The Early Eighties: Development of In-Flight Transfer Alignment—Challenges and Methods

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Abstract. In the late seventies and early eighties, Rafael devolved a very advanced (at the time) transfer alignment algorithm. This required the development of an entire infrastructure for navigation work: strapdown navigation equations, navigation error model, Kalman filter implementation, system level error model, inertial measurement unit, real-time, floating-point computer, test design, implementation and analysis. This paper tells the story of this enterprise, from the preliminary studies to successful operational deployment, by pointing out the different phases and lessons learned.

1 Introduction

This paper is about the development of a navigation system, and touches on a very wide range of engineering topics related to navigation systems. The main goal of the paper is to describe the people, decisions, challenges, problems, and solutions during this project. The dilemma was deciding on the extent to which the underlying engineering and mathematical topics should be detailed. The decision was ultimately made to write a paper without equations, mainly because the subject is so broad that once I started writing equations, I would not know where to stop. Moreover, the main objective of the paper is to provide the reader, who is not necessarily a navigation expert, a history background of the technical achievements. Those who are missing the equations are directed to references in which the relevant ones are described. Of course, the best descriptions are in Itzhack Bar-Itzhack's technical documents.

Itzhack Bar-Itzhack is one of the key individuals in this story. Like many others, I learned a lot from Bar-Itzhack: I took his course at the Technion and read his brochures, which were always on his desk. We knew each other pretty well: Bar-Itzhack worked as a consultant at Rafael; we even played volleyball together. Nevertheless, although the paper is being published in the Itzhack Y. Bar-Itzhack Memorial Symposium, it is not a dedicated memorial to the man. Its main purpose is to depict a picture of engineering challenges and the progress in their achievements.

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To maintain a continuous flow in the paper, we present here, for non-experts, a short description of the technical terms used in the sequel (see [13] for more details).

Accelerometer – an instrument that measures a specific force (acceleration combined with gravity effect).

Gyro – an instrument that measures angular rates.

IMU (Inertial Measurement Unit) – a unit composed of accelerometers and gyros to measure specific forces and angular rates in three orthogonal axes.

Inertial Navigation – a method to calculate position, velocity and angular position from initial conditions and accelerometer and gyro outputs.

Stabilized Platform Navigation System – an inertial system with accelerometers installed on a stabilized gimbal.

SD (Strapdown) Navigation System – an inertial system without any stabilizing gimbals. It is stiff with respect to the body to which it is attached.

SD Navigation Algorithm – an algorithm that integrates the IMU outputs to provide position, velocity and angular position where the IMU is installed rigidly with the body to be navigated.

Transfer Alignment – a method of finding attitude (orientation) of a navigation system from a velocity (or position) reference. To achieve this, the reference data are provided for a certain time and some maneuver during this phase is required. The standard implementation is based on Kalman filtering (see [2] for further description).

Quaternion representation – a method to describe attitude by four normalized *numbers.*

ARU (Attitude Reference Unit) – a method to calculate orientation from direct measurements of gyros and accelerometers, with the underlying assumption that the mean value of acceleration is zero, and therefore the accelerometer's mean value is related to a gravity vector. These units are usually integrated with heading gyro and optional magnetometer.

Captive Flight – the phase in the missile's mission when it is operating but connected to the aircraft.

Free Flight – the phase in the missile's mission when it flies without any connection to the aircraft.

Inertial Mid-Course – the part of free flight when the missile is steered by its navigation system.

2 The Early Years (1974–1980): From Conceptual Study to Design and Implementation

Our story begins in 1974, the year that saw the creation of a missile model with its 6DOF simulation for a medium-range precise air-to-surface missile, later called Popeye. The relatively long range was due to the requirement for a standoff. By standoff we mean that the missile should be dropped beyond the range of most air-defense ammunition.. At that time, Rafael had already gained some experience with precise

TV-guided weapons. Their principle of operation was to present a pilot with an image from the target vicinity; the pilot's task was to recognize the target on this image and correct the missile's course until it hits the target. Implementation of such a system required a seeker, a high-quality TV camera mounted on gimbals to provide stabilization and movement capability, and two-way communication links. Having mastered the concept of terminal guidance, the open question was the midcourse—how to guide the missile with such accuracy that indeed the seeker would point close to the target, and the pilot could recognize it with high confidence. The new challenges were related to the several tens of kilometers range and relatively long flight time. Many guidance concepts, based on the classical ARU approach, that combined accelerometers, gyros, and perhaps an additional sensor to calculate the attitude directly, were analyzed. It took until mid-1975 to understand that for this type of range and for the required electro-optical performance, inertial mid-course was absolute necessary. Moreover, as an outcome of this work, the goal of 200-m accuracy (2–2.5 sigma) was stated as a primary requirement for the navigation subsystem.

No one knows who proposed the strapdown (SD) implementation for such a problem—it could have been Itzhack Bar-Itzhack, or someone influenced by him.

In any case, before the end of 1976, two navigation pioneers went to the United States to visit companies that had made some progress in SD technology. Of course, travel preparations were much more involved back then, without the benefit of Google and Internet searches. They needed to read a lot of professional literature and to consult with every available expert.

They visited three companies (names are withheld for private reasons), and the responses and impressions were diverse:

- At one company, the vendor representatives refused to discuss the implementation issue with guests from Israel. Their assertion was that no business could come of this meeting and they were not interested in teaching the team from Israel how to implement the SD system.
- At the second company, the team found a system that was over 10 times less precise than required. Although the company was interested in cooperation, the low performance did not justify the effort.
- At the third company, the team found a nice prototype of an inertial system that closely matched the Popeye's requirements. They found an engineering and management team that was willing to cooperate. The Israeli team understood that this company would provide good support for the entire navigation system composed of hardware (IMU), navigation software and a Kalman filter for transfer alignment.

Nevertheless, the Israeli Department of Defense decided to develop the Popeye's navigation system in Israel. The Tamam division of Israel Aircraft Industries, Ltd. proposed to use a stabilized platform which they were producing at the time, but the cost ($1M) and size were prohibitive. After a long discussion between all involved parties, three important decisions were made:

- The Popeye navigation system would be of the SD type.
- The hardware (IMU) would be developed by Tamam.
- The navigation algorithms would be developed at Rafael.

So the task of implementing a SD IMU with a price of around $100K, weighing less than 6 kg with errors of 1 deg/h for gyro drift and 1 mg bias for the accelerometer was assigned to Tamam. The assigned project manager just completed M.Sc. degree under the supervision of Itzhack Bar-Itzhack. It was an important project with enormous challenges: sensor development, accompanying electronics, mechanical design, all to be the first of their kind. I am sure that Taman engineers would add the relationships with Rafael's people as one additional and demanding challenge. Eventually the IMU was ready, on time and with outstanding performance. I am certain that the history of this development would provide an excellent foundation for a dedicated paper.

The first man that started to develop navigation algorithms at Rafael tells: "We got the main idea from Itzhack Bar-Itzhack; he presented us with differential equations and explained all of the details. For example, it was his recommendation to use quaternion integration. We performed the detailed work, but every time we progressed, Itzhack Bar-Itzhack was already ahead of us; as we got into a problem or dilemma, he had already studied the issue and came prepared with an analysis, explanations and recommendations."

The task was quite demanding: to design an algorithm that discretizes the navigation differential equations in a way that can be implemented in the proposed Rafael-homemade computer, the μ-Remez. Every multiplication and load was counted and optimized. Eventually a very effective navigation algorithm that fit well into the constraints was developed. The resulting procedure was a multi-rate integration with very carefully selected and optimized discrete integration methods. One interesting example was the quaternion normalization, which was required at quite a high rate. The optimization result was to use a linear approximation for normalization instead of the "standard" deviation by square root of the sum of squares. The testing of the navigation algorithm was combined with 6DOF simulation. From the very beginning, their models matched each one; the same person was in charge of both, 6 DOF simulation and navigation algorithms, so the differences were only because of numerical errors (integration rate and computer resource-saving navigation algorithm). In addition, this platform (6DOF simulation and navigation algorithm) served for an analysis of sensor error effect. One important remark is needed here: the approach then, and during the entire development phase, was not to use "blind" simulation for analysis but to associate it to an analytical (usually simplified) analysis. One could not simply present a result and state: "these are the results that I got from the simulation." Everyone was expected to explain why these results appeared to be reasonable. This work ended with a well-known report describing the proposed algorithm, the main trade-offs, sensitivities and tests. This document is well known in Rafael and is still in use for training the younger generations. The algorithm proposed then has remained basically unchanged, and every navigation system developed at Rafael is based on it.

The challenge of transfer alignment was even more daunting: the differential equations describing the inertial navigation error models were not yet available and it was clear that the discrete time and efficient implementation issues were very demanding. This task was combined with M.Sc. degree dissertation under the supervision of Itzhack Bar-Itzhack. During 1977 to 1979, the navigation error model was developed and formulated it into the framework of in-flight transfer alignment. In particular, the attitude error model required special attention. This study led to a SD version of psi model, which was already known for platform navigation. It was somewhat intriguing that they developed the same equation as in the case of a platform, but with the opposite sign of the drift term. In addition, they proposed an extended sensor error model and integrated it into one combined system. Special effort was dedicated to the random noise integration formula required by the Kalman filter. The analysis distinguished direct sampling from integral sampling, and he provided rigorous analyses for both cases. One of the conclusions was the need for integral sampling, and Tamam developed a mechanism called V/F to provide angular and velocity increments instead of angular rate and accelerations. This dissertation was very extensive, several hundred pages long, with some of the equations written in A3 format, it could in effect be considered a Transfer Alignment Handbook, as it completely covered all models required to develop the transfer alignment algorithm. Unfortunately, this work was defined as classified and was never published. The reason for this was that part of the work dealt directly with the Popeye transfer alignment algorithm. It was based on a Kalman filter with a 12-state vector: velocity error, attitude error, gyro drift and accelerometer bias (all of them in three axes). The velocity error measurement was chosen, based on a comparison between aircraft and SD velocities, with 1-sec intervals between measurements. Those critical decisions were based on common sense and good engineering insight into the dominating phenomena, and were later justified by simulations. For example, acceleration measurements were rejected due to the high flexibility of the wing that Popeye missile was installed underneath and the long time between measurements, related to computer-resource limitations. The states for gyro drift and accelerometer bias were added to allow tracking and compensating for these slow-changing error terms. The time between measurements, 1 sec, was set as the longest time (to save on computer resources) that would presumably allow the required tracking quality. The performance analysis was based on S-shape maneuver during in-flight alignment. The Kalman filter calculations were very computationally expensive and required working with a floating point machine, which was not available in feasible sizes.

The project manager was dedicated to meeting the time schedule for a series of system tests. His message was that the navigation system's development, after 4 years of effort, was still fraught with huge uncertainties; therefore, in the event of a delay or critical problem, he would replace the proposed SD navigation system with a backup one, based on a simple ARU that had already been developed for airframe configuration tests. In this atmosphere, the need to reduce development risks and efforts was vital.

The next task was to build a simulation that would combine SD navigation and in-flight alignment. During this task, an important achievement was found. The observation was that at the cost of a minor approximation in the stochastic part of the model, but without sacrificing the accuracy of its deterministic part, the algorithm's complexity can be reduced. The key observation was that the simplified system transition matrix is nilpotent. The precise calculation of the discrete transition matrix in a time-varying system is related to matrix multiplication, which is computationally heavy. The nilpotent property states that those multiplications come to zero. This observation opened the possibility of calculating the transition matrix by simple integrations (summations). The term nilpotent, that may create negative connotations, was very attractive in the eyes of the project leaders, because it eliminated the need of a special-purpose computer; the new Intel 8086 processor with floating point 8087 coprocessor was able (when working at almost 100% capacity) to carry out the calculations required for all of the navigation algorithms.

3 Years 1980–1985: It Works! Integrations, Tests and First Improvements

The Project Test Plan consisted of several phases, each phase dedicated to testing one of the major subsystems, while the subsystems tested in the previous phases served as the infrastructure for those tests. Table 1 describes the main test plan from the perspective of navigation subsystems

All navigation test analyses were based on the principle of data recording and off-line reconstruction. The idea of recording was to store the entire stream of IMU outputs (6 numbers at 60 Hz) and aircraft navigation blocks (9 numbers at 20 Hz). The requirements for data rate and storage volume were high, but the most demanding requirement was with respect to data quality. To successfully calculate the navigation data, the stream of IMU data had to be close to perfect. Because the navigation algorithm was based on integration, lack of even a single IMU block (for example during maneuvering) could harm the entire task.

Table 1 The project test plan

Test name	Type	Goal	Configuration
B	Captive	navigation concept	Big commercial aircraft, alternative IMU hardware, alternative aircraft navigation system, recording system
104/2	Captive	navigation algorithm + hardware	Dedicated aircraft with its navigation system, dedicated IMU (from Tamam), recording system
104/3	Captive	navigation implementation	Dedicated aircraft with its navigation system, Popeye electronic box (navigation and all other operational computers, IMU) installed in the missile envelope, recording system
107	Captive	seeker tests	As above + seeker
109	Captive	communication tests	As above + communication pod
1004	Free	inertial midcourse	As above but missile with its motor, control and guidance subsystems. Telemetry.
1007	Free	final system test	The complete system

The proposed solution was quite complex, but presumably the best available given early days hardware and software limitations. The recording medium was analog video; dedicated hardware to convert digital data into video stream (and vice versa) was designed and built. To increase data quality, two parallel video recorders were installed. The process of preparing the digital stream data was difficult and long: the first phase was to play the video data and convert it into a digital stream of blocks, and sometimes some reiteration was required. A dedicated mini-computer was involved in this process. The second phase was to merge the blocks from two video recorders; the third was manual corrections of some blocks that were erroneous after the merge. In retrospect, this effort was critical to acquiring essential knowledge and an understanding of navigation system performance and sensitivities.

The analysis of the first navigation test B was difficult; the data-reduction process was very lengthy and then it turned out that the sensor calibration was inconsistent. It took several weeks to find the reason for the problem encountered in this test: bad time synchronization. The surprise was twofold: indeed the temporal synchronization between IMU data and aircraft data was worse than expected, but the system sensitivity to these phenomena was much higher than one might have intuitively expected. Since then, synchronization has become one of the most important integration issues, the topic of many discussions and much testing. We can clarify this theme with a simple example. Assume that we make a 0.5 g (5 m/sec^2) turn with 3 cm/sec velocity noise and we are willing to estimate bias up to 0.5 mg (0.5 cm/sec^2). For acceleration of 0.5 g = 5 m/sec2, 1 msec of synchronization error will produce a measurement error of 0.5 cm/sec, significantly less than the velocity error of 3 cm/sec. However, after 1 sec, the bias error of 0.5 mg will cause a velocity error of 0.5 cm/sec, so the same as the error due to miss-synchronization The observation was that the comparison of error due to miss-synchronization with velocity noise is misleading. The correct comparison is between the synchronization error and the error caused by bias that we are willing to estimate. Indeed, these errors appear with similar correlation to the trajectory. In this case, since we would like to keep the synchronization error well below the error due to the estimated bias, the allowed synchronization error should be on the order of 0.1 msec.

Test series 104/2 was less problematic; integration with the real IMU went smoothly, and the performances and sensor calibration behaved well. This was a great opportunity to optimize the transfer alignment maneuver. The starting point was relatively long S-shaped maneuver, required for a good estimation of the heading error and z-axis drift. It turned out that in a Popeye-type missile, the sensitivity to heading error is relatively low; the simple (albeit non-intuitive) explanation was as follows: if a missile is launched and does not perform any maneuvers, than at the end of the mission its position error will be zero, even if the heading error was large (in this case all other errors are assumed to be zero). In other words, heading error influences system error only if there is acceleration. The most significant acceleration (due to the rocket motor) was at the beginning of the mission. This observation allowed to relax the requirements for z-axis drift estimation and significantly reduced the need to estimate heading error. As a result, a shorter maneuver was proposed which was much easier from an operational point of view. It was based on a single, relatively small turn and the time of captive flight was reduced significanly. An additional result of the 104/2 series was the tuning of the Kalman filter.

On Itzhack Bar-Itzhack, the first navigation group leader relates the following: "In those days, Itzhack Bar-Itzhack was coming in to Rafael once a week to work with us. For me, he was one of the team members, perhaps younger than many of the others. He was always smiling, in a good mood and ready to tell new jokes, some of them not necessary politically correct by today's standards. Nevertheless, from a professional point of view, he was always serious, well-organized and very precise. He was always ready to carry out new assignments, whatever was needed, once he had studied the details of aircraft navigation systems in depth; on one occasion, for example, he proposed a missile trajectory generator algorithm. We always discussed the current issues, problems and plans with him."

The 104/3 tests, performed with the actual navigation system (hardware and software), were relatively extensive; they aimed to cover the entire operational envelope. The software integration was very successful; it worked well from the first flight test. The most important lesson learnt here was the system's sensitivity to flight conditions: for quiet flights very good results were obtained, whereas for low-level, fast flights, the results were worse but still within requirements. The long-flight 104/3 test series, followed by the even longer 107 series, was used to create a huge library of navigation data: real-life trajectories, sensor performance together with post-processing analysis, and error sensitivities for a very broad family of error sources. This library, which was continuously updated with new tests, served as an excellent platform to learn navigation systems and develop new algorithms.

The seeker test series 107 showed a problem that appeared to be related to the navigation system. The seeker pointing errors were too large. Rafael people claimed that this phenomenon was due to aircraft navigation errors, whereas the air force claimed that after position update the aircraft navigation error was about 50 m, and such large pointing errors must therefore be related to the missile. The first task was to plan a test that would separate the error sources. The idea was to keep the seeker tracking a target at known positions, so the system pointing errors could be measured continuously for several tens of seconds. A Kalman filter would be designed with measurements of pointing errors and states of position error, attitude error (in an inertial reference frame) and misalignment between the seeker and the navigation system (related to the body reference system). The Kalman filter implementation was off-line and based on the already existing reconstruction infrastructure. This test showed with high confidence that the pointing errors were due to position errors. Later analysis showed that although the position updates were quite accurate, they did not properly correct for the velocity error and therefore, after 1 min or more, the aircraft accuracy was significantly worse than the specified 50 m. This fact endangered the entire project, but a solution was proposed almost immediately. The initiative was to make auxiliary target updates. The idea was to find, close to the actual target, an auxiliary target with good visibility and known location. Then, from pointing to this target, the system could estimate the pointing errors and correct them (assuming that they came from horizontal position errors). This algorithm was accepted and applied in the system. Years later, pilots still use this procedure with every aircraft working with GPS, claiming that it improves performance; the reason for this is unknown, but my impression is that this procedure survived the GPS era mainly because it makes the mission less boring. In any case, the lessons learned in line-of-sight analyses and the integration with navigation errors were later used to propose installation of the navigation system inside the seeker gimbal [9]. A well-known application of this approach is Rafael's Litening Airborne Navigation and Targeting Pod.

The preparation for the first free flight test, test 1004, went according to plan, but one day before the test, during the final captive flight test, a new feature was tested. During the airframe configuration test, immediately after the launch, strong roll movement was observed. Therefore, the pilot performed a strong roll movement (as fast as he could) to simulate the release roll movement. As a result, in this route, large navigation error appeared. It happened only once and there was a big debate whether to stop the test launch or not. Rafael people (at least the senior ones) wanted to continue; it was the test pilot who persuaded the project managers (from the Ministry of

Defense) to postpone the test and require, from the Rafael team, a solid analysis of the phenomena.

The result of the analysis was surprising: it was essentially a system/hardware problem. It turned out that the actual maximal angular acceleration is much higher than the one specified. Eventually the spec was changed, Tamam made the necessary changes in their design and after several months of intensive work, test 1004 was ready to restart. At the very end of the last test before the launch, an IMU error message appeared. Again, long discussions, collection of all available data, consultations with experts, lasted till late-night hours.

This time the decision was to continue the testing. On the following day, early in the morning, the missile was launched. Before the successful happy ending, the missile was almost terminated by safety personnel due to a lengthy lack of communication with the operations room, first due to telemetry problems, then due to a tape-recorder, that someone had put in the room and created acoustic noise oscillations. At the very last moment the problems were fixed, and everyone in the operations room, including the safety personnel, were able to witness the missile's precision in following its designated route.

4 Post 1985: Still a Lot To Do

After the success of test 1004, the navigation group's involvement in the project has gradually reduced. Then, in 1986, great excitement spread from the Popeye project management: we were going to demonstrate the system in the United States. Project management's view was that since the missile's development had been completed, in order to reduce our costs and time schedule, the aircraft to be demonstrated in the US should mimic the interface that was already integrated in the Popeye missile. At this stage, schedule was very tight and intensive work was required: a few months for implementations and integrations, then a few captive flights for testing and operational training and finally, a full operational launch. In the course of the meetings and tests, we understood that our system had excellent characteristics: the quality of the seeker, the navigation accuracy and the very short and easy transfer alignment procedure were world-class outstanding. From a technical point of view, the process ran very smoothly with no critical failures. One improvement of note was the use of the aircraft simulator to create dynamic trajectories, in order to record the blocks sent to the Popeye and analyze them. In this way we were able to fix some problems well ahead of the flight tests.

During the integration in the US, we understood that changing an aircraft's interface to simulate another interface was an once-in-a-lifetime scenario and that the next time we would need to change our interface. Then we understood that our design lacks the flexibility to support such changes. The problem was related to Kalman filter propagation and the time window for measurements. The first implementation (due to a lack of spare computer resources) was very rigid; the covariance matrix was propagated to a known a-priori measurement time, creating a narrow time window in which the measurement should appear; if it didn't, the measurement was discarded and the system was moved to the next second. In the next version of the transfer alignment algorithms, due to the change in the covariance propagation scheme, the system was ready to receive asynchronous measurements, with the only limitation being the minimal time between measurements.

Another great challenge faced the team when it started work on the inertial navigation system for air-to-air missiles. It was clear that a dedicated maneuver for transfer alignment was out of the question. The approach was to perform a continuous transfer alignment, namely to turn on the missile navigation system before takeoff and keep it working continuously such that the missile would be ready to launch all the time. Since in every aircraft flight there are always periods of some acceleration, sensor errors and pitch and roll angles can be estimated and kept accurate during the flight—after intensive work for proper Kalman filter tuning of course. The only problem is that for long flight periods with no accelerations, the heading error can grow. In an air-to-air missile, due to its huge acceleration, the sensitivity to heading error is much more severe than that in air-to-surface missiles. The solution came from a very interesting direction: the reason that we could not perform a direct alignment (i.e. simply copy aircraft orientation onto that of the missile) was that the missile had been installed under the wing, and its relative orientation was changing during the flight. Indeed this was true, but only for pitch and roll; the heading misalignment (the difference between the aircraft and missile orientations) was almost fixed during the flight. This observation led to adding another state to the Kalman filter, the new state being the heading misalignment, and the resulting 13-state Kalman filter provided excellent continuous transfer alignment. This 13-state Kalman filter has become a standard solution that is implemented in all relevant airborne systems.

The stringent requirement for time synchronization between the aircraft and missile has always been a key issue in aircraft integrations. The number of types of aircrafts which needed to be integrated was constantly increasing, as was the number of Rafael airborne systems that included navigation units. As a result, more and more cases of an aircraft navigation system not providing the required synchronization accuracy began to appear. The obvious consequence was performance degradation, until an important observation was made. It was clear that precise synchronization is required to accurately interpret the system errors during maneuvers. However, one could omit the measurements during the maneuvers and estimate the system errors after a maneuver had been completed. This non-trivial observation claimed that due to the integral nature of the system, there is no significant harm to performance when no measurements are performed during the maneuver itself (but with enough measurements after the maneuver) compared to the case in which all measurements are taken.

At this point our paper is complete; the basic solution for transfer alignment and its essential improvements have been described. During those years, Rafael provided state-of-the-art systems, with a constant line of improvements. Of course the real story never ends, and the navigation group at Rafael continues to develop navigation systems, based on the foundations described here, facing new challenges and producing new achievements.

In my opinion, the secret to accomplishment lies in following these three guidelines, as well illustrated in the story described herein:

- Recruit capable people
- Provide a challenge
- Build an infrastructure and culture to analyze integrations and tests properly and in depth

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