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History of Inertial Navigation

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ABSTRACT

THE GUIDANCE SYSTEM used by the Germans in 1942 in the V-2 missile can be considered to be the first use of inertial navigation. It is true that Foucault defined the gyroscope in 1852 and that Schuler developed the gyrocompass in 1908, but the former device was only a measuring instrument and the latter, although of inertial quality, was only a partial inertial system. The Sperry flight instruments of the late 1920's and early 1930's were attitude-indicating not velocity or position-indicating devices.

Earnest development of inertial navigation systems began in the United States in the late 1940's and early 1950's by the M.I.T. Instrumentation Laboratory, Northrop and Autonetics under Air Force sponsorship. This work led to the inertial guidance systems for ballistic missiles—both land and ship launched. The 1960's brought the Space Age and the advance of inertial guidance in Apollo. During this time inertial guidance systems also found their way into military and then commercial airplanes.

Behind the system development was the simultaneous and necessary development of theory, analysis, components, subsystems and testing.

The author, whose professional career has been simultaneous with the growth of inertial navigation, draws on his personal experiences in the field of direct association with many of the people and events involved.

DEDICATION

This paper is dedicated to Prof. Lev Ivanovich Tkachov of the Moscow Power Engineering Institute, who it was hoped would be a co-author of this paper. A leading figure in inertial navigation in the Soviet Union, his recent death prevented his co-authoring this paper and deprived the world of a fine person.

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INTRODUCTION

Practical inertial navigation is a quite recent achievement, only twenty-five years for serious research and development, and only five years for its commercial use. However, one might possibly say that a partial understanding of some of its principles is much more ancient. For example, in the Bible [1]* we read that the Lord used a plumb-line to identify a particular location!

Before contemplating the making of any operative device it is generally necessary to have the proper scientific and engineering background. Inertial navigation is often referred to as "Astronomy in a Closet", thereby depending on the lore of astronomy and a knowledge of the physics of what could be observed and measured in a closet. The history of inertial navigation, which has been treated by Draper et al [2], Hellman [3], Tkachov [4] and others, is an accomplished fact, but each author sees a slightly different aspect of the same story. The present paper is based, among other things, on the author's professional experience with inertial navigation essentially from its practical origins in the late 1940's. In fact, the author's doctoral thesis [5] first seriously interested him and his advisor, Prof. C. S. Draper, in inertial navigation.

The principles of inertial navigation have been the subject of much literature [2–19], much greater than those treating its history, and will be treated in this paper in only the

* Bracketed numerals refer to similarly numbered references in the List of References.

simplest manner, primarily as they are reflected in the history of the subject. Basically inertial navigation involves the following operations:

(1) measurement of specific force – inertially-referred acceleration plus gravitation
(2) removal of a computed gravitation – generally by feedback – leaving the indicated acceleration
(3) double integration of indicated acceleration
(4) damping or other signal processing – to obtain desired system dynamics
(5) removal of a computed earth-rate
(6) setting of initial conditions – both geometrical and signalwise
(7) knowledge and maintainance of a reference coordinate frame related to the navigational problem and in which the above mentioned processes can be accomplished – this, in practice, is generally the most important and difficult part of the whole operation

The most desirable reference frame in which to solve a navigational problem would be one in which the problem exists naturally; for example, the most common navigation situations are relative to the Earth, hence an Earth-fixed reference frame would be the choice. Unfortunately, Earth-fixed reference quantities that can be measured practically in a closet do not exist. The closest reference frames to the desired Earth-fixed frame are those that are non-accelerated with respect to the "fixed stars". Since Newtonian mechanics (laws of inertia) are expressed relative to the "fixed stars", the name "inertial" was born. The laws of mechanics and gravitation expressed by Newton [20] in 1687 gave the first understanding of the relationships on which inertial navigation could be based, but over two centuries would elapse before instrumentation that could operate practically for navigation would be available.

The next basic scientific background essential for inertial navigation was the ability of Foucault [21] in 1851 to measure the rotation of the Earth inertially and the invention of the gyroscope (from the Greek words *gyros*-turn or revolution – and *skopein*-to view; literally, to view the turning).

The two principal requirements for inertial navigation – association of force with acceleration and gravitation, and a reference frame that was independent of the motions of the vehicle in which measurements for navigation are to be made – were available.

During this time navigation itself had progressed from a well-guarded secret art to a well-developed science with suitable instrumentation and knowledge that served adequately the needs of guiding wooden ships of either sail or steam [22], the final factor being John Harrison's invention in 1765* of the chronometer that at last allowed accurate determination of longitude.

GYROCOMPASS

The advent of steel-hulled ships brought the requirement for a direction-indicator that was not affected by magnetism. This introduced the first, although partial, inertial instrument – the *gyrocompass*. A gyrocompass tries to accurately track the direction of geographic north (the projection of the Earth's daily spin on the horizontal). Note that confusion can exist when magnetic compasses that are stabilized by a gyroscope, either physically or signalwise, are termed gyrocompasses; such devices are gyromagnetic compasses, and are not inertial instruments. Both the theory and practice of gyrocompasses are well treated in many texts [23-31], to which the reader is referred. The article by Wrigley [29] is a relatively short and simplified treatment.

The gyrocompass seeks true north by attempting to find equilibrium between its pendulosity and the inertial rotation of the base carrying it. Accordingly, gyrocompasses are acceleration-sensitive. For many years instruments that gave excellent north-direction indications on land or in sheltered waters became very erratic under the effect of waves on the open ocean. In 1908 Max Schuler, working for Anschütz in Germany, discovered the principle that led to a practical sea-worthy gyrocompass [26, 27]. This principle, Schuler Tuning**, required a relationship between the pendulosity and angular momentum that caused an eighty-

* Harrison's first successful chronometer was built and tested in 1736, but it wasn't until 1765 that the Board of Longitude gave full acknowledgment of the fact.

** The term "Schuler Tuning" was originated by the present author [30] in 1950.

four minute period of oscillation of the gyrocompass' north-indicating direction. Although applied to heading information, Schuler tuning mainly caused the gyrocompass to maintain an extremely accurate indication of the vertical about its east-west axis, even during times of north-south accelerations. Note that, in moving over the Earth, the local vertical (the direction of gravity) does not remain in a constant direction but rotates, essentially geocentrically, one minute of arc for each nautical mile travelled. In writing about gyrocompasses Schuler also presented the tuning requirements for gyropendulums to indicate the vertical [26], however the state of the art in instrumentation was not then (1923) capable of building the required device. For almost fifty years—1908 until the full inertial systems of the 1950's—the gyrocompass' indication of the vertical about its east-west axis was the only such truly accurate measurement of the direction of gravity under accelerated operations.

Schuler's 1908 gyrocompass was a marvel of mechanical ingenuity. In 1911 Elmer Sperry in the United States produced a gyrocompass that was much easier to construct and led to its widespread commercial use, for example, in iron-ore carriers on the Great Lakes. In 1916, in England, S. G. Brown and John Perry also produced a successful gyrocompass. One of the first to show the instrumental concept for a full inertial navigation system was J. M. Boykow [32] of Austria. This reference is the result of several years of work on his part. His ideas show a suitable coupling of accelerometers and gyroscopes, but make no mention of Schuler tuning. Also the quality of instrumentation at that time was not adequate for inertial navigation. Such instruments were represented by the quality associated with artificial horizons and directional gyros—instruments fully adequate for attitude indication [23] but with much too great uncertainties for position indication.

SOVIET ACTIVITIES

In the foreword to Tkachov's [4] book S. A. Danilin recalls his problems as navigator of the Soviet flight from the Soviet Union over the North Pole to the United States in 1937. He was able to start interest in self-contained navigation as a result of his experiences showing how essential such equipment is in polar flights. The work of Boykow [32] was known to the Soviets, as was that of Kofman [33] et al. In 1938, Prof. B. V. Bulgakov [34] of Moscow State University analyzed the basic inertial navigation problem. He concluded that systematic, as well as instrumental, errors would be present and therefore were not correctable by design improvements. Tkachov [4], in 1943, presented a report on the feasibility of navigation without external communication that contained the complete mathematical terms necessary, thus including the possibility of an inertial system without systematic errors. First studies were undertaken by the department of automation of the Moscow Power Engineering Institute. The first Soviet publication mentioning the concepts of strapped-down and stellar-stabilized-platform inertial navigation systems was in 1949 in the journal Prikladnaya Matem. i Mekh. Izd-vo AN SSSR.

GERMAN ACTIVITIES

The first operating inertial system can be said to be that of the V-2 rocket developed by the Peenemunde group in Germany. Kooy et al [35] note that flights were made in July 1942. In addition to two two-degree-of-freedom gyroscopes, the system used an integrating accelerometer to determine the missile velocity, and thus was freed of ground control. This group, under the leadership of Dr. Wernher von Braun, had developed a stable platform with three single-degree-of-freedom gyroscopes and an integrating accelerometer by the end of World War II.

In the late 1940's inertial navigation and guidance was shifting from basically instruments to the combination of instruments into systems incorporating feedback principles. This led to an interesting controversy. The eighty-four minute period incorporated in all inertial force-measuring systems was discovered by Schuler [26] for use in gyrocompasses and gyropendulums, which are both essentially instruments, and not systems—at least in the form with which Schuler worked. Note also that Boykow's [32] ideas dealt with instruments. In 1945 Dr. Siegfried Reisch [36] in Germany reported independent discovery of the eighty-four minute period using inertial components in feedback loops. As feedback systems have been found to be necessary to realize inertial navigation performance from inertial components, claims are made that Reisch, not Schuler, should be credited with use of the eighty-four minute period in inertial navigation systems. The end result is that Schuler's work was known to the American engineers and scientists (reference 30, for example) who developed working inertial navigation systems and which influenced their activities, whereas Reisch's work was unknown to them until fundamental theory and component developments were already well advanced.

UNITED STATES ACTIVITIES

After World War II four different groups in the United States became actively engaged in the development of inertial navigation systems, one for the Army and three for the Air Force.

The Army-sponsored group was part of the Peenemunde group under Dr. von Braun. They brought with them their V-2 experience and produced several successful missile inertial guidance systems notably for the REDSTONE, JUPITER and PERSHING rockets. They were located at Fort Bliss, Texas and subsequently moved to Huntsville, Alabama as the inertial group for NASA.

The three* Air Force-sponsored groups were Northrop Aircraft, Autonetics Division of North American Aviation and the M.I.T. Instrumentation Laboratory (later to become the Charles Stark Draper Laboratory, Inc.).

Air Force-sponsored systems were at first combinations of inertial and stellar functions, as it was doubted at that time that the component requirements for a purely inertial system could be achieved. As the state-of-the-art improved, the system design shifted toward full inertial operation. The principal proponent of purely inertial systems was Dr. Charles Stark Draper of M.I.T., whose experiences as an amateur airplane pilot had convinced him that self-contained systems were operationally preferable to those that could be interfered with by outside environmental factors (natural or artificial).

* A fourth group, Hughes Aircraft, started work on inertial systems, but soon withdrew after some initial work on components.

Northrop started in 1946 to develop a system for the high-subsonic SNARK cruise missile. The principal component work was in stellar trackers and computers. The system relied heavily on the stellar information and only marginally on inertial operation, primarily for geometrical stabilization of the star-trackers. After a few years of development and some short-duration flight tests by 1954 Northrop withdrew from the field.

Autonetics (see Ref. 3) started in 1946 to develop a system for the NAVAHO supersonic cruise missile. Their first system, the SN-1, included a stable platform with three single-degree-of-freedom gyros and two doubly-integrating accelerometers (distance meters) supported on a central gas-supported ball (no gimbals). By 1950 this system was flight-tested with flights of two to three hours. At this time Autonetics introduced the six-gyro NAVAN system for reducing the effects of gyro drift.

The NAVAHO missile project did not survive, but Autonetics ingeniously adapted one of its navigation systems for shipboard use and in 1958 [17] furnished the navigation for the under-the-ice crossing of the North Pole by the nuclear submarine NAUTILUS. Autonetics not only pioneered in the development of inertial navigation systems, but also remained as a prolific manufacturer of such equipment, notably for SINS (Submarine Inertial Navigation System) for POLARIS submarines and for the MINUTEMAN ICBM (Intercontinental Ballistic Missile).

Notwithstanding the work of those previously discussed, the M.I.T. Instrumentation Laboratory under Prof. C. S. Draper was the main spearhead in the development of inertial navigation systems and components for aircraft, ships, missiles and spacecraft [3]. Due to its academic association, however, the Instrumentation Laboratory was not in a position to manufacture equipment itself. Its interest in inertial navigation arose from the studies in aircraft instruments begun by Prof. Draper in 1930 [23]. These studies investigated aircraft instruments (gyroscopes, altimeters, tachometers, accelerometers, etc.) as such, and their use in aircraft operations—including both classroom studies for academic credit and flight-testing.

In 1944, discussions with Col. (later Lt. Gen.) Leighton I. Davis, in charge of the Air Force Armament Laboratory, and Dr. John E. Clemens initiated inertial navigation interests at the Instrumentation Laboratory to develop a long-range self-contained bombing system. This work involved theoretical studies to understand the new problems involved, development of components to meet the desired specifications and flight-testing to find what would be achieved.

In 1949, the system known as FEBE – consisting of an inertial platform with gyroscopes, accelerometers, servo-drives, time-drive, computer (very rudimentary), a sun-tracker and a magnetic compass – made an automatically navigated flight from Massachusetts to New Mexico – 10 hours in a B-29. Although not an inertial system itself, FEBE gave flight data of sufficient value to encourage the development of a purely inertial system.

Development of purely inertial navigation systems proceeded along parallel lines for both airborne and seaborne operations. Later, missile and space operations resulted. SINS (submarine, later ship, inertial navigation system) was started in March 1951, was finished in 1954, initially tested on land in a van (which gave very realistic operating conditions under close monitoring and control), shipboard-tested and given a final report in June 1955. SINS combined for the first time an accurate Schuler-tuned vertical indicator and a gyrocompass, each sub-system geometrically aiding the other. It should be noted that SINS basically gave a bounded latitude indication, but its longitude information was still open-ended. By a fortunate coincidence, the results from SINS in 1955 proved to be exactly what was then needed for navigational operation in the POLARIS submarine. SINS, with some modifications, was manufactured by Autonetics and by Sperry.

During this same time interval the airborne development of SPIRE (space inertial reference equipment) was carried on, resulting in the first fully inertial transcontinental flight, from Massachusetts to California, in February 1953. The success of SPIRE in proving the feasibility of a purely inertial navigation system for aircraft led to the development of SPIRE, Jr., a system much improved in performance and reduced in size and weight, that culminated in March 1958 in a transcontinental flight that was subsequently televised by Eric Severeid on "Conquest" in April 1958.

During the development of SINS and SPIRE extensive research and improvement of inertial components was carried out. For example, the residual drift of gyroscopes was reduced from approximately one earth-rate (15°/hour) to approximately one-thousandth of earth-rate (the *meru*, or milli-earth-rate-unit). With feasibility proven and components of inertial quality developed, the reduction to economically sound inertial systems was carried out by many manufacturers and supported by the government. Among such leaders in the manufacturing field were Autonetics, AC Spark Plug Division of General Motors, Litton Industries, Minneapolis-Honeywell, Kearfott, Sperry and General Electric. Military craft, bombers and fighters, were using inertial equipment in the 1960's, and commercial aircraft by the early 1970's.

By 1954, development of inertial systems for ballistic missiles (due to the relative invulnerability of such guidance) was vigorously pursued by all three military services, with the Air Force the most active. Such missiles as THOR, ATLAS, TITAN, MINUTEMAN, POLARIS, POSEIDEN, PERSHING, etc., resulted, with Autonetics, AC Spark Plug and General Electric as the principal producers of the guidance equipment.

In May 1961, the thrust for inertial guidance turned spaceward with President Kennedy's announcement of the Apollo program. Technical details of the program can be found, for example, in AGARDograph 105 [37]. Although but one of many types of navigation systems used, the inertial systems increasingly won respect for their ability, particularly when behind the far side of the Moon. This nation-wide project of vast expanse reached its literally high point on July 20, 1969 with the landing on the Moon of EAGLE. The Apollo guidance system was developed under the supervision of the M.I.T. Instrumentation Laboratory and manufactured by Delco Electronics, Raytheon Corporation and Kollsman Instruments.

In summation, the inertial navigation systems that, without outside aids, (Astronomy in a Closet), guided NAUTILUS under the polar ice-cap, daily guide our commercial aircraft and aided in the landing of men on the Moon are the realization of the science-fiction visionary of fifty or more years ago and a far cry from the simple arts of our ancestors.

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