Real Time Estimation of rigid body orientation based on inertial sensors measurements

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Abstract

This paper presents a programmable DSP board developed for real-time estimation of rigid body orientation. This work takes place in a research project carried out by students. The project consists of unmanned aerial vehicle's (UAV) attitude estimation. This estimation is processed by an Inertial Reference System (IRS) including the TMS320F2812 processor, low cost integrated Micro Electro Mechanical Systems (iMEMS) such as accelerometers and gyroscopes, temperature sensors, and magnetometers. Gyroscopes provide angular velocities that can be integrated to yield orientation. Accelerometers and magnetometers, pointing to gravity direction and north direction enables drift compensation. So the system performs a drift-free attitude estimation using quaternions for rotations representation. One benefit of this system is that it enables high integration by exploiting the processor's capacities for sensors interfacing. Moreover it takes advantage of the high performance processor to achieve a real time estimation of the body's orientation. For that digital processing includes signals filtering, measurements compensation and a lot of trigonometric functions for Euler angles computing. The system performances can be measured using a PC for results visualisation. The system has been designed to integrate in the future GPS component and pressure sensor. These components will allow more accurate attitude estimation and positioning.

1 Introduction

Supaero has been working on unmanned aerial vehicle (UAV) development for several years. UAV can be piloted by high level orders provided by guidance unit and measurements provided by navigation system. Navigation system is used for attitude and position estimation. Attitude estimation consists of accurate measurements of yaw, roll and pitch that are required for determining a reference frame. Positioning is the expression of the vehicle location in this reference frame. Such a system usually uses GPS coupled to an Inertial Reference System (IRS) [1]. IRS provides measurements with a good short term accuracy and doesn't depend on external signal. However these measurements are affected by low drift. So this system must be calibrated, using GPS measurements for example. Nevertheless, in certain environment such as urban environment, GPS measurements can be corrupted at any moments during long time period. When a low cost IRS is used auxiliary measurements are necessary to provide drift-free attitude. Especially accelerometers and magnetometers can be used to define a North, Down, East frame [2].

The aim of this project is to develop a compact drift-free IRS for attitude estimation. This low-cost onboard unit has been developed by students. It includes low cost sensors that provide measurements processed by the TMS 320F2812 DSP. System integration is described, particularly the major components and DSP. Then the estimation methodology is

presented by insisting on the main operations that affect the computing load. Finally the final product is characterised and extension is proposed allowing GPS/IRS hybridisation and so vehicle positioning.

2   System architecture

This IRS system consists of a compact unit based on the TMS320F2812 processor. This unit is designed to yield 3D measurements by integrating sensors mounted on 3 orthogonal boards. Tri-axial Gyroscope provides angular velocities around three orthogonal axis, which must be integrated to estimate orientation. To compensate orientation drift, tri-axial accelerometer and tri-axial magnetometers are implanted. These components permit to determine respectively the gravity and the north direction. Moreover measurements provided by the accelerometers could be used in the final project by the navigation algorithm. All the measurements are temperature sensitive. Compensation needs to measure the temperature with a temperature sensor. Finally the system integrates a barometric pressure sensor and a GPS component. These components are not used by the algorithm presented in this paper. In the final project they will enable attitude estimation improvement and position estimation.

2.1 Gyroscopes

Gyroscope is used to achieve angular motion measurement, providing an output signal proportional to the angular rate. A monolithic integrated circuit from Analog Devices (ADXRS300) is proposed for this system. This low cost component combines mechanical structures with signal processing circuitry. Three identical components are used for measurements around three orthogonal axis. Signals delivered by the gyroscopes are amplified and applied to the processor's ADC module. The main features of the gyroscope are given here:

- Range : ±300 °/s
- Sensitivity : 5mV/(°/s)
- Bandwidth : DC to 2 KHz
- Noise density : 0.1 (°/s)/√Hz

2.2 Accelerometers

By considering that the acceleration is small and effective for a short duration, accelerometers can be used to determine gravity direction. For this application iMEMS accelerometers from Analog Devices (ADXL202JE) are implanted. This component includes 2 accelerometers and signal processing circuitry. It provides 2 PWM signals at 1KHz, with duty cycles depending on the acceleration along 2 orthogonal axis. PWM conditioning enables direct connection to the capture unit of the processor's event manager. So this event manager is used for duty cycle measurement. The main features of the accelerometer are given here:

- Range : [-2g ; +2g]
- Sensitivity : 12.5 %/g (PWM Duty Cycle)
- Bandwidth : 6 KHz
- Noise density : 200µg√Hz

2.3 Magnetometers

Magnetic sensor achieves measurement of the magnitude of external magnetic fields. So three sensors, by sensing the Earth's magnetic field, can be used as heading sensor. For this system a solid state component has been selected. This component delivered by Honeywell provides a differential signal proportional to the magnetic field applied along its main axis. Signal conditioning such as Differential to common mode conversion is added at the input of the TMS320F2812 ADC module. The main features of the magnetic sensor are given here :

- Sensitivity depending on the power level : 1mV/V/Gauss
- Noise density: $16. \, 10^{-6}$ Gauss$\sqrt{Hz}$
- Bandwidth : 5MHz
- Heading error taking into account noise, hysteresis and linearity : 0.15°

2.4 Temperature sensor

The Maxim MAX6666 temperature sensor is used for IRS sensors calibration (temperature compensation). Providing a PWM signal at 35Hz it can be directly connected to the capture unit. As it is done for accelerometers, the processor's event manager is used for duty cycle measurement.

2.5 Global architecture

The global architecture is given on the Figure 1.
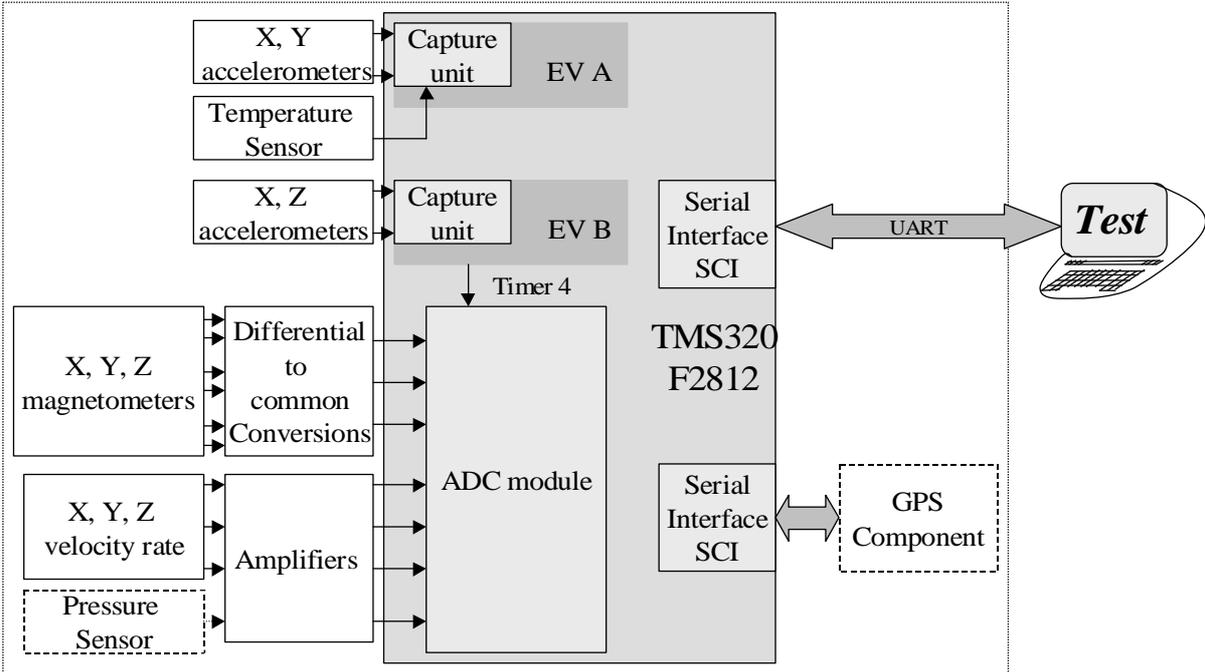

Figure 1: IRS architecture

As represented Figure 1, the project includes a pressure sensor (Motorola MPX 4105) and a UBLOX GPS component. This Figure shows their connections to the DSP. These components are not used by the algorithm implanted at the present time. In future they will be exploited for navigation computing.

3   Pre-processing

Heading signals and angular velocities, provided by magnetic sensors and gyroscopes, are represented in a 12 bits format at the output of the ADC module. Accelerations and temperature are determined by measuring the duty cycle of the PWM signals with the event managers. Event managers registers permit a 16 bits representation.

Sensors signals (accelerations, heading signals, angular velocities) are sampled at 1KHz but processed for attitude estimation at the rate of 100 Hz. A FIR filter is used for sensors signals denoising. Filtering is followed by decimation for sample rate conversion. These two operations can be processed simultaneously using a 50 coefficients-polyphase FIR filter. Including 10 branches, this architecture reduces the computing load to 5 operations (multiplication-accumulation) per mS and per channel.
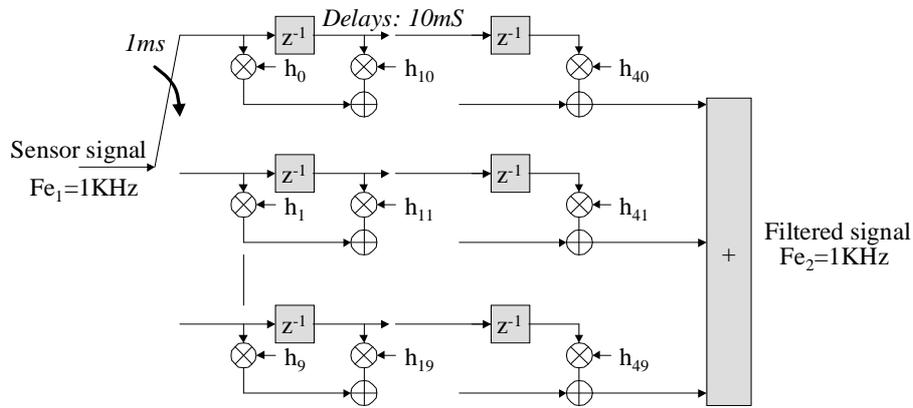

Figure 2: Signals filtering. 10 phases-FIR Filter

After filtering operation parameters are coded in IQ24 format. Then bias due to the temperature variations are compensated, taking into account the temperature measurement, and angular alignments are achieved by applying an orthogonality correction.

$$\underline{P} = K.\left[\underline{M} - \underline{b} - k_T (T - T_{ref})\right]$$

(1)

$\underline{P}$ is the corrected magnitude vector when $\underline{M}$ is the measured magnitude vector, $\underline{b}$ vector represents bias measurements, T is the measured temperature and T_{ref} the reference temperature, k_T is a scale factor depending on the sensitivity to the temperature, and K is a matrix deduced from the sensor sensitivity and from the geometry.

4   Attitude Estimation

Attitude can be defined by a set of angular positions from a frame to another reference frame. Here the earth-fixed reference frame is the North-East-Down coordinates frame centred at the initial position of the body (NED frame). To express the rotation from the body frame to this reference frame, different techniques can be used (Euler angles, quaternions, rotation matrix). For this application quaternions are preferred to Euler angles to eliminate singularities associated with attitude estimation [1], [2]. So equations of rotational motion are integrated using quaternions integrator. The rotational matrix is deduced from the angular rates provided by gyroscopes. Due to the low accuracy of such sensors (gyro drift of about 1000 deg/h), the

attitude estimated from these measurements suffers errors. Therefore attitude correction is applied to achieve improved performance. Figure 3 represents the software actigram.
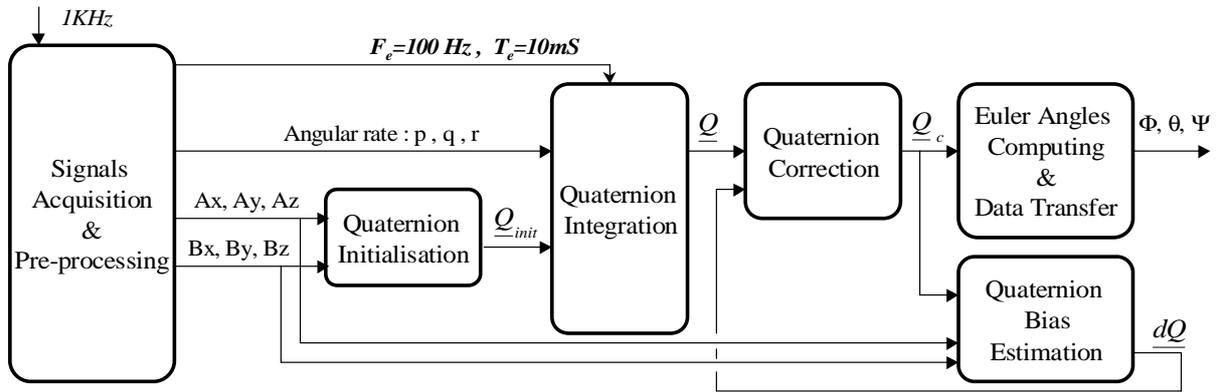

Figure 3: Software Actigram

4.1 Initialisation

The system must be initialised to determine the initial values of the quaternions. Measurements provided by tri-axial accelerometer and tri-axial magnetometer are averaged during 3 sec and used to determine the Gravity direction and the North direction in the mobile frame, and so to express the coordinates of a North, East, Down frame $\left(\vec{N}_m, \vec{E}_m, \vec{D}_m\right)$ in the mobile frame. These coordinates are used for Euler angles computing :

$$\Psi = a\tan 2\left(Em_x, Nm_x\right) \quad ; \Psi \text{ is the Yaw}$$
$$\theta = a\tan 2\left(-Dm_x, \sqrt{Nm_x^2 + Em_x^2}\right); \theta \text{ is the pitch} \tag{2}$$
$$\phi = a\tan 2\left(Dm_y, Dm_z\right); \quad \phi \text{ is the roll}$$

And initial quaternions $\underline{Q}_{init}$ can be expressed from these angles :

$$q_0 = \cos\left(\frac{\phi}{2}\right)\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{\Psi}{2}\right) + \sin\left(\frac{\phi}{2}\right)\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{\Psi}{2}\right)$$
$$q_1 = \sin\left(\frac{\phi}{2}\right)\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{\Psi}{2}\right) - \cos\left(\frac{\phi}{2}\right)\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{\Psi}{2}\right)$$
$$q_2 = \cos\left(\frac{\phi}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\Psi}{2}\right) + \sin\left(\frac{\phi}{2}\right)\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\Psi}{2}\right) \tag{3}$$
$$q_3 = \cos\left(\frac{\phi}{2}\right)\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\Psi}{2}\right) - \sin\left(\frac{\phi}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\Psi}{2}\right)$$

4.2 Quaternions Integration

Tri-axial gyroscope provide angular rates (p, q, r) for rotation estimation. This rotation can be expressed by updating the quaternions vector.

Quaternions integration is performed using the Wilcox method to integrate the differential equation :

$$\dot{Q} + AQ = 0 \quad \text{with } A = -\frac{1}{2}\begin{bmatrix} 0 & p & q & r \\ -p & 0 & -r & q \\ -q & r & 0 & -p \\ -r & -q & p & 0 \end{bmatrix} \text{ and } Q = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

$$Q = \cos(X)\,I + T_e\,\frac{\sin X}{X}\,A\,Q \tag{4}$$

where I is the Identity matrix, $X = \sqrt{\det(A\,T_e)}$ and $T_e = 10\text{mS}$ is the updationg time

4.3 Quaternions Bias Estimation

Quaternions, which then define the roll, pitch and yaw angles, are used to compute the transformation matrix from the reference frame(NED frame) to the mobile frame. So the theoretical Gravity vector, oriented towards the Earth centre can be expressed in the mobile frame, using this transformation matrix. It can be compared to local vertical coordinates returned by the tri-axial accelerometer. In the same way, local North vector is defined in the mobile frame and compared to the local magnetic field provided by the tri-axial magnetometer. The differences on down and north coordinates are induced by errors on quaternions estimates. These errors can be computed by taking advantage of the orthogonal projection properties of the pseudo inverse.

The transformation matrix from the reference frame to the mobile frame is defined from quaternions $\underline{Q}_c$:

$$R_{N2m} = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_1 q_2 + q_0 q_3) & 2(q_1 q_3 + q_0 q_2) \\ 2(q_1 q_2 - q_0 q_3) & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2(q_2 q_3 + q_0 q_1) \\ 2(q_1 q_3 + q_0 q_2) & 2(q_2 q_3 - q_0 q_1) & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix} \tag{5}$$

The Gravity vector expressed in the reference frame is :

$$\vec{D}_{NED} = [0\ 0\ g]^T \tag{6}$$

North magnitude (m) and inclination (I) depend on the location. These parameters have to be determined to express the North vector :

$$\vec{N}_{NED} = m.[n_1 \quad 0 \quad n_2]^T = m.[\sin(I) \quad 0 \quad \cos(I)]^T \tag{7}$$

Using the transformation matrix these vectors can be defined in the mobile frame.

$$\vec{D}_m = R_{N2m}\vec{D}_{NED}, \quad \vec{N}_m = R_{N2m}\vec{N}_{NED} \tag{8}$$

An error vector, resulting from bias on quaternions estimate, is obtained by comparing the coordinates of these vectors to those of the vectors $\vec{B}$ and $\vec{A}$ which represent tri-axial magnetometer and accelerometer measurements.

$$\vec{E} = \begin{bmatrix} \vec{E}_G \\ \vec{E}_N \end{bmatrix}, \text{ where } \vec{E}_N = \vec{N}_m - \vec{B} \text{ and } \vec{E}_G = \vec{D}_m - \vec{A} \tag{9}$$

By noting the Jacobian Matrix X (6 raws, 4 columns), biases on quaternions $\underline{dQ}$ are expressed from this error vector $\vec{E}$:

$$\underline{dQ} = \left(X^T * X\right)^{-1} X^T \vec{E} \quad \text{where X} = \begin{bmatrix} \dfrac{\partial \vec{Dm}}{\partial q_0} & \dfrac{\partial \vec{Dm}}{\partial q_1} & \dfrac{\partial \vec{Dm}}{\partial q_2} & \dfrac{\partial \vec{Dm}}{\partial q_3} \\ \dfrac{\partial \vec{Nm}}{\partial q_0} & \dfrac{\partial \vec{Nm}}{\partial q_1} & \dfrac{\partial \vec{Nm}}{\partial q_2} & \dfrac{\partial \vec{Nm}}{\partial q_3} \end{bmatrix} \quad (10)$$

Greville Algorithm [3] has been implemented to compute the pseudo-inverse required by this processing.

4.4 Quaternions Correction

The error vector $\underline{dQ}$ is used to correct quaternions after integration. The corrector model is given here :
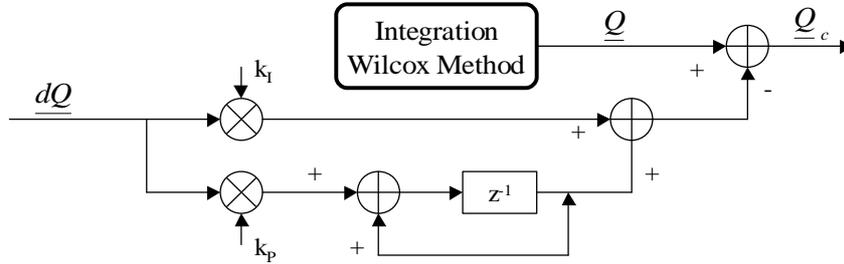

Figure 4: Control unit

4.5 Euler angles computing

Orientation is defined by three angles : Yaw, Pitch and Roll. These angles can be deduced from the quaternions :

$$\begin{aligned} \Psi &= a\tan 2\big(2(q_0 q_3 + q_1 q_2), q_0^2 + q_1^2 - q_2^2 - q_3^2\big), \\ \theta &= a\sin\big(2(q_0 q_2 - q_1 q_3)\big), \\ \phi &= a\tan 2\big(2(q_0 q_1 + q_2 q_3), q_0^2 - q_1^2 - q_2^2 + q_3^2\big) \end{aligned} \quad (11)$$

After computing Yaw, Pitch and Roll are transmitted by SPI interface to a PC. Used during the development step, PC allows data visualisation and IRS assessment.

5 Assessment

Figure 5 shows the system structure. The code is written in C. Special configuration enables hardware validation. In this mode, PC connection displays samples of filtered signals. In other respects, the filtering algorithm was executed on DSP, using pre-registered data. It achieves good estimation. The algorithm uses a lot of trigonometric functions. Data have been represented in IQ24 format and the IQmath library permits to produce highly efficient assembly code. Finally the code has been applied to sensors samples for yielding attitude estimation. In that case the system provides Yaw, Pitch and Roll. These angles are transferred to the PC for visualisation. Up to now the system couldn't be calibrated. Especially

Gyroscopes pre-processing requires calibration to determine magnitude and orthogonality corrections. Appropriate test bench has to be used to apply known angular rates.

The length of the Flash memory used for code implementation is 1C0A words. The computing load has been evaluated by measuring the duration of the processing. This duration is 200uS or 50uS depending on whether the code is executed in flash or internal Ram memory. These values are largely lower than the sample period (T_e=10mS) and this application doesn't need to copy time-critical portions of code from Flash memory into internal RAM memory.
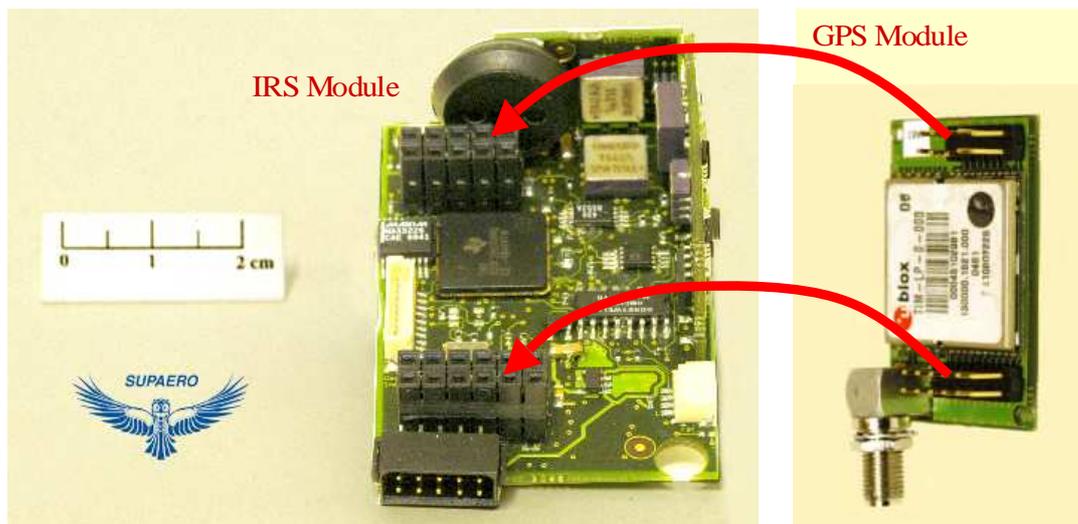

Figure 5: System integration

6   Conclusion and future prospect

Students have contributed to this project. Filtering methodology, including Kalman filtering for GPS hybridization has been proposed and studied by a group of 4 second-year students from SUPAERO, during an internal project of one month. A second-year student, from an Electronic Engineering School (ESME) has carried on this study during a summer project, with the aim to develop the C code for the IRS module. The present board was designed by a student from IPST (Engineering school for adults) during his final project. Algorithms concerning the IRS were implanted by another student from IPST. The workload, including study, coding, hardware conception, represents approximately one student year.

The next step of this project concerns calibration. Finally GPS/IRS hybridization is to considered. This implementation requires algorithm coding and evaluation in term of computing load.

7   References

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