

Seven Reasons to Fully Calibrate a Redundant IMU

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Introduction

The purpose of this treatise is to explain why a full-order Redundant IMU (RIMU) calibration filter is preferred over a reduced-order calibration filter.

A calibration model for a 3-axis IMU often comprises a set of 3 biases, 3 scale factors, and 6 misalignments in a 3×3 scale factor/misalignment matrix, for a total of 12 calibration parameters. Scale factor asymmetry will be discussed shortly. The 12 calibration parameters can be estimated by a 3-axis calibration filter and attitude measurements. A RIMU has $n > 3$ active sense axes. The Northrop-Grumman SIRU, for example, has $n = 4$ sense axes. (We count sense axes rather than gyros because some gyros measure angular rate about two axes.) The total number of calibration parameters is $4n = 16$. Although calibration algorithms have recently become available [1–3] to estimate the full set of physical calibration parameters of a RIMU, people still use calibration filters designed for 3-axis IMUs [3]. Thus the $4n$ *physical parameters* are not fully calibrated. One may wonder if the reduced-order filter really works, and if so, why does it work and what is lost? Obviously it does work, or people wouldn't be using a reduced-order filter. The questions about why it works and what is lost are answered in [4]. In this paper, we will concentrate on what is lost and why the full-order calibration filter is preferred.

3-Axis Calibration Filters

There are three ways in which people have used a 3-axis calibration filter to calibrate a RIMU.

1. Calibrate three sense axes and ignore the remaining $n - 3$ sense axes. This method is not satisfactory since the gyros are not all calibrated.
2. Calibrate n sets of 3 gyros and average the results. The resulting calibration is sub-optimal because strong correlations are ignored [5].
3. The third method requires a little preliminary explanation. Angular rate is sensed in a RIMU through an $n \times 3$ matrix \mathbf{G} , which maps the 3-dimensional body angular rate onto the n sense axes of the gyros. The body angular rate is computed from the n gyro measurements by using the pseudoinverse of \mathbf{G} . The 3×3 scale factor/misalignment correction matrix premultiplies this pseudoinverse in the 3-axis calibration filter.

Observability

The 3 biases and the 9 parameters of the 3×3 scale factor/misalignment correction matrix are called *body-referenced parameters*. This is to distinguish them from the $4n$ physical parameters. A linear mapping from the physical parameters to the body-referenced parameters was derived in [4]. This mapping is not invertible—one cannot determine the physical parameters from the body-referenced parameters. Therefore a linear combination of physical parameters cannot be estimated by a 3-axis calibration filter. This linear combination of physical parameters is not observable in the body angular rate. Therefore the unobservable component of the physical parameters does not affect attitude estimation.

If some linear combination of physical parameters is not observable and does not affect attitude estimation, then why should we be concerned about fully calibrating the physical parameters? Actually, there are several important reasons to fully calibrate the physical parameters of a RIMU. These reasons will be given in the following sections.

Full calibration is possible by updating the filter with what are called *parity residuals* (also called *null-space measurements*). Recall the mapping from the n gyro measurements to the 3-dimensional body angular rate. Information is lost in the *null space* of this mapping. The parity residuals contain this information. The physical parameters are fully observable by updating the filter with the parity residuals in addition to attitude measurements.

Observability results in [4] are improved and summarized in [2, Table 1].

Fault Detection

Another use for parity residuals is fault detection. Hard faults are easy to detect, whereas soft faults require greater sensitivity. Soft faults can be detected reliably (and isolated for $n > 4$) by fully calibrating the RIMU. Note that soft faults may be momentary and operation may continue.

If a sense axis fails, the mapping from physical parameters to body-referenced parameters changes. The body-referenced parameters therefore become invalid when a sense axis fails, even momentarily. However, the physical parameters for the functioning sense axes remain valid and calibration and attitude determination can continue.

Parameter Trending and Sanity Checks

Estimates of the physical parameters of the gyros are needed for long-term performance and health monitoring through monitoring of trends in the parameters. “Sanity checks” can be also be applied to the physical parameters for quality control, whereas the non-physical parameters are more difficult to interpret.

Scale Factor Asymmetry

Let us now consider scale factor asymmetry. Scale factor asymmetry is present in most types of gyros, particularly the SIRU. It is important to calibrate scale factor asymmetry because it otherwise increases attitude estimation error and causes a monotonic growth in attitude propagation error. (Attitude propagation is prediction of attitude using gyros without the benefit of corrections from attitude sensors such as star trackers.) Unfortunately there is no 3-axis body-referenced parameterization for scale factor asymmetry when $n > 3$. One must estimate the n physical asymmetric scale factors. The asymmetric scale factors can

be estimated by using attitude measurements, but their observability is poor. It turns out that asymmetric scale factors are very observable in the parity residuals! Therefore it is of great benefit to update the calibration filter using parity residuals.

Since parity residuals have to be used to estimate scale factor asymmetry and are needed for fault detection, it is necessary to estimate the physical biases, symmetric scale factors, and gyro axis misalignments.

Process Noise

One other reason to have physical parameters in the calibration model is that process noise should be modeled independently for each physical parameter. Although process noise can be modeled for the body-reference parameters, important correlations and the physical interpretation of the process noise are lost.

Rotational Misalignments

Rotational misalignments (a rotation vector) of the attitude sensors should also be calibrated along with the gyro parameters. A linear combination of gyro axis misalignments is also a rotational misalignment of the gyro [6]. Rotational misalignments cannot be estimated for all attitude sensors and the gyro too because the rotational misalignments will not be completely observable, which will cause divergence of the calibration filter. Therefore one set of rotational misalignments has to be eliminated. Typically this is done by designating one attitude sensor (a star tracker, for example) to be a body reference sensor (or master sensor), which is not parameterized with a set of rotational misalignments. If the body reference sensor is occulted, failed, or turned off, the rotational misalignments will become unobservable and the calibration filter will eventually diverge. The divergence is limited, however, if the occultation is brief. Because the RIMU operates continuously, divergence can be avoided by designating the RIMU to be the body-reference sensor. A set of rotational misalignments should therefore be eliminated from the $2n$ gyro axis misalignments. Methods for doing this are derived in [6]. Gyro axis nonorthogonality parameters remain after eliminating the set of rotational misalignments.

Conclusion

We have identified seven reasons to fully calibrate a RIMU, rather than using a calibration filter designed for a 3-axis IMU. In summary, these reasons are

1. Sensitive detection of soft faults, or errors, in the gyro.
2. The non-physical body-referenced parameters become invalid when a sense axis fails, even momentarily, whereas the physical parameters remain valid.
3. Trends in the physical parameters can be followed for long-term performance and health monitoring.
4. “Sanity checks” can be applied to the physical parameters for quality control.
5. Scale factor asymmetry can be estimated more accurately.
6. Process noise can be modeled with a correct physical model.
7. A rotational misalignment can be removed from the gyro axis misalignments to prevent possible divergence.

Therefore calibration filter designed for a 3-axis IMU is not sufficient to calibrate a redundant IMU, which has more than 3 sense axes.

The RADICAL™ RIMU Attitude Determination/Calibration filter estimates the full set of calibration parameters and has many features for simple and reliable operation. It is designed for on-board real-time operation, ground-based processing, and for desktop design and analysis. RADICAL™ is available as Commercial Off-The-Shelf (COTS) software.

For further information, see www.acsinnovations.com or contact the author by e-mail at mpittelkau@acsinnovations.com, or call 540-751-1110.

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