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1964 STATE OF THE ART NAVIGATION, GUIDANCE AND CONTROL

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Introduction

The funds invested by the Department of Defense in guidance, control and navigation for fiscal year 1964 alone would purchase over 235,000 Cadillacs at $5,000 each. This is a far cry from the fixed rifle sight, the sextant, the eyeball, and the "chewing gum on the windshield" of yesteryear. There are other major government customers of guidance and control technology today in addition to the DoD, must significant being the National Aeronautics and Space Administration (NASA) and the Federal Aviation Agency (FAA).

Where do we stand today in this technology? How did we get here? What significant progress has been made during the past year? Where do we appear to be headed in this technology? These are factors motivating this paper. Partial answers to some of these questions will be given. Obviously, a complete answer to any one question cannot be given in any single short discussion of the subject.

Definitions

The purpose of the guidance system is to control the position and velocity of a vehicle. If the system indicates position and velocity but does not attempt to control these quantities in a closed loop fashion, then it is common to refer to it as a navigation system instead of a guidance system.[1] Most aircraft inertial systems are navigating systems; all missile inertial systems are guidance systems.

Figure 1a shows a generalized functional diagram of a guidance and control system.[2] In order to minimize guidance errors, the system must reduce the effect of interfering quantities and it must respond quickly to command signals. An inertial guidance system is fundamentally mechanized as a specific force measuring system using single-axis accelerometers which operate in coordinates that are determined by gyros.

The guidance system operates as a force vector control system; i.e., the system must change the direction and magnitude of controllable forces (lift, drag, thrust) in such a way that the vehicle reaches its desired point in space and time.

It is usual in the theory of dynamics of rigid bodies in three dimensions to separate the motion of the center of mass from the motion of the body around the center of mass. Guidance is the process of moving the center of mass of the vehicle along some desired path. Stability and control problems are associated with motion about the center of mass. Both guidance and control will be discussed briefly in this report.

There are three fundamental techniques commonly used for navigation or guiding:

1. Inertial systems
2. Systems relying entirely on radiation data, viz. optical, radio, radar and infrared systems. Among these systems are the radio or radar command systems and homing systems (terminal guidance systems).
3. Externally aided inertial systems (combination of methods 1 and 2).

Level of Effort

It is interesting to compare the relative emphasis placed at this time in the United States on these fundamental guidance techniques. Indicators of emphasis might be dollars expended, scientific and engineering manpower engaged in research and developments, numbers of approved projects etc. Probably the most meaningful indicator is programmed funds. Fig. 1 shows the relative breakdown by military departments of Fiscal Year 1964 DoD funds for guidance systems and components.

There are some rather interesting and informative results shown in this figure. For example, it is seen that the Department of Defense spends about one-half of its guidance research and development money on inertial guidance and about one-half on other forms of guidance and navigation (e.g., command guidance systems, satellite navigation systems, etc.). In production, however, 80% of the guidance investment is going into inertial systems. "Production" is used here to represent procurement of systems off assembly lines for operational systems. The apparent inconsistency in emphasis between R&D and production is largely due to the high unit costs of inertial systems in large scale production. Therefore, even though there is a balance in inertial and non-inertial work in the R&D phases, the investment required to produce inertial systems is considerably greater than for radiating guidance systems.

Fig. 2 shows the breakdown of guidance of funds by military departments.

It can be seen from Figs. 1 and 2 that the Army, with only 14% of the total guidance budget, spends 3/4 of these funds on non-inertial guidance. The Air Force, on the other hand, with 61% of the total guidance budget, spends 87% of its guidance funds in the inertial area. The Navy, with 1/4 of the total guidance effort, splits these funds almost equally between inertial and non-inertial guidance. For the overall Department of Defense, more than 70% of its total guidance expenditures are for inertial guidance.

It is interesting to compare the breakdown of effort between research, development, test, and evaluation of guidance components and systems and the procurement of production systems for operational inventories. Fig. 3 graphically demonstrates this breakdown. It can be seen from this figure that the funds are production oriented for inertial systems and R&D oriented for non-inertial systems.

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Because of space and time limitations, it is not possible to cover adequately in this paper the spectrum of all types of guidance, navigation, and control. In view of the fact that about 3/4 of the total guidance and control effort of the Department of Defense is in the inertial field (see Fig. 1), this paper will be devoted to discussing the character of our research and developments in this area. I hope that the AIAA state-of-the-art paper for next year on guidance and control will emphasize the non-inertial area in order that two years will adequately cover the entire field.

Before leaving the subject of non-inertial guidance and navigation, it seems appropriate to list brifely some of the types of work which this area encompasses:

1. Visual and infrared guidance:
    a. Low light level TV
    b. Beam riders
    c. Homers (e.g., Walleye)
    d. Command and Control (e.g., Bullpup)
2. Microwave
    a. Beam riders
    b. Homers (e.g., Shrike)
    c. Command and Control (e.g., Rascal)
    d. Data correlation (e.g., Mace, Pinpoint, Tercom)
    e. Terrain following radar
    f. Ground mapping radar
    g. Earth navigation by artificial satellites
    h. Radio and Loran C

None of these areas will be discussed in the following sections. Instead, guidance and control by inertial techniques alone will be discussed.

Background

Inertial guidance, at the age of 40, is now growing into manhood. And, as most men will affirm, this brings with it growing pains. Inertial guidance is no exception.

What is inertial guidance? Wrigley et al[1] define inertial guidance with succinct clarity as "guidance without the use of any radiation, either natural or man-made." The theorist views inertial guidance as a special problem in classical mechanics, the engineer views inertial guidance as a supreme challenge in precision instrumentation, the military tactician views inertial guidance as a special and important tool responsible in large part for rapidly changing techniques for winning wars, the industrialist views it as big business, and the management executive views it as an important part of the defense industry complex. Thus, depending on the viewer, inertial guidance is at the same time an art, a science, a discipline, an investment, a weapon, and an economic factor. And to all it is at some times both a challenge and a problem.

The Record Book

In citing the age of 40 years for inertial guidance, I have assumed that inertial guidance was born on July 15, 1924, with the issuance of U.S. Patent 1501886 to C. G. Abbot. Abbot, for the first time as far as we know, used gyros to establish a three-axis gyros platform and a gravity pendulum in his system which had very limited inertial capabilities.

Sir Issac Newton is credited with formulating the law of inertia, which is the first of his three laws of motion and from which the name "inertial navigation" is derived. The clue for his general law of inertia was disclosed to Newton by the writings of Galileo a generation earlier, however. Galileo wrote in his Two New Sciences:

> ". . . any velocity once imparted to a moving body will be rigidly maintained as long as the external causes of acceleration or retardation are removed, a condition which is found only on horizontal planes; for in the case of planes which slope downward there is already present a cause of acceleration; while on the planes sloping upward there is retardation; from this it follows that motion along a horizontal plane is perpetual; for, if the velocity be uniform, it cannot be diminished or slackened, much less destroyed."

Galileo's significant discovery was a very great departure from the ideas of motion than prevalent which had been solidly accepted since Aristotle wrote them in Mechanics centuries before:

> "The moving body comes to a standstill when the force which pushes it along can no longer so act as to push it."

It took great wisdom and perception for Galileo to distinguish inertia and friction in the light of Aristotle's teachings which had been accepted for hundreds of years, and it took courage to speak out against them. Galileo lacked none of these noble qualities.

Slater[3] suggests that "inertial guidance" should be called "Newtonian guidance" because the law of gravitation is of equal significance to its functioning as the laws of motion. Other descriptive names have been suggested such as "quiescent guidance" and "non-radiating guidance". We do not know specifically who first coined the term "inertial guidance", but it is a term so common that it is likely to stay with us.

An inertial guidance system operates in a coordinate system which is not rotating or accelerating with respect to the "fixed stars". An inertial or Newtonian coordinate system is one in which Newton's laws are valid. This is an "inside out" type of definition which bothered Einstein and was one of the anomalies of Newtonian physics which led him to search for a broader description of nature. When the classical physicist is asked to define an inertial coordinate system, he generally replies with the second sentence of this paragraph, perhaps with the additional explanation that we can distinguish an inertial coordinate system by the fact that a body on which no external forces are acting moves uniformly in such a coordinate system. If we then ask the classical physicist what does it mean to say that no forces are acting on a body, he replies that it means the body moves uniformly in an inertial coordinate system. Such "around the circle" reasoning brings to mind the ancient question of the chicken and the egg -- which came first.

The classical physicist is forced to admit, under pressure, that he can find an inertial coordinate system only if he can get away from all material bodies and free himself from all external influences. When asked what he means by getting away from all external influences, the physicist states that he means he is in an inertial coordinate system. Again there arises the chicken and the egg.

Einstein[4] asks the question: "Can we formulate physical laws so that they are valid for all coordinate systems, not only those moving uniformly but also those moving quite arbitrarily, relative to each other?" He goes on to say: "If this can be done, our difficulties will be over. He shall then be able to apply the laws of nature to any coordinate system."

Einstein solved the problem of formulating physical laws for every coordinate system with his general relativity theory. This theory, when applied to inertial coordinate systems, is the special relativity theory. The general and special relativity theories are not in conflict, the one is included in the other as a special case.

A number of coordinate systems must be considered in any mechanization of an inertial guidance system. Non-gravitational specific force measurements are made in inertial coordinates. The aircraft or missile is navigating or being guided from point to point on the earth, hence it is necessary for the system to mechanize or remember coordinates rotating with the earth; this is concomitant to saying that the system must carry a clock since, for all practical purposes, the earth's angular velocity vector is constant. Knowledge of the vehicle's coordinates is required because guidance commands are implemented in these coordinates through thrust vector control or by deflecting aerodynamic surfaces. We therefore see that at least three coordinate frames or their equivalent are required in any mechanization of the guidance system.

Early History

The exact birth date of inertial guidance is open to opinion and interpretation. It is safe to say, though, that this did not take place with any single event nor can the credit for its discovery be given to any single individual. Inertial principles were used at an earlier date than Abbot's patent in 1924 in navigating instruments. The shipboard gyrocompass, for example, was invented in Germany in 1908 by Dr. Hermann Anschütz-Kaempfe[5], being made practical by Dr. Max Schuler. For the first time to our knowledge, this application elevated the spinning rotor from the role of a toy or mathematical novelty to that of useful instrumentation. Dr. Anschütz-Kaempe was issued a patent for the gyrocompass in 1908 and Dr. Elmer A. Sperry followed closely with his first U.S. patent in 1911. Companies were formed in the U.S. and Germany bearing the names of these pioneering engineers and these companies have continued to be leaders in the gyroscopic field.

Interestingly enough, the invention of the artificial horizon using gyroscopes predated the airplane and the gyrocompass. This capability was proposed for marine sextants for those cases where the navigator could see the stars but could not see the horizon. This invention, recorded in 1896 by Admiral Fleurias[6] of the French Navy, consisted of a small top mounted in a vacuum box which was attached to the sextant. Lines ruled on the glass lenses were used to observe the vertical as the top precessed around the vertical. Because of its crude nature and because there were not enough opportunities to apply this system, this invention long ago apparently has disappeared from common knowledge.

Schuler Tuning

The Anschutz and Sperry gyrocompasses were gyroscope-pendulum combinations and suffered from lack of accuracy during turns. Anschütz was greatly troubled in 1906 as he was working on the development of the gyrocompass by a paper published by O. Martienssen[7] which showed the gyrocompass would have very large errors under north-south accelerations. He contracted with Dr. Maximilian Schuler who was to look into the problem. Schuler determined that the gyrocompass reading would be insensitive to applied accelerations if its pendulous element had a natural period of oscillation of 84 minutes in the Earth's gravity field. Wrigley[8] calls this condition "Schuler tuning". Schuler tuning immediately improved the gyrocompass art; however, Schuler[9] reported when his first paper on this subject was published in 1923 that insofar as known to him at that time, no one had succeeded in building a gyropendulum as a vertical indicator with a period longer than 30 minutes. He goes on to say that precision gyroscopic instrumentation for the latter purpose will eventually achieve the goal of an 84 minute period.

Schuler's paper is paraphrased and interpreted by Wrigley in reference 8 and translated in its entirety from the German by John M. Slater in Appendix A of reference 10. Schuler appears to be well aware of the great significance of his findings but apparently did not believe inertial navigation was practical without celestial azimuth information. Schuler tuning was not widely known in the United States until after Wrigley's paper was published in 1950. Today, it is a common characteristic of most inertial guidance systems and an elementary bit of knowledge in the minds of every engineer working in the field.

Engineering Research and Production

The technical literature concerning gyroscopes following the invention of the gyrocompass shows a distinct trend away from examining the problem from the classical mechanics standpoint to that of emphasizing purposeful applications and to improving the performance characteristics. We can still see the influence of earlier works, but more and more we see the mind and hand of the practical engineer at work. Reference 11 contains a comprehensive listing of papers published in periodicals through the year 1941.

Around the time of World War I, various companies throughout the world began to manufacture gyroscopic instruments for marine and aircraft applications. Sperry Gyroscope Company was the first such company started in the United States. Another early United States company in the gyro field was the Arma Division of American Bosch Arma Company. Arma started making floated gyros in the early 1920's. (Note that Anschütz relied on liquid flotation from the very beginning in his gyrocompass to minimize disturbing torques.) Arma reports that it has designed, developed, and fabricated over 7500 gyros for compasses, over 1800 precision stable platforms, and has produced 11 land navigation systems using a north-seeking gyrocompass. Arma has the distinction of building the Atlas missile inertial system, the first operational all-inertial ICBM in the United States.

Norden entered the gyro field about 1930 as one of the early entrants in this field in the United States. The scope of Norden's systems work includes bombing, navigation, fire control, missile guidance, reconnaissance, terrain warning and clearance. Norden also produced the AN/ASB-1 and AN/ASB-7 bombing equipment used extensively in Navy heavy attack aircraft.

Boykow and the V-2

One of the most remarkable men who contributed to the development of Trägheitsortung (inertial guidance) was Johann Maria Boykow, a German actor and naval officer who conceived a stable platform similar to that used in many inertial navigation systems today. Boykow's U.S. patent is dated February 22, 1938. Among his numerous inertial conceptions is a platform stabilized with three single-degree-of-freedom gyros and carrying two accelerometers. Velocity information is fed back to torque the two horizontal gyros in order to maintain local coordinates.

The first practical inertial guidance system was developed by the Peenemünde group of German scientists for the V-2 rocket. This system consisted of a gyro assembly with a clock-driven pitch programmer. The gyro system provided an inertial coordinate system and controlled the missile's attitude. One pendulous integrating gyro accelerometer was mounted along the thrust axis to measure velocity and to give a discrete signal to the engine to shut if off when the required velocity was achieved. This system introduced gravity as a bias in open loop fashion.

Boykow worked for some time with the Peenemünde group but did not contribute a great deal to solving any of the many practical problems facing that pioneering group. Among those who did make substantial contributions to the success of the V2 guidance system were Walter Haeussermann, director of the Guidance and Control Laboratory at NASA's George C. Marshall Space Flight Center, Huntsville, Alabama, Dr. Helmut Schlitt of Bell Aerosystems Company, and Theodor A. Buchhold of General Electric.

Post-World War II

The V-2 inertial guidance system, primitive by today's standards, was the only operable system in the world until 1949 when prototype aircraft inertial navigations systems were flight tested in the United States. The first U.S. flights involved systems developed at M.I.T., North American Aviation, Northrop Aviation, and at Hughes Aircraft Company. The M.I.T. system, called FEBE, was flight-tested in a B-29 flown from Massachusetts to New Mexico in the spring of 1949. The Hughes system was tested in a B-26 that was scheduled to fly from Lake Muroc to Fort Bliss in the late fall of 1949, but an emergency landing was made in Sacramento as a result of fuel exhaustion. The Hughes system consisted of Sperry A-12 autopilot gyros (drift rate about 0.5 degree per minute) mounted in a platform supported by a gimbal system which was about 3 feet in diameter. The system was housed in a B-29 gun turret which was mounted inside the B-26 aircraft for the test flight. Two stars were monitored by a telescope capable of night stellar tracking in order to compensate for the very large gyro drift rates. Continuous navigation accuracy better than 6 miles was recorded in the Hughes flight.

John M. Siater in his very interesting introduction to reference 10 says the following about state of inertial guidance in this country at that time:

> "As of early 1946, it is not apparent that even the principles of inertial navigation were clearly understood or defined. On the one hand, efforts were persisted in to make use of gravity vertical references under hopelessly unsuitable conditions; and on the other, in many proposals to make use of accelerometers and integrators, there was a lack of understanding of the principles of feedback for gravity compensation. Many concepts which seem obvious now were not so then, and to lay the foundations of inertial guidance required the efforts of a large array of talent, and a good deal of time.
>
> "The inertial navigation system in its modern form, including gyro-stabilized accelerometers, integrators, and computers for gravitational acceleration was apparently evolved rather than invented, in this country during 1946 and 1947, by personnel in one or more of the organizations mentioned."

Contributing Organizations

A number of educational institutions are carrying out research and educational activity in areas associated with inertial guidance. Most significant is the MIT Instrumentation Laboratory.

Other educational institutions involved with inertial guidance from the educational or research standpoint include UCLA, California Institute of Technology, Polytechnic Institute of Brooklyn, Stanford, Cornell, Case Institute of Technology, University of Virginia, University of Michigan, City College of New York, University of Minnesota, and Ohio State University. This list is by no means complete.

No historical analysis of inertial guidance would be complete without words of recognition for Dr. C. Stark Draper, director of the MIT Instrumentation Laboratory. Draper recognized the possibilities of inertial guidance in the 1930's and has worked incessantly toward the fulfillment of these early dreams. He has been called the father and mother of inertial guidance. The practical realization of inertial guidance systems depended on development of precision gyros and accelerometers; Draper's genius is that he recognized instruments of sufficient precision could be built while many other engineers and scientists doubted. Draper's faith has been confirmed many times over.

The following brief summary of the early activities in inertial guidance at MIT is quoted from reference 12:

> "MIT Instrumentation Laboratory work on inertial guidance was a direct continuation of studies in aircraft instruments started at the Massachusetts Institute of Technology in 1930. These studies were largely concerned with gyroscopic devices from the standpoint of basic theory, design, and manufacture and with applications of inertial space to the operating problems of aircraft and naval vessels. The theoretical aspects of these problems received much attention in graduate courses and research work associated with regular academic work at the Institute. World War II developments of gunsights for warships and aircraft fully occupied the capabilities of the Instrumentation Laboratory until the end of 1944. At that time, discussions with members of the Armament Laboratory of the Wright Air Development Center led to the initiation of a project directed toward the development of non-radiating bombsights for aircraft. The great difficulties to be overcome before any project of this kind could be successful were formidable. Details were necessarily vague, but the great improvements to be made in gyro units, accelerometers, servodrives, amplifiers, time drives, etc., were recognized. All of the essential problems were attacked at the same time, with the clear realization that several years of continuous and coordinated effort would be needed before the possibilities and limitations of inertial-guidance systems could be established. The Instrumentation Laboratory has followed this plan since 1945 with support from the Air Force and Navy in advancing the state of the inertial guidance art by building and testing systems of various types. These types have been selected to cover the full spectrum of theoretical and practical problems associated with inertial guidance."

Many industrial organizations are responsible for the stature to which inertial instruments and systems have risen. Many important organizations have already been cited in this paper; other equally important ones have been omitted. A partial list of significant organizations involved would include the following: AC Spark Plug, Arma, Autonetics, Bell Aerosystems, Belock, Bendix Corporation, Daystrom, General Electric Company, General Precision Incorporated, Giannini, IBM, ITT, Lear, Ling-Tempco-Vought, Litton, Minneapolis-Honeywell, Motorola, Norden, Nortronics, Raytheon, Reeves, Republic Aviation Corporation, Ford Instrument Company, Sperry Gyro Company, United Aircraft Corporate Systems Center, and Whittaker.

This growth of competence and capability in a large number of different organizations stimulates great competition in this field. This stimulation is good in many ways, but it also presents the customer with many difficulties. James Farrior[13] wisely recognized this condition:

> "Today's customer finds himself faced with a bewildering array of components and systems being presented by a large number of firms, each claiming certain superior features for their products and presenting increasingly larger amounts of statistical data to support their claims. This intense competition has undoubtedly been partially responsible for the rapid improvement in the state-of-the-art. However, it is hard to see, from the manufacturing standpoint, how the large guidance and control industry can continue to thrive on the somewhat limited number of missiles and space vehicles being built, which indicates that it is probable that in the future an increased effort will be put into the further development of such other markets as commercial and military navigation systems for ships and planes. Many concerns will find that the capabilities they have developed will put them in good position to enter other still expanding markets, such as medical, scientific, and industrial devices."

Inertial Components

Inertial sensors are used to obtain information on orientation and accelerations relative to a reference frame in which Newton's laws are valid. Orientation (attitude) measurements, the frame of reference, is maintained by gyros in an inertial system. Gyros are therefore the source of angular information. Acceleration measurements, which are integrated two times to provide distance, are the source of linear information. Missiles and space vehicles operate in three dimensions, hence three independent angular and linear measurements must be instrumented. Cruise vehicles (aircraft, ships, submarines) operate essentially in a two-dimensional plane (the earth's surface), hence require instrumentation for three angular measurements and only two linear measurements. Altitude measurements in cruise systems are normally not sensed by inertial techniques. The altitude channel, which is parallel to the gravity vector, is unstable in an inertial navigation system for cruise vehicles. It is interesting to note that in an orbital system, where gravity is balanced by centrifugal force and the "free fall" or zero-g condition exists, the instability in the altitude channel of an inertial system disappears; the unstable axis rotates 90° and now shows up as the range channel.

Gyroscopes

Orientation relative to inertial space requires some physical factor that can be geometrically isolated from its surroundings. The only factor that has fulfilled this requirement in a practical engineering sense to date is the angular momentum of a spinning rigid body. Only three laboratory concepts among the exotic or unconventional angular sensors do not use the concept of angular momentum; namely, those that use vibratory momentum, nucleons (which exhibit spin momentum, but can hardly be classed as rigid bodies), and the transit-time difference of two beams of radiation which are propagating in opposite directions around the same closed path. Otherwise, the array of unconventional angular sensors are merely different ways of isolating spin momentum from its environment. Any physical quantity having directional characteristics which can be maintained in the face of interferences can be used for spatial orientation reference. To the best of our knowledge, no radically new concepts have appeared during the past year which cannot be classed fundamentally as spinning rigid bodies, vibratory momentum devices, nucleon devices, or closed-path radiation devices.

The two primary properties of gyros which are utilized in navigation systems are:

1. The property of pointing to a fixed direction in space. This property is one of the fundamental properties of matter. Newton's first law, the law of inertia, states that everybody remains at rest or continues in uniform motion in a straight line unless acted upon by some external force. As applied to a rotating body, inertia causes a rotating body to continue with its present angular velocity about a fixed axis of rotation until action upon by some external torque. A practical gyro instrument, however, drifts due to unwanted torques resulting from less than perfect machining, bearing and lubrication frictional torques, slight changes in material properties causing mass unbalances, dust and other foreign matter causing undesirable torques, material impurities and imperfections, dimensional instability of machined parts, and degassing.

2. Its ability to convert an angular velocity to a torque, and vice versa. The spin vector precesses toward the torque vector. Understanding the operation of a gyro is therefore a three dimensional problem. This gyroscopic property is reversible -- i.e., a torque input results in an angular velocity output (precession) and an angular velocity input (forced precession) results in a torque output.

Gyros are naturally classified into two main categories depending on which of these two primary properties are predominant in the instrumentation. These categories are shown in Fig. 4. The two-degree-of-freedom gyro (2DF) is sometimes called a "free" or "amount" gyro; it uses the property of gyroscopic "rigidity in space" and can be used to measure directly a vehicle's angular deviation from any given reference coordinate system. The interaction of torque, spin, and precession is the primary property instrumented in a single-degree-of-freedom gyro (SDF). SDF's may be either "rate" gyros (angular velocity output) or "rate integrating" gyros (angular displacement output). A "rate" gyro has an elastic or spring restraint (torque proportional to displacement) to counteract output gyroscopic torques (see Fig. 4). A "rate integrating" gyro has a viscous restraint (torque proportional to velocity). Some 2DF gyros are also instrumented as "rate gyros".

An inertial navigation system requires either two 2DF gyros or three SDF gyros in order to establish inertial coordinates in three dimensions. The "quality" of this inertial reference depends on the precision of the gyro instruments.

The floated integrating gyro with electromagnetic centering is the most accurate unit available today when operations involve thrust and gravity. Random drift characteristics of production gyros vary a great deal depending on what the customer is willing to pay. Unit costs and percentage of yield in production (i.e., the percentage of those produced which pass acceptance inspection) are highly correlated numbers. If the customer wants very high performance and makes this a required specification, then the number of assembled gyros which pass acceptance tests can be expected to be low, the number of rejects high, and the cost of acceptable gyros high. It is not unusual for yields to be a few percent and unit costs to be measured in tens of thousands of dollars.

Reasonable progress has been made during the past year at improving the inherent accuracy of these instruments, at obtaining this accuracy with a higher fraction of units produced, for longer periods of time, and at less cost and weight. New materials such as ceramic rotors are being introduced bacause of certain favorable material properties. Case rotation to reduce mass unbalance drifts is being practiced on a wider scale. Modulating angular momentum to separate error sources in order to improve accuracy through better compensation has been demonstrated in a number of gyro laboratories. The long debate over gas bearings vs. lubricated ball bearings continues with progress being made on both fronts. The fundamental physics of lubrication, long a speculative subject, is now beginning to be understood. The race between gas bearings and ball bearings is still competitive; there are merits to each type depending on the specific requirements of the system being instrumented.

A practice which is gaining favor in some applications such as submarine inertial navigation systems (SINS) and some ballistic missile platforms is the use of a redundant gyro to calibrate the basic platform gyros. The redundant gyro is sometimes the same type of instrument that exists in the platform, but case rotation and other techniques are utilized to improve its performance. The redundant gyro is a "standard" to which other gyros in the platform are calibrated.

One of the significant areas in which the gyro state-of-the-art has advanced in recent years is in digital pulsed-torquing. This advance, when coupled with the very significant advances realized in computer technology, has made strap-down inertial systems (no gimbals, body-mounted gyros and accelerometers) approach competitive performance with conventional gimballed systems for some applications where vehicle angular rates are not too high.

Spinning Mass Gyros: Free rotor types

The free rotor gyro operates in principle the same as the gimballed gyro. The rotor in this case is spherical in shape. This gyro exists in various forms depending on the method used for supporting the rotor. The three primary support methods are gas bearings, electrostatic forces, and magnetic forces. The rotor generally has an electrically conductive rim which is driven as an eddy current motor by a case-mounted stator.

In the gas-bearing-supported rotor, the gap between the rotor and case is filled with gas under pressure. The gap in the electrostatic supported gyro is a vacuum and the rotor is kept centered by electrostatic forces. The motor in this instance is used to start the gyro and get it up to speed. The rotor then coasts for a period of months since friction torques in the vacuum are extremely small.

A very interesting, although not necessarily the most practical, electromagnetically supported gyro is the "cyrogenic gyro". In this instance, the rotor is immersed in liquid helium and is a superconducting sphere, which magnetic lines of force do not penetrate. Interaction of supercurrents flowing at the surface of the sphere and the external magnetic field provides the supporting force as well as affording stability without a separate servo control. The principal error sources in cyrogenic gyros are asphericity and erroneous center of gravity location of the rotating sphere, trapped stray magnetic fields, energy transfer owing to read-out devices, and lack of knowledge of the superconducting state. A severe difficulty which remains to be solved are AC losses in the superconductor. General Electric Co. and the Jet Propulsion Laboratory are two primary centers of cyrogenic gyro research.

Another interesting free rotor gyro uses a rotating fluid sphere instead of a metallic ball.

Gyros used in space systems should be designed specifically for the space environment. The zero-g condition coupled with the requirements for low power consumption and long times of operation results in somewhat different design criteria than in gyros used near the earth's surface. It is possible that some of the unconventional gyros may be useful in space applications.

The electrostatic gyro (ESG) has demonstrated performance on a par with the best of any other type of gyro. This gyro consists of a spherical beryllium shell suspended in a hard vacuum by strong electric fields. The spherical shell is the rotor and is spun up to a high speed and permitted to coast. Credit for conceiving the electrostatic gyro is due to Dr. A. T. Nordsieck, then of the University of Illionis.

The primary sources of drift in ESG's are mass unbalance of the rotor, magnetic torques resulting from interaction of induced currents in the rotor with the exciting magnetic field, and electric torques due to geometric imperfections in the suspending field and the rotor.

It is well known in electrostatics that the suspension by fields of a body with constant charge distribution is not stable in all directions. In the ESG, fields are created by placing high voltages across electrodes arranged concentrically with the rotor. These voltages are carefully controlled by servo techniques to force the rotor continuously toward the center of the gyro case. The rotor never comes in contact with the case. The operation of the ESG requires continuous use of a high performance servo, otherwise it would be ideally suited for space applications. Minneapolis-Honeywell and General Electric Co. are industrial concerns performing ESG R&D on a government funded basis.

Vibrating Momentum Gyros

There has been no significant progress made in vibratory momentum gyros in recent years. This concept was first described as the tuning fork gyro in the literature in 1953 by Sperry engineers. Almost continuously since, the government has supported research on these devices, usually in the form of vibrating crystals such as quartz or piezoelectric ceramics.

The linear momentum of a vibrating mass is the analog of the angular momentum of a spinning rigid body. Linear momentum can be used as an inertial characteristic for measuring angular motions.

Gulton Industries investigated the use of a radially vibrating ceramic disk as an angular rate sensor. The difficulty with this concept was isolating the driving frequency from the pick-off frequency. Westinghouse uses a ceramic cylinder; under an oscillating excitation voltage, the moment of inertia about the longitudinal axis ocillates. The piezoelectric cylinder acts as a crystal to control the frequency of the driving oscillator. The primary difficulty with this device is null stability.

Nuclear Gyros

Nucleons are much better magnetometers than gyros. As a solid state gyro, they might appear to be useful. Although progress has been made in the last year, it appears that the use of nucleons as gyros in practical instruments must await many years of laboratory research.

The nuclei of certain atoms exhibit an angular momentum and a magnetic moment. The nuclear angular momenta are normally randomly oriented in space. They can, however, be statistically oriented by the action of an external magnetic field on the nuclear magnetic moments. The resultant macroscopic angular momentum is stable with respect to inertial space.

Nuclear magnetic moments can be observed by means of magnetic resonant effects and atomic beams. Various methods using these techniques have been considered for mechanizing nuclear gyros. Basically, angular rotations of the case are measured with respect to an ensemble of nuclei aligned in inertial space.

Laser Gyros

The laser gyro measures the transit-time difference of two beams of radiation which are propagating in opposite directions around the same closed path. This is an application of the lesser known of Michelson's two famous experiments with light. The laser furnishes adequate energy levels with coherent wave patterns to permit reasonably accurate and sensitive levels of rate measurements. There remains much research ahead before these instruments will be of practical use.

Accelerometers

All acceleration-measuring devices in use today employ the inertia reaction effect of a proof mass, in some cases restrained to a null position, and in others absorbed by a counter reaction. As with gyros, no accelerometers of radically new concept have appeared during the past year.

Inertial velocity-measuring devices, as such, are non-existent, due to the fact that unique inertially-referred velocity is meaningless. Velocity data obtained by measuring the motion of the surrounding medium, such as by aircraft pitot tubes and ship's logs, have been used for many years. Velocity measurements by electromagnetic radiation methods such as with doppler radar in aircraft and doppler sonar in ships is constantly being improved. Velocity measurements relative to the earth's electric or magnetic fields is a theoretical possibility, but the variations in these fields make this impractical.

In most current models of accelerometers, the proof mass is manifested as pendulous unbalance, and generally is supported by flotation. It is a well known fact from Einstein's principle of equivalence that an accelerometer cannot separate gravitational acceleration from inertial acceleration. These effects are separated by computing gravity and subtracting it from total measured acceleration in the feedback loops, the process known as Schuler tuning.

Pendulous accelerometers

The null-reading torque-balance pendulous accelerometer is very common. It may have either analog (steady) or digital (pulsed) measurement data. Such units can be made quite simple and relatively inexpensive and small while providing reasonable accuracy. Pulsed torquing also permits the inherent direct integration required to give velocity information in digital form. This type of accelerometer provides adequate performance for most requirements.

Magnetic drag-cup velocity meter

A sketch of the principle of operation of this accelerometer is shown in Fig. 6. The permanent magnet and the electrically conductive cup are closely spaced coaxial cylinders. The sensing element is a simple pendulum which deflects when subjected to accelerations. When the pendulum deflects, the signal generator sends an electric signal to the motor which is proportional to deflection of the pendulum. Other electromagnetic methods may be used instead of the signal generator to sense rotations of the pendulum. The motor rotates the permanent magnet in such a direction as to torque the pendulum back to "null" through electromagnetic coupling of the drag cup and permanent magnet.

An ideal Newtonian fluid is one in which the stress is a linear function of shear. In the instrument sketched here the permanent magnetic cylinder electromagnetically induces a drag torque in the conductive cup which is proportional to angular velocity, hence the electromagnetic coupling acts as a Newtonian fluid.

This type of accelerometer is another variation of the simple pendulum. It is unique in the sense that it effectively uses a differentiating element (the drag cup coupling) in the feedback loop to achieve integration. Motor speed is proportional to acceleration; total shaft angle rotation of the motor is proportional to velocity-hence the name velocity meter. This instrument is accurate and is in large scale production for ballistic missile guidance systems.

Pendulous integrating gyro accelerometer (PIGA)

The most accurate accelerometer in production today is the pendulous integrating gyro accelerometer (PIGA). Its use is desirable where high accuracy is required, particularly where accurate velocity measurements are essential such as in ballistic missiles and space booster operations. Gradual improvements are being made today in these instruments.

A sketch to illustrate the principles of operation of the PIGA is shown in Fig. 7. In this instrument, the force measuring mechanism is a simple pendulum. An integrating gyro is used to provide precision measurement of the torque generated by the pendulum when it is accelerated. The output of this accelerometer is a signal proportional to velocity. This output is the angle θ of the motor shaft shown in the sketch; more precisely, the output is an electrical signal proportional to this angle. The rotational rate of the motor is proportional to acceleration.

When the PIGA is accelerated along the input axis, the pendulous mass lags as if it were a simple pendulum which is free to rotate about the output axis. As the output axis rotates, the signal generator generates an electrical signal proportional to the angle of rotation.

This signal is amplified and drives an electric motor which rotates the gyro gimbals about the input axis at a rate proportional to the applied acceleration. The total angle of rotation θ is proportional to the first integral of acceleration i.e., velocity.

The rotation of the motor shaft forcefully precesses the gyro about the input axis and causes the gyro to generate a torque about the output axis in such a direction as to balance the pendulous torque generated under the applied acceleration. Gyro precession properties are therefore used to balance the torque generated by the unbalanced pendulous mass. The PIGA is a complex unit that is expensive to build. It is, however, the most accurate type of accelerometer which is currently in large scale production.

Vibrating string accelerometer (VSA)

This instrument employs the physical principle that the natural frequency of a taut string is proportional to the square root of the tension. If one end of the string is attached to a mass which is free to move when the instrument is accelerated, then the natural frequency of the string increases if the mass tends to stretch the string.

In a practical instrument, the vibrating string is actually a metal tape which is constrained to vibrating in one plane in order to improve measurement accuracy. Two strings are attached to a proof mass located between the strings, see fig. 8. The mass is constrained to moving in one dimension only, the "input" or "sensitive" axis. The strings are metal and are caused to vibrate by electromagnetic methods; i.e., the tapes are in a magnetic field and will vibrate when a current runs through them. The vibration is maintained at a constant amplitude and at the natural frequency of the strings by means of servo feedback techniques.

When the accelerometer is accelerated in the direction of its input axis, the tension is increased in one string and decreased in the other. The difference frequency is proportional to the applied acceleration. The sum of the two frequencies is maintained constant by a tension adjust mechanism in order to improve the accuracy and linearity of the instrument.

The integral of the difference frequency, the number of difference cycles (measured as pulses), is a direct measure of velocity. This instrument can therefore be looked upon as an integrating accelerometer.

The VSA is in large scale use in this country. Its output is a series of pulses which makes it a natural instrument for use with digital systems.

Vibrating quartz accelerometer

The vibrating quartz accelerometer is analagous to the vibrating string accelerometer. It consists of resiliently supported mass-loaded capacitor plates which are used in conjunction with an inductor or resistor to form an acceleration responsive oscillator. Since no driving magnets are required such as in the vibrating string accelerometer, this may result in a simpler and cheaper unit.

Mosbauer accelerometer

An interesting exotic accelerometer is one that utilizes the Mosbauer effect. This is the unclear analog of the vibrating string accelerometer. The extreme accuracy inherent here has permitted experimental proof of the gravitation-time relationship of general relativity. However, its very sensitivity makes its practical vehicle-borne use questionable. It certainly requires considerably more laboratory research.

Other accelerometers

As an indication of the large numbers of different types of accelerometers which have been examined or are currently being studied at various companies and laboratories, the following list is representatives:

Electrostatic accelerometer	Bell Aerosystems
Pressure differential accelerometer	Case Institute
Piezoelectric accelerometer	Gulton
Liquid column accelerometer	QMF and CIAF
Seismic mass accelerometer	Research, Inc.; Kearfott; and Whittaker
Semiconductor accelerometer	Diamond Ordnance Fuze Laboratory
Radioactive accelerometer	Frankford Arsenal
Piezoresistive accelerometer	Frankford Arsenal
Chatter piezoelectric accelerometer	Bureau of Standards
Lenz Law pendulous accelerometer	Donner Scientific Co.
Vacuum Tube accelerometer	MIT, Calidyne, RCA
Polar coordinate accelerometer	White-Rodgers
Capacitive accelerometer	Lockheed Missiles and Space
Statham Accelerometer	Naval Air Material Center
Contact accelerometer	RAE Farnborough
Barium Titanate accelerometer	Bureau of Standards
Ramberg Vacuum-tube accelerometer	Bureau of Standards
Strain accelerometer	Autonetics
Variable reluctance accelerometer	Gulton

Differential transformer accelerometer	Gulton
Bender seismic system accelerometer	Gulton
Photocell miniature accelerometer	JPL
Manometer spider tube accelerometer	Nortronics

Computers

The past year has brought about very sifnificant progress in computer engineering. Microelectronics, discussed for a number of years in the literature, has become an engineering reality during the past year. One of the largest and most significant of the microelectronics programs is the MINUTEMAN guidance system development program. Others are the Bureau of Weapons AN/ASN-44 aircraft inertial navigation program, the BuWeps Loran C navigation receiver, AN/ASA-27 airborne digital computer for the Grumman F-2A aircraft, and the guidance computer for the MMRBM weapons system.

Microelectronic circuits have a way of permitting us "to eat our cake and have it too." Weight and power loads are significantly reduced, computational speeds increased, reliability greatly increased, and heat dissipation requirements reduced (hence heavy environmental cooling equipment can be removed or reduced). In order to realize the greatest benefits in production of microcircuits, it is important to keep the number of different logic circuits required in a given computer at a minimum. This requirement presents special constraints on the logic designer. Ideally, a new microelectronic computer would consist of interconnection of many chips of only one type of logic circuit. In fact, however, the best of currently designed computers require 12 to 20 different types of microcircuits to make up the complete computer. Some microcircuits are easier to produce than others, and some companies seem to have more success than others at producing. In the past year we have solved some of the problems limiting large scale production of microcircuits. Costs of individual chips are still high, but these costs have almost been cut in half during this period.

I believe that one is safe in predicting that microelectronics will become commonplace in the near future, not only in computers but in platform electronics, sensor electronics, and communications circuits as well. The cost of complete systems will probably be as low or lower than the cost of an equivalent system built from conventional discrete solid state circuit elements. Electronic system reliability will continue to improve very greatly as part counts are reduced.

Conscientious efforts are now underway in a number of organizations to advance the state of the art in fabrication of memory elements and in the hardware of interconnecting microelectronics wafers. Memory technology includes thin films, magnetic ferrites, metallics, semiconductor memories, electromechanical memories, and core-rope memory.

There is somewhat of a tendency on the part of guidance system designers to use digital circuits in too many places. Some savings in system cost, complexity, and weight can be realized in some applications at little penalty in accuracy if analog or DDA systems are used instead of digital arithmetic computers. Unnecessary sophistication should be avoided even if sophisticated tools are available.

Advances in computer technology have brought about changes in systems technology. There is a tendency more and more in advanced ballistic missile guidance systems to use explicit guidance equations because of the greater targeting flexibility these equations provide rather than the more conventional guidance equations which use perturbation techniques. Explicit equations are particularly attractive when external data are utilized to update the trajectory; as an example of this type of application is the use of azimuth or position data obtained from star sensors.

In some advanced systems under development, comprehensive trade-off studies have been conducted to determine the degree of centralization of data-processing desired. Cost, weight, reliability, and operational mission factors are often of paramount concern in deciding whether or not one central data computer is desired rather than a number of different smaller computers associated with the various subsystems which go together to make up the overall system. In some instances, the system can be viewed as an information processing problem, in which case the computer becomes the heart and core of the system. As microelectronics become more common, this trend is likely to grow.

Computers with higher and higher computational rates and larger capacity have now made strap-down inertial systems an engineering reality. In these systems, the physically stabilized platform is replaced by a mathematical problem -- many processes carried out physically in normal systems are performed mathematically, thus placing a much greater load on the computer and the inertial sensors.

Guidance Systems

The trend continues toward smaller, more accurate, more flexible guidance systems. There have been during the past year some significant changes in emphasis from that of previous years, however. These changes include emphasis on the capability for low-cost production of aircraft and short-range missile guidance systems, high-g capabilities for reentry guidance and for guiding high acceleration anti-missile missiles, and integrated space guidance system design to include in one basic guidance system the capability for performing boost, in-orbit, and reentry guidance functions. Each of the systems areas is discussed briefly in the following sections.

Aircraft

Aircraft inertial navigation systems may be divided into the following three categories depending on the gyro reference coordinate system used:

1. Inertially fixed system

2. Earth fixed system

3. Local vertical fixed system

These systems may also be categorized in many other ways:

1. Disposition of sensitive axes of the accelerometers relative to the gyro reference axes.

2. Three-gimballed or four-gimballed systems (the latter is often used to reduce programming requirements or maneuver limitations for preventing gimbal lock).

3. The use of 3 single-degree-of-freedom (SDF) gyros or 2 two-degree-of-freedom gyros.

4. The use either of analog or digital computer. Digital techniques, either arithmetic or digital differential analyzer (DDA), are required in systems of very high accuracy.

5. Whether or not externally measured velocity information is used as an input to the inertial system. Velocity measured by doppler radar, for example, is often used to damp the inertial system. If the aircraft carries a long range air-to-surface missile, it is common to use doppler velocity, after being smoothed in the inertial system, as initial or launch velocity for the missile system.

6. Whether or not position information derived external to the inertial system is used as an input to the inertial system. Such position information is generally of the form of angular position measurements of stars, or electromagnetic radiation data such as measured by radio. Continuous tracking of stars makes possible gyro drift compensation in-flight as well as providing a means for obtaining a stellar fix. Accurate knowledge of the vertical and angular measurement capabilities of the star sensors are two of the performance-limiting factors with the stellar system.

It is clear from the foregoing list that aircraft inertial navigation systems can take many shapes and forms depending on the permutations and combinations selected. Each particular configuration has its own merits and disadvantages, hence the most desirable system for any particular aircraft system is a strong function of what characteristics the customer feels are most important.

Operational reaction times influence greatly the accuracy of initial alignment in vertical and azimuth. Reducing reaction times is still one of the major difficulties with aircraft inertial navigation systems. Obtaining accurate launch vertical, azimuth, position, and velocity is of particular difficulty in carrier-based aircraft because these data must be transferred from some external source, such as SINS. The master navigational source itself has errors, and additional errors are introduced in the process of transferring the information from one navigational system to the other. Considerable progress has been made in the past year at improving transfer of angular information in carrier based systems.

A natural way around the problem of reaction time is to use stellar-doppler-inertial aircraft systems. Initial conditions can be effectively set into the inertial system after take-off by using stellar derived data. These systems have larger part counts, hence the cost is high and reliability is not as good as in pure inertial systems. Additionally, weather influences the operation of the system. We still have difficulty seeing stars accurately at low altitudes in the daytime, particularly in high haze or humidity conditions, even when the sky is clear. Obviously, clouds interfere with the operation of such systems.

Stellar sensors for use in aircraft and missile systems generally are one of three basic types: photomultiplier tubes, vidicon tubes, or solid state sensors. Photomultiplier tubes have been used for many years but have been replaced in recent years more and more by vidicon tubes and solid state detectors. Much progress has been made in the last year in both of the latter two types of sensors. I believe one is safe in predicting that eventually most sensors used in aircraft navigation systems will be of the solid state type. There is room for much improvement in this area, however, in sensitivity, accuracy, cost, reliability, and maintainability.

Probably the most significant trend in aircraft navigation systems which has only recently developed real momentum is the emphasis on system cost in large production quantities. The Air Force, with the blessing of the Secretary of Defense, has established as a goal a unit cost of $25,000 per system in large production quantities for a one nautical mile per hour system. Such a goal is an ambitious one, but it appears to be attainable. It appears difficult to achieve such a cost goal using conventional floated gyros, hence it is possible the low cost requirements may be the motivating force leading to application of unconventional sensors.

Along with the need to reduce production costs is the need to integrate the navigation system more fully with the flight control and flight instrumentation systems. There is a tendency today to develop completely separate flight data systems, autopilot systems, and navigation systems as well as fire control systems for those aircraft equipped with weapons. Obviously, many of the measurements required of each of these systems could be made with the same sensors. Much more use over and above ground position data can be made from the data gathered by the inertial sensors and the stable platform. We would like to see more efforts in this direction in the future.

One of the significant milestones of the past year was the successful test by the FAA of inertial navigators in many trans-Atlantic flights. Another significant milestone was flight test measurements of accelerometer and velocity matching techniques for transferring information from a master navigator in an aircraft to slave guidance systems of missiles carried aboard the aircraft.

Although aircraft inertial navigators have been tested in one form or another since 1949, it was not until the 1960's that systems were produced in any significant quantities. Today, we have over 1000 operational military aircraft equipped with inertial navigators. Anyone who has flown any of these aircraft knows first hand the great value of precision on-board position determination -- value from the standpoints of both military usefulness and safety of flight. I believe that one is safe in predicting a much larger percentage of the aircraft inventory, military as well as commercial, will be equipped with inertial navigators in the future.

Most of the operational aircraft systems in the field today have been built by Litton Systems, Inc. These include the F-104, W2F, P3V, and A2F aircraft. Autonetics developed the stellar-doppler-inertial system for the B-70. Sperry had systems responsibility for the bomb-navigation system in the B-58; this system is a doppler-inertial system monitored by radar and an astrotracker. Norden designed the ASB-7 system for Navy heavy attack aircraft; this is a doppler system which also incorporates a stable platform. Autonetics has bombing-navigation system responsibilities for the A5A Vigilante aircraft.

Ships and Submarines

Ships inertial navigation systems (SINS) presents the most severe gyro accuracy requirements of all inertial navigation and guidance systems. SINS has a big advantage over aircraft, missile, and space systems, however, in that size, weight, and power considerations are much less constraining. Gyro performance in SINS is generally one or two orders of magnitude better than gyro performance in missile systems. The relation between gyro drift and navigational accuracy is very straightforward, one minute of arc corresponds to one nautical mile at the earth's surface. Hence, a gyro which drifts at the rate of 0.1 degree per hour drifts 6 arc minutes per hour, or 6 nautical miles per hour. Present operational SINS systems have much better performance than this.

The Navy first contracted in 1948 for the development of a combination gyrocompass and stable vertical as progress in the MIT FEBE airborne system led to speculations concerning potential marine applications. This Navy program at MIT, called MAST (Marine Stable Element), was tested in the laboratory in 1952 and at sea in 1953. As a result of early component and subsystem tests, and as greater understanding of inertial navigation evolved from early systems analysis, Dr. Stark Draper and his MIT subordinates suggested to the Office of Naval Research the development of a Ship (Submarine) Inertial Navigation System (SINS). A study program of this system was started in June 1950 and hardware development started in March 1951. SINS was completed in mid-1954, tested in a moving van shortly thereafter, and tested at sea in late 1954 and early 1955. The final report on this program was submitted by MIT in June 1955.

The great success of the SINS development at MIT led the Navy to install inertial navigation systems in Polaris submarines. Ultimately, SINS systems were installed in other Navy ships such as aircraft carriers and in range ships for the Atlantic and Pacific Missile Ranges.

Most of the Polaris submarines are being equipped with Autonetics or Sperry SINS systems. Advanced SINS work is also being carried out at Nortronics, MIT, and Honeywell, among others.

Recent progress in SINS has been in the direction of higher accuracy and higher reliability. At the same time, considerable reduction in size, weight, and power has been achieved. Improved gyros and techniques of monitoring platform gyros with a redundant gyro are among the important improvements of recent years.

Missiles

The most comprehensive inertial guidance developments in the United States are for our ballistic missile systems. Following are the organizations with primary responsibilities for the guidance portion of the major missile programs:

1.	ATLAS E and F	Arma
2.	TITAN II and III	MIT and AC Spark Plug
3.	POLARIS A1,A2, and A3	MIT and General Electric
4.	MINUTEMAN	Autonetics
5.	MMRBM	General Precision Aerospace
6.	SKYBOLT	Nortronics
7.	JUPITER	Army Huntsville, Ford Instruments, and Bendix Eclipse-Pioneer
8.	PERSHING	Army Huntsville, Ford Instruments and Bendix-Eclipse Pioneer
9.	THOR	MIT and AC Spark Plug

Additionally, we have developed a number of inertial guidance systems for cruise missile, which are more like aircraft systems than ballistic missile systems. The major ones have been:

1.	HOUND DOG	Autonetics
2.	SNARK	Nortronics
3.	NAVAHO	Autonetics
4.	MACE	AC Spark Plug
5.	REGULUS	AC Spark Plug
6.	RASCAL	Bell Aerosystems

Missile guidance systems have grown smaller and more accurate with each new development. The past year or so have brought on advances which are probably more significant than in any single year since the missile programs began after World War II. Some of the advances are as follows:

1. Microelectronic computers have brought about significant reductions in size, weight, and power while at the same time improving reliability.

2. Revolutionary new platform concepts have evolved and have been shown to be technically practical. Instead of supporting the stable platform with conventional gimbals wrapped around the inner package, it is now possible to float the stable platform as a ball inside a concentric sphere. Flotation permits high-g operations. In a ballistic missile, this means the missile can be guided throughout its trajectory, including reentry, instead of just during the boost phase as is now done.

3. Flotation of conventional gimballed systems to increase g capabilities without degradation in performance has been demonstrated to be feasible.

4. With the capability of guiding during high accelerations using techniques (2) or (3) above, it is possible to maneuver the reentry vehicle to improve penetrability without loss in accuracy.

5. Within the past year and a half, stars have been tracked during boost for the first time. Considerably improved measurements of the sky light background during day and night have been recorded. These measurements have been made from high flying aircraft, balloons, and ballistic missiles.

6. Considerable technical progress has been made in gyrocompassing techniques and accuracies for both mobile and fixed missiles.

There has been a steady reduction in inertial measurement unit (IMU) physical size from the garbage can size of previous years to the basketball size of recent years. Now, we are seeing systems in advanced development which are the size of a softball.

Production costs, of secondary concern to accuracy and reliability in long range ballistic missile systems, is of major importance in short range missiles. The DC Automet guidance system in the Army's LANCE missile is one attractive approach toward lower guidance system costs. The Navy is developing a low cost inertial system for a ship-to-shore fire support missile of tactical ranges.

<u>Space Guidance and Control</u>

The emergence of space exploration has kindled men's minds and has brought on a host of challenging new engineering problems, not the least of which are injection guidance, in-space navigation and attitude control, and reentry guidance. NASA has entered the guidance field as an important customer as well as a significant house for guidance research at its various research centers. Of particular interest is the guidance laboratory at the George C. Marshall Space Flight Center in Huntsville, Alabama. This laboratory, headed by Dr. Walter Haeussermann, has evolved from the original Peenemunde organization and must be credited with many original developments in the inertial guidance field from the first V-2 guidance system to the Saturn guidance system currently being tested. Dr. Haeussermann's team has concentrated on missile guidance concepts since it was originally organized in the late 1930's and early 1940's. In the early 1950's, this group began seriously to look at orbital and space guidance problems and concepts.

Attitude control of orbital spacecraft is closely related to the guidance problem, particularly in some instrumentation approaches. Many organizations and individuals have contributed significant work in this area; these organizations include MIT, JPL, APL, RCA, Lockheed, General Electric, Minneapolis-Honeywell, United Aircraft Corporate Systems, and Reeves Instruments.

Reliability is of great importance in all guidance systems, particularly in space missions. In order to obtain the required reliability in booster guidance, it is necessary that a few standard boosters have the ability to inject into suitable trajectories a variety of spacecraft with widely different space missions. It is only through such repetitive use that the reliability can be improved to the very high level required.

Space not only introduces new problems into the guidance and navigation art, it also introduces new solutions to age-old problems. The following quotation is taken from Vice Admiral John T. Hayward's very interesting paper[14] on space technology and world navigation:

> "Space is a great stepping stone for improving man's standard of living and for broadening his knowledge of the world in which we live. I feel that the Navy satellite navigation system is one of the great fundamental strides upward in the direction of utilizing space to improve the world as we know it."

NASA in the Apollo program and the DoD in the Standardized Space Guidance System (SSGS) are approaching the space guidance problem from widely divergent views. Each concept appears to be sound for the particular objectives being sought.

The SSGS concept views the space mission as a whole from launch to touchdown. The same basic system, or portions thereof, is used for boost, injection, in-orbit guidance and attitude control, retrothrust, and reentry. The APOLLO concept, on the other hand, views the space mission as a series of separate phases, each of which requires a separate guidance and control system with appropriate interfaces between phases. The Saturn booster, the Command and Service Module, and the Lunar Excursion Module, for example, each has its own independent guidance and control system.

Space guidance and control hardware is largely an outgrowth of missile technology. The TITAN III booster, for example, uses a modified version of the TITAN II guidance system. The SATURN booster uses hardware which is a logical extension of JUPITER and PERSHING technology designed by Dr. Haeussermann's team at the Marshall Space Flight Center and manufactured by Bendix. The APOLLO IMU, designed by MIT and manufactured by AC Spark Plug is an outgrowth of the POLARIS Mk II system which was designed by MIT and manufactured by General Electric.

The space environment is vastly different from the missile environment. Operating times are much longer; accelerations and vibrations run the gamut from nothing in space to very high levels during boost and reentry; power requirements, reliability, and temperature control problems are generally severe in both missile and space applications. Strap-down inertial systems appear to be practical in orbit and may be useful for boost and reentry as well. Microelectronics are just as important in space as in missiles, if not more so. Long time space operations put a premium on electromagnetic sensors such as infrared horizon scanners, star trackers, and ground tracking data links. Pure inertial systems, without external aids, are not practical for space applications except for very short missions.

Passive attitude control for satellites in the form of gravity gradient stabilization has made considerable progress in the past year, particularly as a result of space experiments performed by the Applied Physics Laboratory, Johns Hopkins University. Gravity gradient control of communication and navigation satellites should be common in the future.

Information Exchange

One of the important recent advances made in the guidance and control field is in communications among scientists and engineers interested in this field and actively engaged in work in the field. The AIAA, for example, has convened two specialists meetings in guidance and control. The first of these, under ARS sponsorship prior to formation of the AIAA, was in August 1961 at Stanford; the second was in August 1963 at MIT.

Among the difficulties in communication among guidance and control specialists are considerations of military security and company proprietary rights. The high security classification placed by the military departments on inertial guidance in the late 1940's and most of the 1950's began to be relaxed about 1957 or so. As a result, the unclassified literature has expanded tremendously in the past 5 to 7 years. Today there are at least seven books on the open market which are devoted exclusively to inertial guidance and inertial sensors. Additionally, there are numerous other books containing one or more chapters which discuss the subject in an excellent manner.

I believe that there are adequate opportunities now for researchers in this field to report their work through technical journals of the AIAA, the IEEE, Institute of Navigation, and through many other privately owned technical publications. Those doing research in the field should feel a certain degree of obligation to report their work if it is significant. Those who sponsor research in the government and with company in-house funds should encourage widespread publication. Those who review papers for publication and to a certain degree therefore control the quality of reported research have an obligation to be firm in publishing only the highest quality and to minimize reporting of redundant research or "reinventing the wheel". Those in the government who pass on the security classification of proposed papers have a dual obligation to ensure adequate flow of technical information while, at the same time, not compromising national security. In general, quantitative performance capabilities of specific inertial sensors and the military characteristics of most weapons systems are all that need be classified.

Flow of information because of proprietary restrictions is often more limiting than that due to military security classification, particularly these days when there is great competition for a limited number of contracts. It is important, of course, for any company to protect its own interest in new ideas and concepts -- after all, it is new techniques which are being sought in R&D competitions. But we often see the proprietary shroud carried too far.

Significant evidence of increased communications among guidance and control engineers in the late 1960's, in addition to the AIAA guidance and control summer meetings previously mentioned are:

1. The annual "Unconventional Inertial Sensors" symposia sponsored jointly by the Bureau of Naval Weapons, AFSC Research and Technology Division, and Republic Aviation Corporation. These symposia were held in the fall of 1962 and 1963.

2. The annual classified guidance and control converence for government scientists, engineers, technical managers, and program managers. These meetings were held in the Spring, 1963 and 1964, and are limited to government personnel from the FAA, NASA, Army, Navy and Air Force.

3. The establishment of the Control, Guidance, and Navigation Subpanel of the Supporting Space Research and Technology Panel, Aeronautics and Astronautics Coordinating Board.

4. Other specialists' meetings such as the Institute of Navigation meeting in 1963 on low cost inertial navigation and the AFSC meeting in 1962 at Holloman Air Force Base on inertial guidance testing.

Though not of a hardware nature, improved communications in the guidance and control field during the last few years is of as much significance to advancing this technology as any hardware developments.

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Biography

Commander Robert Clifton Duncan is presently assigned as Chief, Guidance and Control Division at the NASA Manned Spacecraft Center. From 1961 through 1963 he was staff assistant to the Director of Defense Research and Engineering. He previous Navy assignments included the Astronautics Development Division, Office of Chief of Naval Operations, and tours of duty in three Navy fighter and heavy attack squadrons.

Commander Duncan graduated from the Naval Academy in 1945 and subsequently was awarded S.M. and Sc.D degrees by the Massachusetts Institute of Technology in the field of guidance and control. He is the author of a number of technical papers and one book, "Dynamics of Atmospheric Entry," (McGraw-Hill, 1962). He is a member of the AIAA Technical Committee on Guidance and Control, the NASA Research Advisory Committee on Guidance, Control, and Navigation, and Sigma Gamma Tau.

Figure 1 - DISTRIBUTION OF FY 1964 GUIDANCE AND CONTROL FUNDS BY INERTIAL AND NON-INERTIAL CATEGORIES

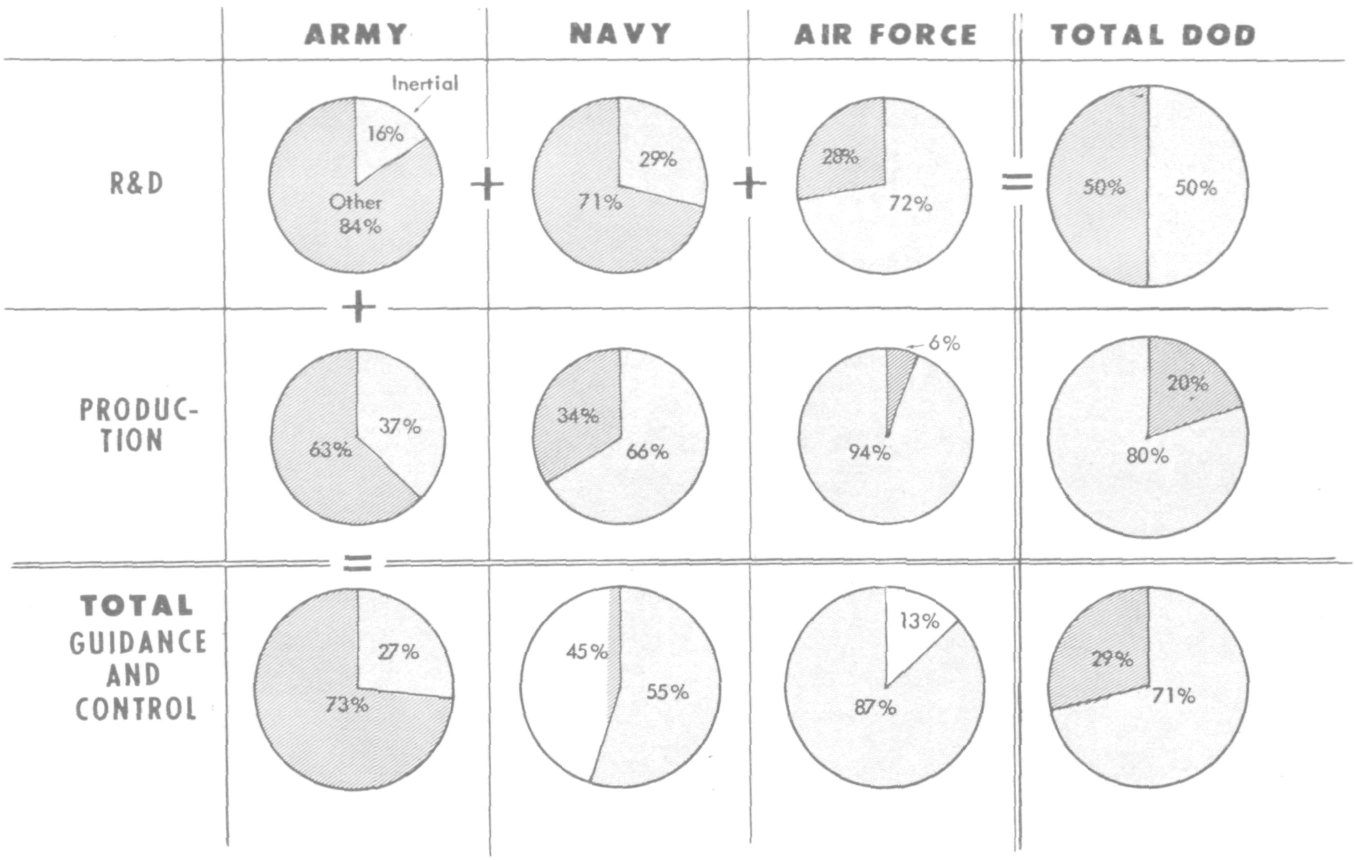


FIGURE 1A. GENERALIZED GUIDANCE AND CONTROL SYSTEM

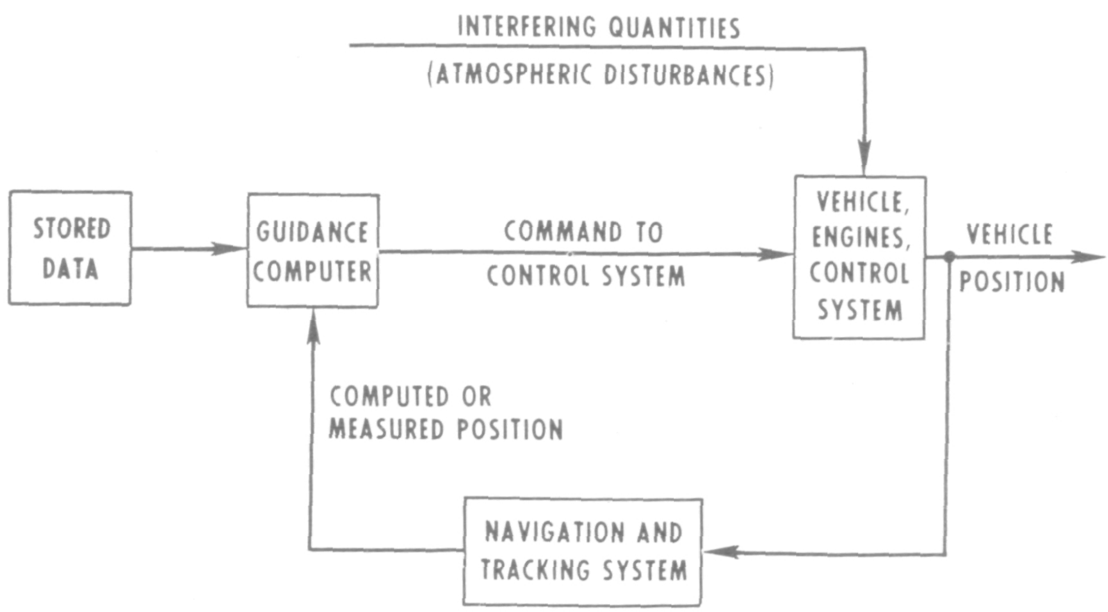


Figure 2 - DISTRIBUTION OF FY 1964 GUIDANCE AND CONTROL FUNDS BY MILITARY DEPARTMENTS

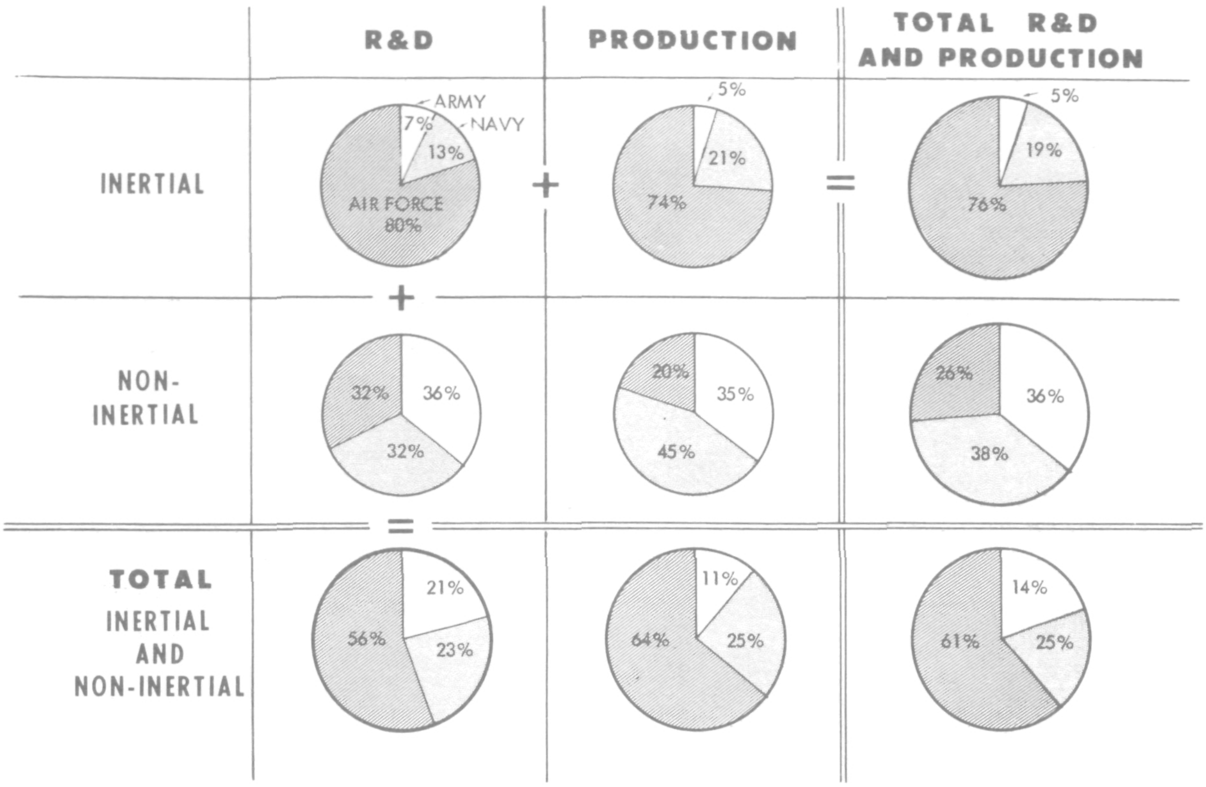


Figure 3 - DISTRIBUTION OF FY 1964 GUIDANCE AND CONTROL FUNDS BY R&D AND PRODUCTION CATEGORIES

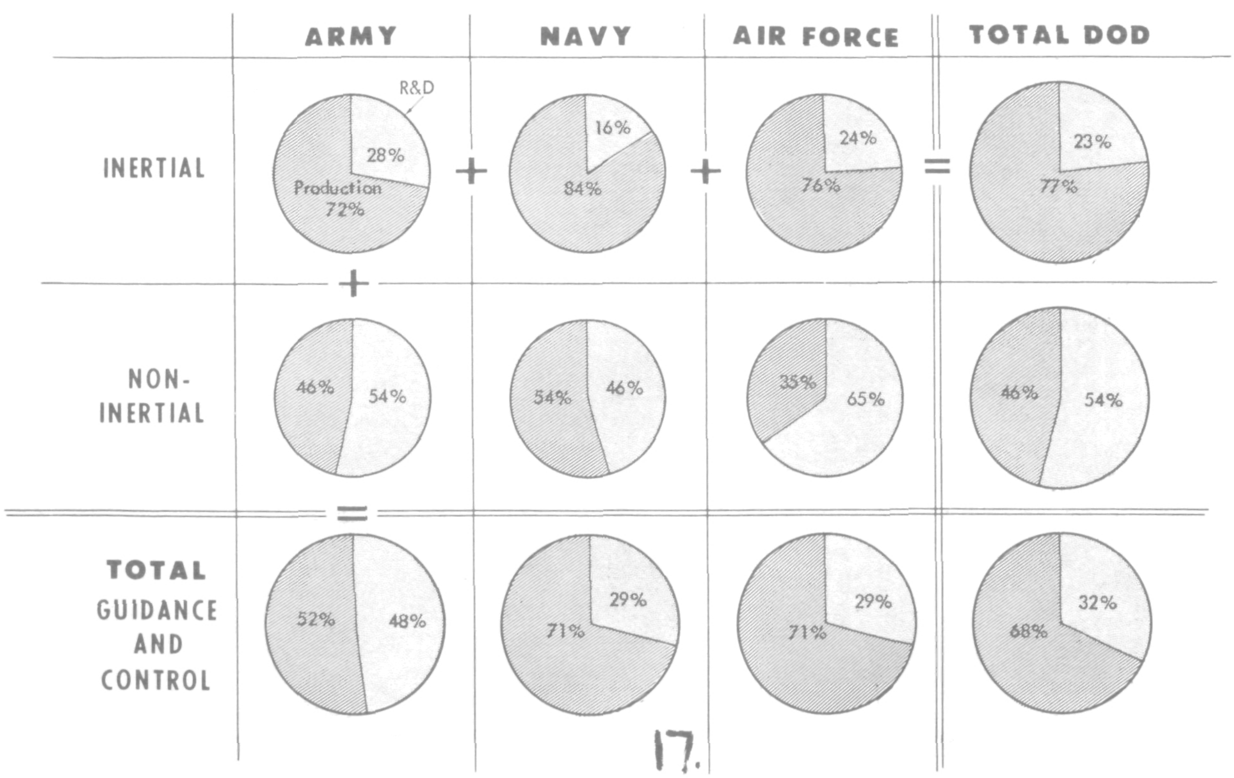
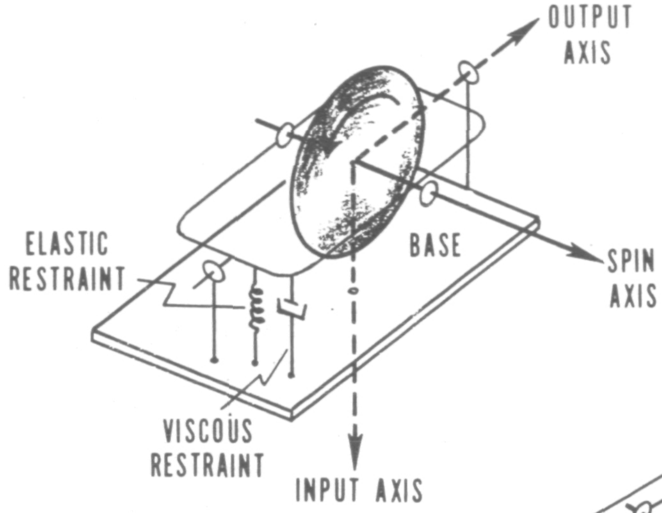
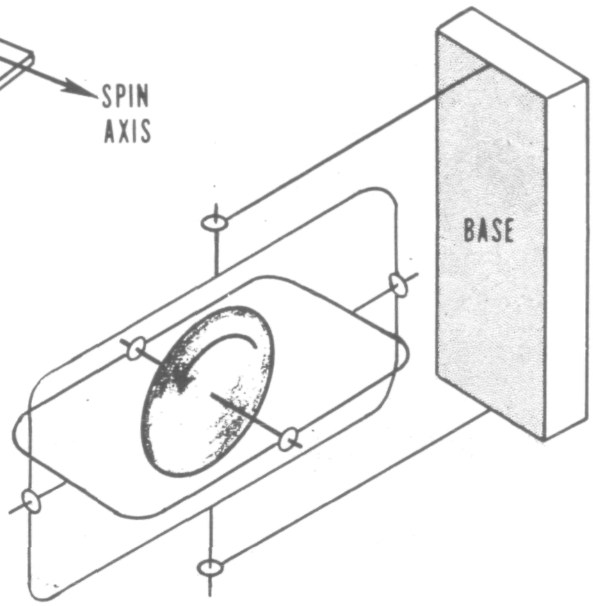


FIGURE 4. TYPES OF INERTIAL GYROS



a. Single Degree of Freedom Gyro



b. Gimbailed Two Degree of Freedom Gyro

FIGURE 5. FREE ROTOR TWO DEGREE OF FREEDOM GYRO

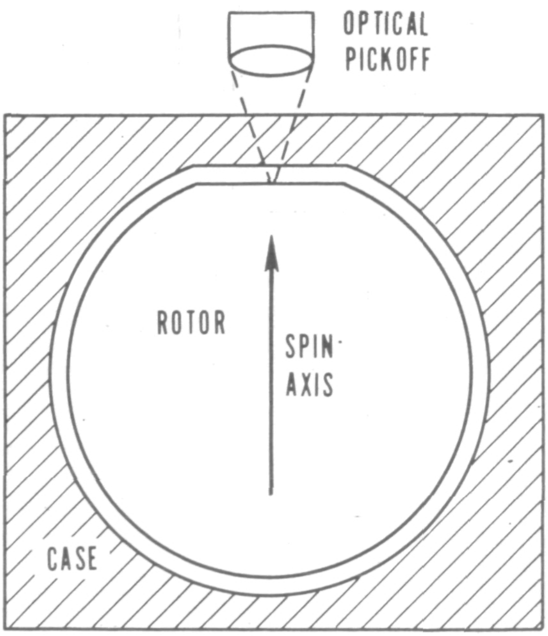


FIGURE 6. MAGNETIC DRAG-CUP VELOCITY METER

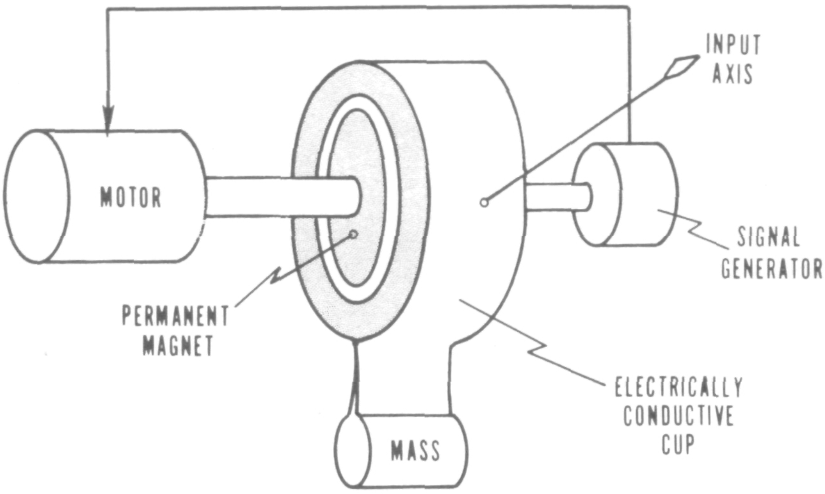


FIGURE 7. PENDULOUS INTEGRATING GYRO ACCELEROMETER (PIGA)

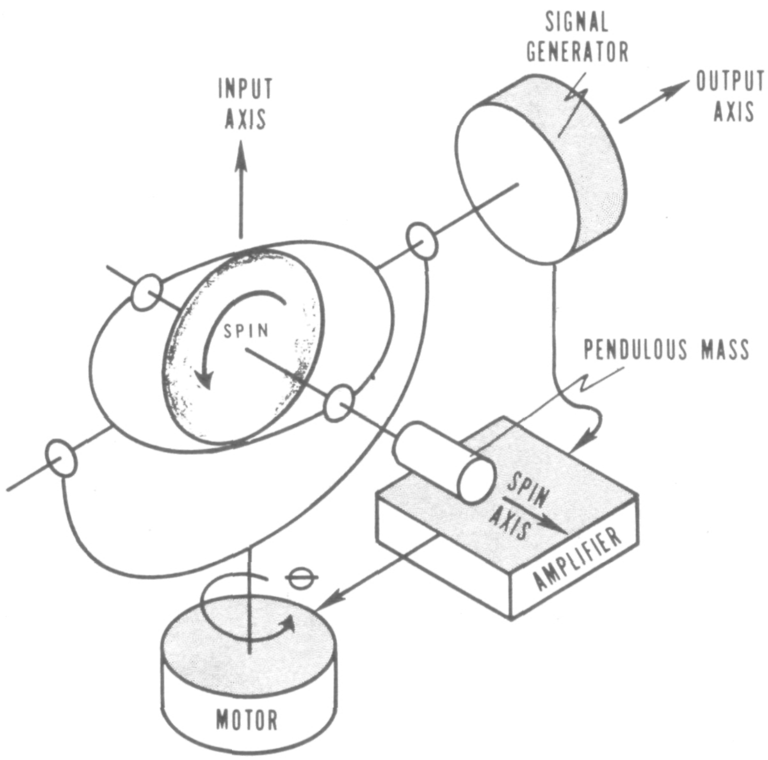


FIGURE 8. VIBRATING STRING ACCELEROMETER