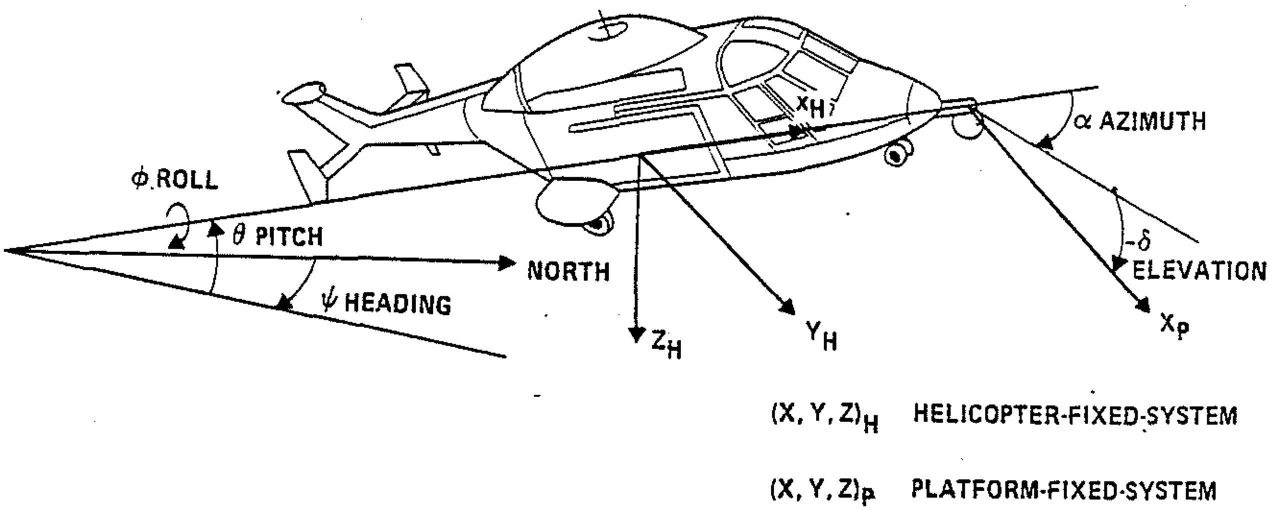

Figure 5 Definition of Reference Systems.

In configuration 3 only the values p_H, q_H, q_p, r_p, α, δ and a_z of Table 2 are available directly from sensor signals. The rest, especially attitude θ, ϕ and heading ψ have to be determined by integration of sensor signals (r_H, a_x and a_y are evaluated within this procedure).

The evaluation of the attitude and heading is carried out in the three computational steps, shown in the block-diagram, Fig. 6 (C1 - C3).

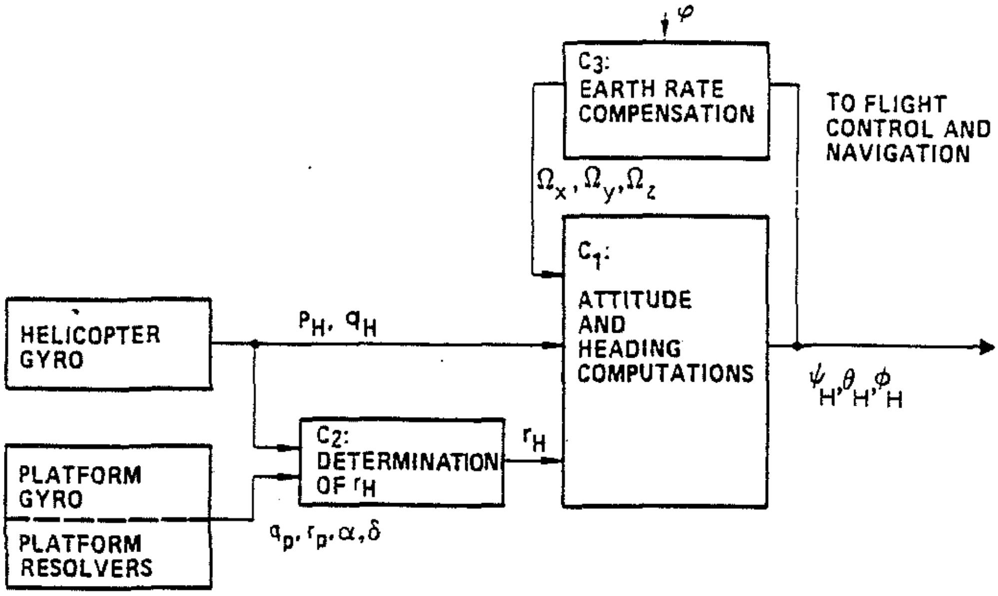

Fig. 6 Determination of Attitude and Heading from the Sensor Signals.

C1: For the attitude and heading computation a relatively simple strapdown algorithm was selected /3/. Other algorithms (for instance quaternions) would be applicable too.

The differential equation (1) shows the dependence of ϕ_H, θ_H, ψ_H on the rate measurements p_H, q_H, r_H and the earth rate in the helicopter system. The transportation rate is neglected.

$$\begin{bmatrix} \dot\phi \\ \dot\theta \\ \dot\psi \end{bmatrix}_H = \frac{1}{c\theta_H} \begin{bmatrix} c\theta & s\theta s\Phi & s\theta c\Phi \\ o & c\theta c\Phi & -c\theta s\Phi \\ o & s\Phi & c\Phi \end{bmatrix}_H \cdot \begin{bmatrix} p - \Omega_x \\ q - \Omega_y \\ r - \Omega_z \end{bmatrix}_H \tag{1}$$

c : cos
s : sin
$\Omega_x, \Omega_y, \Omega_z$, Earth rate components φ:Geographic latitude

C2: In Eq. (1) p_H and q_H are direct measurements of the helicopter gyro whereas r_H has to be determined in a second computational step. The relation between helicopter and platform rates leads to Eq. (2), where the unknown rate r_H is a function of other helicopter and platform measurements.

$$r_H = \frac{1}{c\delta} \left[r_P - c\delta\dot\alpha - s\delta c\alpha\, p_H - s\delta s\alpha q_H \right] \tag{2}$$

C3: The third step is the computation of the earth rate compensation, Eq. (3), which is a function of ϕ_H, θ_H, ψ_H and the geographic latitude .

$$\begin{bmatrix} \Omega_x \\ \Omega_y \\ \Omega_z \end{bmatrix}_H = \left[\phi\right]\left[\theta\right]\left[\psi\right]_H \cdot \begin{bmatrix} \Omega c\varphi \\ o \\ -\Omega s\varphi \end{bmatrix} \tag{3}$$

$[\psi]$ is the abbreviation of the direction cosine matrix of angle ψ /3/.

Attitude and heading of the helicopter are determined by equations (1) to (3), however, initial conditions are not yet considered. To fill this gap, the problem of initial alignment to vertical and north has to be solved.

ALIGNMENT AND AIDING OF THE ATTITUDE AND HEADING REFERENCE

The subject of this section is again configuration 3. For the first two configurations alignment and aiding are well-known procedures. Aiding in principle is a continuous alignment with reduced time constants to eliminate the effects of gyro drift and other disturbances.

In particular the following steps are treated:

- Vertical alignment and aiding
- Alignment and aiding to magnetic north
- Autonomous initial alignment

Vertical Alignment and Aiding

For the flight control the accelerations a_{xH} and a_{yH} in the helicopter system are required. The transformation of the platform accelerometer measurements a_{xp} and a_{yp} into a_{xH} and a_{yH} is given by Eq. (4):

$$\begin{bmatrix} a_x \\ a_y \end{bmatrix}_H = \begin{bmatrix} c\alpha & -s\alpha \\ s\alpha & c\alpha \end{bmatrix} \begin{bmatrix} a_x \\ a_y \end{bmatrix}_P \tag{4}$$

During unaccelerated flight and on the ground the following relations between the accelerometer measurements a_{xp}, a_{yp}, a_{zH}, the gravity g and the attitude ϕ'_H, θ'_H for vertical alignment and aiding is valid:

$$\Theta'_H = \arcsin\left[\frac{a_{xP} \cdot c\alpha - a_{yP} \cdot s\alpha}{g}\right]$$

$$\phi'_H = \arctan\left[\frac{a_{xP} \cdot s\alpha + a_{yP} \cdot c\alpha}{a_{zH}}\right] \tag{5}$$

These values are filtered to eliminate vehicle accelerations and compared with attitude angles θ_H and ϕ_H (see C4 in Fig. 7). The difference is fed back to the computation step C1 where a signal to rotate the computed coordinate system is generated.

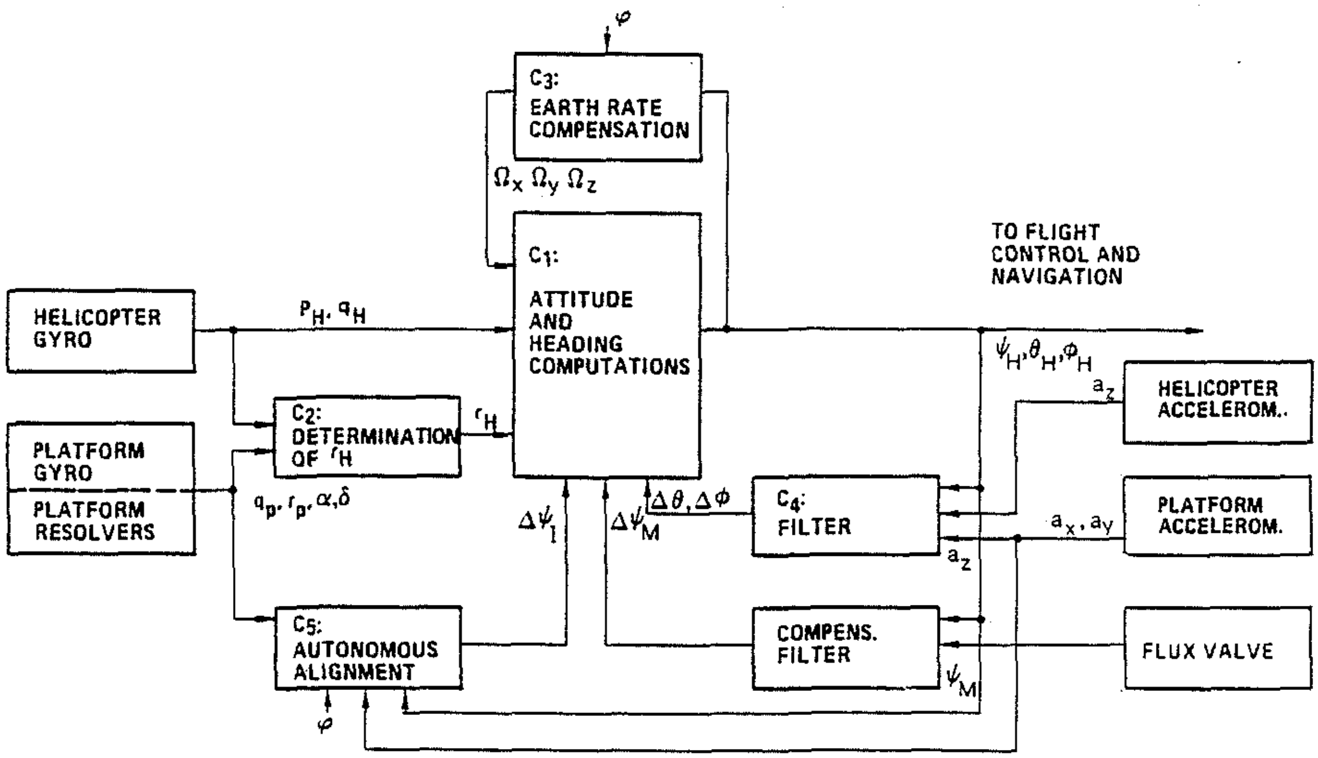

Figure 7 Alignment and Aiding of Attitude and Heading.

Alignment and Aiding to Magnetic North

For the alignment to magnetic north a Flux Valve is required. The Flux Valve signal is filtered, compensated and compared with ψ_H (Fig. 7). The difference is again fed back to C1 in order to rotate the reference system about the vertical.

The result is a magnetic heading reference with an expected accuracy of 0.5° to 1° (1σ).

Autonomous Initial Alignment

An additional benefit of the proposed configuration 3 is the feasibility of an autonomous initial alignment to true north with the required accuracy.

The selected dry-tuned-gyros of medium accuracy (1°/h, see Table 1) are sufficient for stabilization and free heading modes up to one hour. An autonomous initial alignment in the usual gyro-compass-mode however would lead to an alignment error of about 6°, which is 10 times larger than required.

The trick to get an alignment accuracy of about 0.25° to 0.5° is a measurement in two azimuth-positions of the stabilized platform, see Fig. 8. For the first measurement, the platform is roughly aligned to true north. In this position a specific gyro-compass procedure is performed to determine the offset angle ψ_p from true north (Eq. 6). Then the platform is rotated in azimuth by 180° where $_p$ is determined by another gyro-compassing procedure.

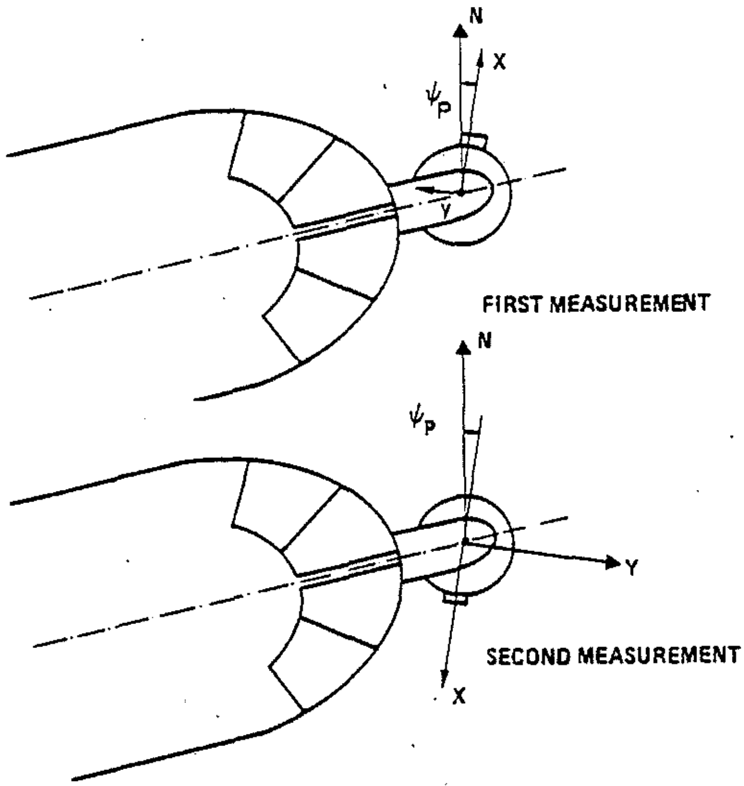

Figure 8 Autonomous Initial Alignment by Two-Position Measurement.

Both individual values of ψ_p include errors which depend on the drift of the y-axis platform-gyro, but in opposite directions. Therefore, the error is cancelled by the mean value of both measurements (Eq. 7).

$$\psi_P = \frac{1}{t_1 - t_o} \int_{t_o}^{t_1} \arcsin \left[\frac{-q_P \, c\Phi_P + r_P \, s\Phi_P + \dot{\theta}_P}{\Omega c\varphi} \right] dt$$

with:

$$\phi_P = \arctan \left[\frac{q_{yP}}{a_{zH}} \right]$$

$$\dot{\theta}_P \approx \frac{\dot{a}_{xP}}{g} \qquad (6)$$

(small θ)

To eliminate the influences of disturbances, $_p$ is determined by an integration over some minutes.

$$\bar{\psi}_P = \frac{\psi_{P(1)} + \psi_{P(2)}}{2} \qquad (7)$$

An error-investigation of this initial alignment procedure shows the following results:

- The error $d\,\psi_p$ is small, if the pre-alignment ψ_p is good.
- Errors of platform roll angle ϕ_p have no influence
- For small angles ϕ_p (up to 5°) the influence of the platform-gyro z-axis drift is tolerable else two further measurements are required.
- The critical value is the error of the pitch-rate measurement ($\dot{\theta}_p$). Changes in the pitch angle of the platform during the gyro-compassing are caused by slight movements of the helicopter. The location of the x and y-accelerometers on the stabilized platform and not in the aircraft enables the detection of these errors by the x_p-accelerometer and their compensation (Eq. 6).

The required heading ψ_{HI} of the helicopter is derived from the heading of the platform ψ_p by equation (8):

$$\psi_{HI} = \bar{\psi}_P + \arc\tan\left[\frac{s\alpha\, c\phi_H}{c\alpha\, c\theta_H + s\alpha\, s\theta_H\, s\phi_H}\right] \tag{8}$$

In the diagram, Fig. 7 , the autonomous alignment (C5) and the feedback $\Delta\psi_I = \psi_{HI} - \psi_H$ to the heading computations C1 are shown.

The autonomous alignment completes the attitude and heading reference which is now available for navigation and flight control purposes.

NAVIGATION

The usual navigation system for helicopters is a Doppler Navigator. The signals of the attitude and heading references and the Doppler are inputs to the dead reckoning computation (Fig. 9). where the position (grid-East and North) and the geographic latitude φ are determined.

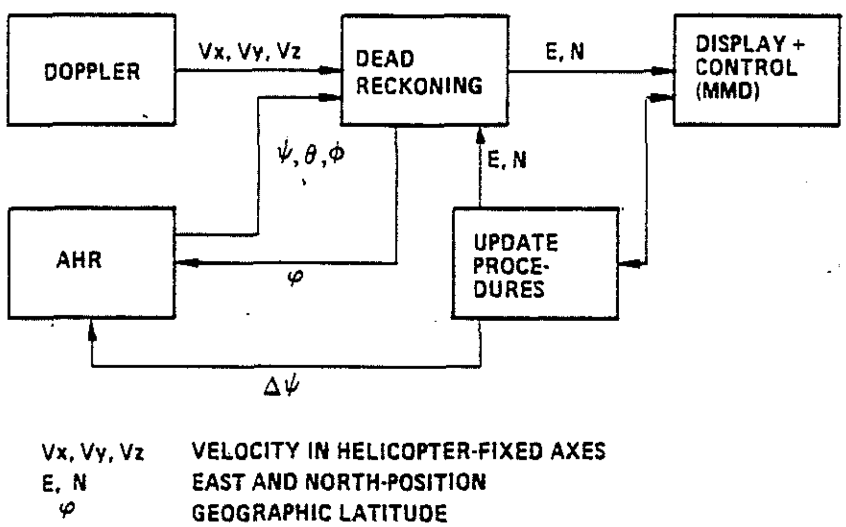

Figure 9 Navigation, Functional Diagram.

For control and display a multi-function keyboard and display or a moving/projected map display would be the best solution. The navigation system may be completed by update-procedures which correct heading and position as shown in Fig. 9.

The accuracy of the navigation depends primarily on the accuracy of the AHR and the Doppler. For a Doppler-accuracy of 0.3% of V_g (1σ) and a gyro drift rate of 1°/h (1σ) the expected accuracies for configuration 3 are listed in Table 3.

FUNCTION	ACCURACY	
	MAGNETIC HEADING REFERENCE	AUTONOMOUS ALIGNMENT AND FREE (DIRECTIONAL) HEADING
HEADING	$0.75^0 - 1^0$ (1σ)	$0.5^0 - 0.75^0$ (1σ)
POSITION	1% - 1,3% CEP	0.75% - 0,9% CEP

Table 3 Navigation Accuracy (Expected Values)

Especially in high dynamic (low level) flights where the accuracy of the flux valve decreases the free (directional) mode is advantageous.

CONCLUSION

In the preceding sections "inertial" functions of a helicopter are defined and three different realization-concepts are presented. The third concept, which requires a minimum number of sensors is investigated in detail. Two 2-axis strapdown gyros and three accelerometers are sufficient for flight control, sight-stabilization and, without additional hardware, for an attitude and heading reference. This is feasible by appropriate integration and multiple use of sensor signals.

As a special benefit of this concept a procedure for autonomous initial alignment to True North has been derived. With the medium-accuracy gyro of the stabilized platform, initial alignment is possible with a satisfactory accuracy by a two-position measurement.

In conclusion the presented concept provides more functional performance than a conventional concept with a minimum of weight, volume and cost.

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