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A Review of Inertial Guidance Systems its Principles, Applications, and Future Directions

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ABSTRACT

Inertial guidance systems have been a crucial technology for navigation and control in various industries, including aerospace, defence, marine and industrial applications. This paper provides an overview of the working principles and applications of inertial guidance systems. We first introduce the basic components and operation of inertial guidance systems, including accelerometers and gyroscopes. We then discuss the various applications of inertial guidance systems in detail, highlighting their importance in aerospace, defence, marine, robotics. We explain the benefits and limitations of inertial guidance systems, including their accuracy, reliability, and ability to operate in GPS-denied or jammed environments. We also discuss the challenges and future directions in inertial guidance system research and development, such as improving accuracy, reducing size and weight, and addressing the issue of drift over time. Overall, this paper provides a comprehensive overview of the state-of-the-art in inertial guidance systems and their potential to revolutionize various industries and applications.

INTRODUCTION

Inertial guidance system is an electronic system that continuously monitors the position, velocity, and acceleration of a vehicle, usually a submarine, missile, or airplane, and thus provides navigational data or control without need for communicating with a base station.

Inertial Navigation System based on Newton's classical mechanics, The linear acceleration and angular velocity of the carrier can be obtained by the inertial sensitive device, and the speed, position and posture of the carrier can be obtained by processing this information through integral operation.

The basic components of an inertial guidance system are gyroscopes, accelerometers, and a computer. The gyroscopes provide fixed reference directions or turning rate measurements, and accelerometers measure changes in the velocity of the system. The computer processes information on changes in direction and acceleration and feeds its results to the vehicle’s navigation system.

There are two fundamentally different types of inertial navigation systems: gimbaling systems and strapdown systems. A typical gimbaling inertial navigation system, such as might be used on board a missile, uses three gyroscopes and three accelerometers. The three gimbal-mounted gyroscopes establish a frame of reference for the vehicle’s roll (rotation about the axis running from the front to the rear of the vehicle), pitch (rotation about the axis running left to right), and yaw (rotation about the axis running top to bottom). The accelerometers measure velocity changes in each of these three directions. The computer performs two separate numerical integrations on the data it receives from the inertial guidance system. First it integrates the acceleration data to get the current velocity of the vehicle, then it integrates the computed velocity to determine the current position. This information is compared continuously to the desired (predetermined and programmed) course.

In a strapdown inertial navigation system the accelerometers are rigidly mounted parallel to the body axes of the vehicle. In this application the gyroscopes do not provide a stable platform; they are instead used to sense the turning rates of the craft. Double numerical integration, combining the measured accelerations and the instantaneous turning rates, allows the computer to determine the craft’s current velocity and position and to guide it along the

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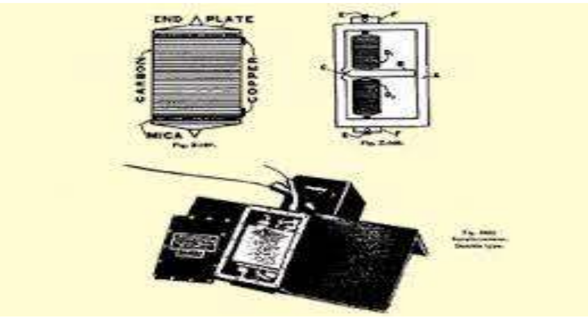
desired trajectory. In this paper we discuss the advancements and applications of inertial guidance system in the fields of warfare and civilian purposes.

HISTORY [1]

In the early 1930's, visionary engineers and scientists began thinking about practical self-contained systems for the guidance, navigation, and control of aerospace vehicles in inertial space. Starting with the development of the first gyro compass in 1908, this technology was perfected in the race for improved intercontinental ballistic missile accuracy. Since the end of the cold war, the technology has continued to advance with a focus on systems of lower size, weight and power for a given accuracy. Future systems promise to revolutionize guidance, navigation, and control, with complete lowcost inertial measurement units as small as 0.03 cubic inches.

The Draper Laboratory's Apollo GN&C System derived from an enhancement of Polaris instruments and the development of a highly reliable digital computer marked the beginnings of manned Space flight. This development spawned the widespread implementation of inertial systems in military and then commercial aviation. An entire industry grew out of these developments, and the contributions of the companies that provided the industrial manufacturing base for inertial systems are highlighted.As the technology evolved, many single degree-of-freedom applications gave way to the introduction of the Dynamically Tuned Two Degree-of -Freedom Gyro (DTG), which in many applications were subsequently displaced by the Ring Laser Gyro (RLG). Similarly, with the advent of faster and more powerful digital computers, inertial gimbal system technology has been displaced by strapdown implementations.With the recent advancements of hardware design and manufacturing, low-cost light-weight micro-electro-mechanical (MEMS) IMUs have become ubiquitous, which enables high-accuracy localization for, among others, mobile devices and micro aerial vehicles (MAVs), holding huge implications in a wide range of emerging applications from mobile augmented reality (AR) and virtual reality (VR) to autonomous driving.



PRINCIPLES OF INERTIAL NAVIGATION SYSTEM

Inertial navigation system (INS) must determine its direction relative to North. It does so by using its gyroscopes to sense the Earth rotation rate vector. The Earth does not rotate very rapidly, one revolution in twenty-four hours, yet an inertial navigation gyroscope must be accurate to better than one thousandth of that rate.the output of the accelerometers must be integrated electrically or numerically into velocity, and then integrated again into position. As a result, even small errors in the accelerometer outputs can lead to large growth in the velocity and position errors. Further, accelerometers cannot distinguish between gravity and the acceleration of motion. Therefore, for navigation, the orientation of the accelerometers relative to the gravity vector must be known precisely.However, gyroscopes measure rotation rates or angular displacements, but cannot directly measure orientation relative to a reference coordinate system. Gyroscope errors cause drifts in orientation relative to gravity, causing acceleration errors, in turn leading to velocity and position drift with time.

Accelerometer in one dimension can basically be seen as a process operating of Newton’s second law where a mass is attached to a spring within a reference frame. There are two main principles of accelerometers where one is to measure the displacement of the mass and the other one measures frequency of a vibrating element are changing (mass) it's caused because of tension changing. The accelerometer measures linear acceleration and by integrate the signal twice we can obtain the position.

The working principles of a gyroscope where the rotation around respective axes. The gyroscope introduces capacitance changes to detect these displacements. Based on this, the angular velocity of the INS can be measured and by integrate the signal, we can obtain orientation

Classifications of Systems

Gimbal[2]

To understand and categorize stabilization and gimbal technology it is helpful to begin with a look at the development cycle that it has gone through inside and outside of the film industry.

Gen-1: The WESCAM Stabilized Remote Camera System

This was the first commercially available gyro stabilized remote camera system. Originally developed by Westinghouse Canada (later Istec Ltd. which became Wescam Inc. and is now Pictorvision Inc.), it represented the state of the art when it was introduced in the 1960's. The basic technology has undergone many refinements over the decades by Wescam and SpaceCam. This stabilization technology relies on the angular momentum generated in three, orthogonal, large mechanical rate gyroscopes (gimbaled fly wheels) to augment the natural inertia of the camera platform. This artificial mass or synthetic inertia is used passively to maintain a stable platform that the camera is steered relative to. A servo system uses the angular rates measured by the precession of the gyros to cancel any disturbances. A dome enclosure keeps the wind and weather out and an internal passive vibration isolation system minimizes the vibration input to the system. The line of sight stability (<5 micro radians RMS jitter)of the original WESCAM type systems is still unsurpassed in the industry today.

Gen-2: The Classical Active Gimbal System

While this technology predates the Gen-1 gimbal technology in military use, it was not used commercially in this industry until after Gen-1. In its commercial introduction this under-performed the established Gen-1 technology on the grounds of stability. It was however, simpler, lighter, less expensive and exhibited better steering performance than the Gen-1 technology. These systems close rate loops directly about each gimbal axis. Rate sensors such as small mechanical sensing gyros are used to sense angular rates relative to inertial space.

These rates are summed with the steering commands to stabilize and steer each axis. The actuator can be either a direct-drive or a geared motor. The use of a geared actuator will increase coupling forces substantially and limit the bandwidth of the system by an order of magnitude. The structure between each successive gimbal axis is subjected to the high frequency torques of the actuator. Compliance in this constraint structure will directly limit the bandwidth of the control system. For this reason Gen-2 gimbals are incapable of high bandwidth performance with the large cameras used in the motion picture industry.

Gen-3: The Active Follow-up Gimbal System

This technology takes a limited travel, high performance inner gimbal and mounts it on an outer follow-up gimbal. The inner gimbal provides the high bandwidth stabilization and fine steering performance, while the outer gimbal provides the coarse steering over a large field of regard. The inner gimbal uses high performance, direct drive actuators and the outer gimbal uses geared actuators. The high frequency torques is still applied through the inner gimbals' constraining structure. With the large cameras of the film industry the compliance of this structure limits the bandwidth of the stabilization system.

With the use of Fiber Optic Gyros (FOG's) the stabilization performance of this type of gimbal approaches that of the Gen-1. It is, however, still simpler, lighter, and less expensive than the Gen-1 with better stability and steering than the Gen-2.

Gen-4: The Unconstrained Actuator Active Follow- up Gimbal System

The Pictorvision XR avoids the bandwidth limitation of the Gen-3 gimbal system by using a patented process of torquing across the constraining structure instead of through it. The high frequency torques is applied directly from the outer gimbal to the camera base plate. Combined with a high performance FOG based Inertial Measurement Unit

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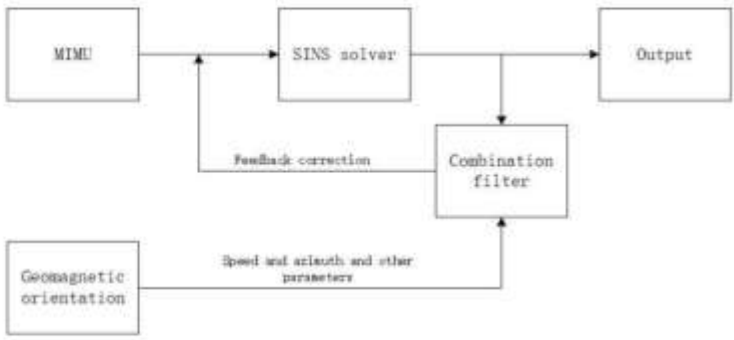
(IMU), this stabilization system raised the bandwidth so high that the structural compliances of the camera system became the limiting factor. To raise the stabilization bandwidth even higher the XR makes use of a "camera sled" to stiffen the camera, lens and magazine.

The Pictorvision XR (formerly Wescam) represents the current state of the art with geared head like steering and the ability to stabilize and steer the industry's longest lenses (beyond 2000mm on HD).

With the most advanced stabilization technology, Pictorvision is focused on steering quality and offers a variety of new steering modes and steering resolvers to "raise the bar" in the art of camera steering.



Schematic diagram of strapdown inertial navigation system

Principle of strapdown inertial navigation system [3]

Different from the platform-type inertial navigation system, the strap-down inertial navigation system has the advantages of small size and light weight , while having a relatively simple system structure, it can also ensure higher accuracy and reliability. Based on this, this article adopts strapdown inertial navigation system. Taking into account the earth's rotation, it is necessary to convert multiple coordinate systems to ensure the accuracy of navigation and positioning. Commonly used space coordinate systems include earth rectangular coordinate system, launching inertial coordinate system, geocentric inertial coordinate system, body coordinate system, data processing coordinate system and so on. In the strapdown inertial navigation system, the carrier will be fixed together with the inertial device and move together. The angular acceleration ω1 of the carrier coordinate system relative to the inertial system measured by the inertial device can be obtained by subtracting the angular velocity ω2 of the navigation coordinate system relative to the inertial system to obtain the relative angular velocity ω of the two coordinate systems, and the attitude matrix can have this relative angular velocity in real time Calculated. When the attitude matrix is known, the linear acceleration f1 obtained by the accelerometer can be transformed into the platform coordinate system, and the attitude angle can be directly calculated by the attitude matrix. The schematic diagram of the strapdown inertial navigation system is shown in Figure 1.

Gyroscopes [4]

Any physical quantity having directional characteristics that 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 of an unclassified nature 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.

Gyros are naturally classified into two main categories depending upon which of these two primary properties are predominant in the instrumentation. The two-degreeof-freedom (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 (SDF). An SDF may be either a "rate" (angular velocity output) or a "rate-integrating" (angular displacement output) gyro; the former has a spring restraint (torque proportional to displacement) to counteract output gyroscopic torques , whereas the latter 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 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 for operations involving thrust and gravity. Reasonable progress has been made during the past year in improving the inherent accuracy of these instruments and in 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 because of certain favourable material properties. Case rotation to reduce mass unbalance drifts is being practiced on a wider scale. Modulation of angular momentum to separate error sources and thus permit better compensation has been demonstrated in a number of gyro laboratories.

Spinning mass gyros: free-rotor types

In principle, the free-rotor gyro operates in the same way as the gimbaled gyro. Its rotor, which is spherical, may be supported by gas bearings, electrostatic forces, or magnetic forces. The rotor generally has an electrically conductive rim that is driven as an eddy current motor by a case-mounted stator. For a 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 in a vacuum, and the rotor is kept centered by electrostatic forces. The motor is used to start the gyro and obtain a desired angular momentum; the rotor then coasts for months, since friction torques in the vacuum are extremely small. A very interesting, although not necessarily the most practical, electromagnetically supported gyro is the cryogenic gyro. In this instance, the rotor is a superconducting niobium sphere immersed in liquid helium. Magnetic lines of force do not penetrate it. The supercurrents flowing at the surface of the sphere interact with the external magnetic field to provide the supporting force as well as affording stability without a separate servo control. The rotor is suspended within a segmented bearing assembly, which is also made of niobium. The magnetic flux, which flows in the gap between the rotor and the bearing segments, is produced by two circular bearing coils wound with niobium wire surrounding an evacuated cylindrical enclosure housing the gyro. Normal excitation current of 1 amp produces a flux density at the rotor surface of approximately 1000 gauss. Continuous current flow has been maintained during gyro operation from an external supply, but a persistent superconducting current could also be used. Two torquers located in the center of the rotor act as magnetic bearings to maintain spin axis alignment to the gyro case during rotor spin up. Motor drive torques are produced by a superconducting stator also mounted in the center bore of the rotor. Because of the limited angular freedom (1.5°) between the gyro rotor and the torque-motor assembly, a cryogenic gyro of this type would be mounted on a stabilized platform that is servo driven to follow the rotor spin axis. The principle error sources are asphericity and erroneous center-of-gravity location of the rotating sphere, trapped stray magnetic fields, and energy transfer due to readout devices. A severe difficulty that remains to be solved is a.c. loss in the superconductor. The General Electric Company and the Jet Propulsion Laboratory are the two primary centers of cryogenic gyro research. Another interesting free-rotor gyro uses a rotating fluid sphere instead of a metallic ball. It does not appear to require the degree of sophistication in manufacturing that conventional gyros of the same characteristics require, A spinning mass of high-density, low-viscosity fluid (rather thanthe conventional heavy wheel) provides the angular momentum. Viscous shear at the boundary of the fluid sphere causes it to rotate at the same speed as the cavity; in the absence of inputs, the pressure distribution at the cavity boundary is symmetrical along the spin axis. If a rate with a component orthogonal to the spin axis is introduced, the angular momentum of the fluid sphere will cause it to try to remain fixed in space, and a small angular separation will exist momentarily between the cavity spin axis and the fluid-sphere spin axis, creating an asymmetric pressure distribution. Two ports in the cavity channel the fluid to a transducer, which measures the pressure differential with respect to the cavity spin axis. Since the ports are rotating in space with the cavity, and the angular difference between the fluid and cavity spin axis is fixed in space or a sufficient time interval, the pressure differential measured will vary sinusoidally, with a period equal to the period of the cavity rotation and an amplitude proportional to the magnitude of the input rate. Now, by introducing appropriate phasesensitive demodulation with respect to a voltage obtained

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from a reference generator on the gyro rotor or cavity, components of the input rate can be found in two axes. Since the viscous shear at the cavity boundary will eventually return the fluid body to its original position colinear with the cavity axis, a step function angular input will lead to an instantaneous angular displacement that will decay to zero in an exponential manner. Gyros used in space systems should be designed specifically for the space environment. The zero-gr condition, coupled with the requirements for low power consumption and long times of operation, result in somewhat different design criteria than utilized 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 hollow spherical beryllium rotor suspended in a hard vacuum by strong electrical fields.Credit for conceiving the ESG is due A. T. Nordsieck, then of the University of Illinois. The primary sources of drift in the ESG are mass unbalance of the rotor, magnetic torques resulting from interaction on induced currents in the rotor with the exciting magnetic field, and electrical 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 ESG requires continuous use of a high-performance servo; otherwise, it should be ideally suited for space applications, provided that the techniques in internal compensation are fully developed. Honeywell and General Electric Company are industrial concerns performing government-funded research on it.

Vibrating momentum gyros

In the vibratory momentum gyro, first described as the tuning-fork gyro in 1953 by Sperry engineers, the linear momentum of an 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 pickoff frequency. Westinghouse uses a ceramic cylinder; under an oscillating excitation voltage, the moment of inertia about the longitudinal axis oscillates. The piezoelectric cylinder acts as a crystal to control the frequency of

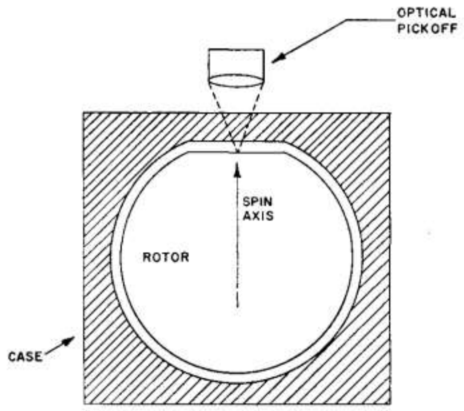

Fig. 4 Free-rotor, two-degree-of-freedom gyro.

the driving oscillator. The primary difficulty with this device is null stability. No significant progress has been made in recent years.

Nuclear gyros

Nucelons are much better magnetometers than gyros. As solid-state gyros, they might appear to be useful. Although progress has been made in the last year, it appears that the practical use of nucleons must await many years of laboratory research. The nuclei of certain atoms exhibit an angular momentum and a magnetic moment. Their angular momenta are normally randomly oriented in space, but they can be statistically oriented by the action of an external magnetic field. The resultant microscopic angular momentum of a nucleus 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

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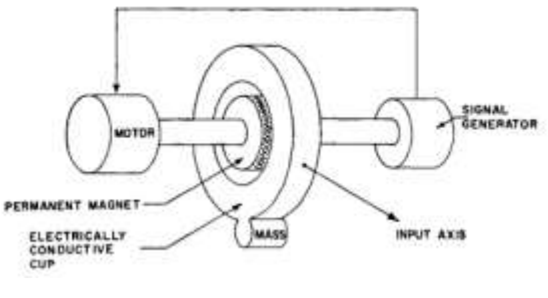
The laser gyro measures the transit-time difference of two beams of radiation which are propagating in opposite directions around the same closed path. This is an application of the lesser known of Michelson's two famous experiments with light. The laser furnishes adequate energy levels with coherent 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. No accelerometers of radically new concept have appeared during the past year. Inertial velocity-measuring devices, as such, are nonexistent because unique inertially referred velocity is meaningless.5 Velocity data obtained by measuring the motion of the surrounding medium, such as by aircraft pitot tubes, have been used for many years. Velocity measurement by electromagnetic radiation methods, such as Doppler radar in aircraft31 - 32 and Doppler sonar in ships, is constantly being improved, as evidenced by the accuracy with which earth-guided space probes have been deployed. Velocity measurement relative to the earth's electric or magnetic fields is a theoretical possibility, but the variations in these fields make this impactical for the accuracies desired and/or required. 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; hence the former is computed and subtracted from the measured acceleration in the feedback loop, 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. 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. the signal generator sends an electrical 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. The drag torque induced in the conductive cup is proportional to angular velocity; hence the electromagnetic coupling acts as a Newtonian fluid (stress is a linear function of shear). This type of accelerometer 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 velocity, and hence the name velocity meter. This instrument is very accurate and is in large-scale production for ballistic missile guidance systems.

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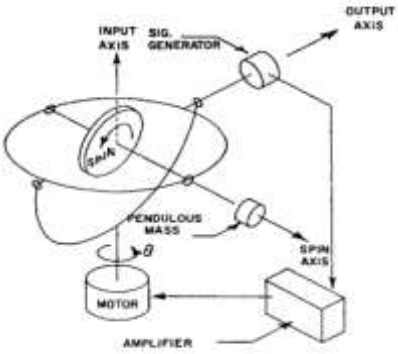

Pendulous integrating gyro accelerometer (PIGA)

The PIGA is the most accurate accelerometer in production today. Its use is desirable when accurate velocity measurements are essential, such as in ballistic missiles and space booster operations, even though it is expensive. An integrating gyro precisely measures the torque generated by the pendulum when it is accelerated; the pendulous mass lags as if it were a simple pendulum, 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 that rotates the gyro gimbals about the input axis at a rate proportional to the applied acceleration. The total angle of rotation 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 it to generate a torque about the output axis in such a direction as to balance the pendulous torque generated under the applied acceleration.

Vibrating string accelerometer (VSA)

The natural frequency of a taut string is proportional to the square root of the tension; therefore it increases if a lagging mass tends to stretch the string, or vice versa. In a practical accelerometer, the vibration string is actually a metal tape that is constrained to vibrating in one plane in order to improve measurement accuracy. Two tapes are attached to a proof mass located between the strings. The mass is constrained to moving in one dimension only, the "input" or "sensitive" axis. The metal tapes are placed 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 servo-feedback techniques. An acceleration in the direction of the input axis increases the tension in one tape and decreases it in the other. The resulting difference frequency is proportional to the applied acceleration. The sum of the two frequencies is held constant by a tension adjustment mechanism to improve the accuracy and linearity of the instrument. The integral of difference frequency, the number of difference cycles (measured as pulses), is a direct measure of velocity. The VSA can therefore be looked upon as an integrating accelerometer. It is in large-scale use in this country. Since its output is a series of pulses, it is a natural instrument for use with digital systems.

Vibrating quartz accelerometer

This accelerometer is analogous to the VSA. Resiliency supported, mass-loaded capacitor plates are used in conjunction with an inductor or resistor to form an accelerationresponsive oscillator. Since no driving magnets are required, this unit may be simpler and cheaper than a VSA.

Mossbauer accelerometer

An accelerometer utilizing the Mossbauer effect is the nuclear analog of the VSA. 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.

Particle accelerometer

The goal of the inertial sensor designer is to create a device that is free of all effects except the physical effect to be measured. The sensitive element of an inertial sensor is suspended by a low-loss suspension in a low-loss medium. The low-loss suspension is perhaps the most difficult to obtain; electric force appears to be the most nearly ideal suspension technique, because it works only on the surface of the suspended mass, so that losses are confined to the dielectric and are small or nonexistent. Electrostatic suspension of large masses would require extremely high electric gradients in an ultra-high vacuum, but it is theoretically possible to use a charged particle as the proof mass. The charge/mass ratio of the particle should be chosen as high as possible; hence the surface/volume ratio should be high, which in turn means that the radius should be as small as is practical. The charged particle reference device is directly applicable as an instrument for sensing accelerations in that they are capable of sensing accelerations along three axes simultaneously. Some development is currently being funded by the government on these particle devices. However, a great deal of laboratory investigation must be conducted before this approach reaches the practical stage.

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, Table 1 is representative

USES OF GYROS IN AIRCRAFTS, SHIPS & SUBMARINES, MISSILES

Aircraft

Aircraft inertial navigation systems may be divided into the following three categories according to the gyro reference coordinate system used: 1) inertially fixed system, 2) earthfixed system, and 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-gimbaled or four gimbaled systems (the latter are often used to reduce programing requirements or maneuver limitation for preventing gimbal lock); 3) use of three SDF gyros or two 2DF gyros; 4) use of either analog or digital computer; the latter, either arithmetic or digital differential, is required in systems of very high accuracy; 5) whether or not externally measured velocity information is used as an input (e.g., Doppler radar is often used to damp the inertial system; an aircraft carrying a long range air-to-surface missile often uses Doppler velocity after smoothing it, as inertial or launch velocity for the missile system); and 6) whether or not position information derived external to the inertial system is used as an input; such information is generally of the form of angular measurements of stars, or electromagnetic radiation data such as measured by Loran C. Continuous tracking of stars makes possible gyro drift compensation in flight, as well as providing a means for obtaining a stellar fix; however, the vertical and angular measurement capabilities of the star sensors limit the performance capability of the stellar system. 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. Considerable progress has been made in the past year in 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 takeoff 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.

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: 1 min of arc corresponds to 1 naut mile at the earth's surface; hence a rate of 0.1 deg/hr is 6 naut miles/hr. 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 after progress in the FEBE airborne system led to speculations concerning potential marine applications. The resulting MAST (Marine Stable Element) system was tested at sea in 1953. As a result of early component and subsystem test, and as a greater understanding of inertial navigation evolved from early systems analysis, MIT suggested to the Office of Naval Research the development of SINS, which was begun in March 1951, completed in mid-1954, and tested at sea in late 1954 and early 1955. The great success of the SINS development at MIT led the Navy to install inertial navigation systems (by Autonetics or Sperry) in Polar is submarines. Ultimately, SINS systems were installed in aircraft carriers and in range ships for the Atlantic and Pacific Missile Ranges. Advanced SINS work is also being carried out at Nortronics, MIT, and Honey well, among others. Increases in accuracy and reliability, together with considerable reductions in size, weight, and power, have been achieved. Improved gyros and techniques of monitoring platform gyros with a redundant gyro are among the important improvements.

Missiles

The most comprehensive inertial guidance developments in the United States are for our ballistic missile systems. Table 2 shows the organizations with primary responsibilities for the guidance portion of the major missile programs. Inertial guidance systems have also been developed for cruise missiles, which are more like aircraft systems than ballistic missile systems. Examples are shown in Table 3. Missile guidance systems have grown smaller and more accurate with each new development. Some of the advances of the past year or two are as follows: 1) Microelectronic computers have brought about significant reductions in size, weight, and power while at the same time improving reliability. 2) New platform concepts have been shown to be technically practical; it is now possible to float the stable platform as a ball inside a concentric sphere, thus permitting high-0 operations. This means that a ballistic missile can be guided throughout its trajectory, including re-entry, instead of just during the boost phase as is now done. 3) Flotation of conventional gimbaled systems to increase g capabilities without degradation in performance has been demonstrated. 4) With guidance using techniques (2) or (3), it is possible to maneuver the re-entry vehicle to improve penetrability without loss in accuracy. 5) Stars have been tracked during boost. Considerably improved measurements of the sky light background during day and night have been recorded by 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 the size of an inertial measurement unit (IMU); systems in advanced developmentare the size of a soft ball. Further size reduction appears to be beyond the foreseeable state-of-the-art. Production costs, of secondary concern to accuracy and reliability in long-range ballistic missile systems, is of major importance in short range missiles. The d.c.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 ship-to-shore fire-support missiles of tactical ranges

ARMY APPLICATIONS OF MEMS.[5]

DOD applications of MEMS fall under three broad areas; namely, 1) inertial measurement, 2) distributed sensing and control, and 3) information technology applications. Inertial measurement applications include weapons safing, arming, and fuzing; competent munitions; platform stabilization; and personall vehicle navigation. Distributed sensing and control applications include condition-based maintenance, situational awareness, miniature analytical instruments, identification of friend or foe (1FF), biomedical devices, and active structures. DOD information technology applications include mass data storage and displays. The Army applications, which are subsets of the broad DOD applications areas, are discussed below. The key Army missile applications for MEMS devices are weapon safing, arming and fuzing, platform/seeker stabilization, vehicle/personal navigation, condition-based maintenance (CBM), compact encoders for actuator position feedback, radio frequency (RF) components, miniature analytical instruments, aerodynamic flow control, and mass data storage.

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Figure 1 provides the MRDEC MEMS application profile for missile system technology.

Inertial Measurement Applications.

The Army has a requirement for low cost, small volume guidance systems for small missiles, aircraft, land vehicles, and future micro-unmanned autonomous vehicles.8 A MEMS-based inertial measurement unit (IMU) with the appropriate reliability could substantially reduce cost for tactical missiles. The tactical missile requirements range from the low performance, platform and seeker stabilization and flight control and autopilot operations, to the high performance navigation and vibration sensing systems.

Weapon fuzing, safety, and arming.

Army missiles present requirements associated with fuzing and safety and arming (S&A) devices. Most mechanical S&A devices use acceleration to develop the forces needed to operate the mechanical safety logic, which is one of three parts of the S&A device. Low-flight acceleration is common in missiles, and the potential mechanical forces can be very small, thereby complicating the design of the S&A device. A significant number of ordnance fails to detonate as planned, which reduces the effectiveness of military operations and becomes a safety concern. MEMS accelerometers have the potential to overcome these problems via rugged designs. They offer multi-mode functions in one fuzing device, which can improve operation, safety, and reliability. Also, they are ideal for S&A devices that require low-cost devices and/or have unique flight environments.

Missile seeker/sensor stabilization.

A low performance (200 — 1,000 deg/hr) inertial system, coupled to the gimbal mechanism on the missile seeker, can aid in providing tracking pointing stabilization in missile systems. MEMS represent alow cost, small volume approach to missile seeker stabilization.

Personal/vehicle navigation.

Similar to aircraft, Army weapon systems use inertial sensors for inertial navigation, attitude heading and reference systems (AHRS), flight control, sensor stabilization, weapon initialization and fire control. The function ofthe inertial navigation system is to provide long-term position, velocity and attitude information to the seeker during flight. The performance requirements for the inertial instruments (gyroscopes for measuring rotation rates and accelerometers for measuring linear accelerations) and systems (IMU-acombination of a three-axis gyro and a three-axis accelerometer) differ, depending on the specific application. The primary measures of performance for the gyro and accelerometer are bias stability or drift rate, scale factor, and dynamic range. The gyro performance requirements for missile systems are primarily determined based on the time offlight and weapon initialization and reference. The bias stability requirements are provided for several classes ofArmy missile systems and ground equipment: 1) air-to-air missiles (>10 degfhr), 2) air-to-ground missiles (between 0.01 and 10 deg/hr), and 3) AHRS and military ground vehicles or and navigation systems (< 0.01 deg/hr). Provide representative low, medium, and high-accuracy requirements for accelerometer and gyroscope performance for some identified Army missile system programs. MEMS inertial sensors, which have been proven to be robust in harsh environments such as surviving high-g forces during projectile launch, are ideal for the low performance, vehicle navigation applications. Furthermore, the low-cost MEMS IMUs can be used in inertial navigation applications to augment the Global Positioning System (GPS) receivers during shortduration GPS dropouts. Accurate personnel position location is required for combined arms operations to be effective. GPS receivers, which are presently used by military commanders to control the movements oflarge groups ofsoldiers and equipment, are not effective in heavily wooded areas, urban locations, and in structures. Soldiers run the risk of exposing themselves to enemy forces. MEMS technology offers a miniaturized, low-cost, low power, personal navigation unit which can augment GPS receivers during brief dropouts.

Distributed Sensing and Control Applications.

The Army has a requirement for condition monitoring, embedded diagnostics and prognostics for various missile systems. Other Army distributed sensing and control applications include optical MEMS-based encoders to provide position feedback on actuators in missile systems, RF components for missile guidance and radar systems, miniature analytical instruments, and microactuated active structures for aerodynamic control to reduce drag and enhance maneuverability in aircraft and missiles.

FUTURE DIRECTION OF INERTIAL GUIDANCE SYSTEM

Inertial guidance systems are used in a variety of applications, including aerospace, defense, and navigation. Improving the accuracy, reducing the size and weight, and addressing the issue of drift over time are all important areas for future research and development in inertial guidance systems.

1. Improving Accuracy: One approach to improving accuracy in inertial guidance systems is to use more precise sensors. This can be accomplished by developing better accelerometers and gyroscopes, or by combining multiple sensors to reduce error. Another approach is to use advanced algorithms and data processing techniques to improve the accuracy of the measurements.

2. Reducing Size and Weight: Inertial guidance systems can be quite large and heavy, which can limit their use in certain applications. One approach to reducing size and weight is to use micro-electromechanical systems (MEMS) technology to miniaturize the sensors and control electronics. Another approach is to use fiber optic gyroscopes, which are smaller and lighter than traditional mechanical gyroscopes.

3. Addressing the Issue of Drift Over Time: One of the main challenges with inertial guidance systems is that they tend to drift over time, leading to errors in position and orientation measurements. To address this issue, researchers are exploring a range of solutions, including advanced algorithms for error correction, improved sensor calibration techniques, and the use of external reference systems such as GPS.

4. Integration with Other Technologies: Another area for future research and development is the integration of inertial guidance systems with other technologies, such as computer vision and machine learning. By combining inertial guidance with these other technologies, it may be possible to achieve even greater accuracy and reliability in navigation and positioning applications.

5. Application-Specific Improvements: Finally, future research and development in inertial guidance systems will likely focus on developing application-specific improvements. For example, in aerospace applications, researchers may focus on improving the performance of inertial guidance systems in high-altitude environments or in the presence of electromagnetic interference. In navigation applications, researchers may focus on developing systems that are better able to handle urban canyons or other challenging environments.

CONCLUSION

Inertial Guidance Systems are a crucial component of modern navigation and positioning technology. They work on the principles of measuring the acceleration and rotation of a body to calculate its position and orientation relative to a reference frame. These systems find application in various fields like aerospace, defence, and navigation, where accurate and reliable positioning and navigation are critical.

In recent years, there have been significant advancements in sensor technology, algorithm development, and integration with other technologies like GPS, computer vision, and machine learning, resulting in higher accuracy, reliability, and accessibility of Inertial Guidance Systems.

Future research and development in Inertial Guidance Systems are expected to focus on improving accuracy, reducing size and weight, addressing drift over time, integrating with other technologies, and developing application-specific improvements.

In summary, Inertial Guidance Systems are an essential technology for modern navigation and positioning, and future advancements are likely to lead to more accurate, reliable, and accessible systems for a range of applications.

REFERENCE:

1. W. WRIGLEY, History of Inertial Navigation, NAVIOATION: Journal of The Institute ofNavigation Vol. 24, No. 1, Spring 1977

2. Mike Lewis,Stabilization, Steering, and Gimbal Technology as it relates to Cinematography, Toronto, PV-Labs Inc, 2012

3.Jianpeng Chen*, Zhen Yang, Sisi Ye and Qingsong Lu, Design of Strapdown Inertial Navigation System Based on MEMS, Academic Journal of Computing & Information Science 3 (4), 110-121, 2020

4. ROBERT CLIFTON DUNCAN, ALF S GUNNERSEN JR,Inertial guidance, navigation, and control systems,Journal of Spacecraft and Rockets 1 (6), 577-587, 1964

5.Tracy D. Hudson, Deanna K. McMillen, Paul R. Ashley, Paul B. Ruffin, and Janet Baeder, Micro-electromechanical system (MEMS) component research and development for Army missile applicationsPart of the SPIE Conference on Acquisition, Trackinq, and Pointinq XIII • Orlando, Florida • April 1999

6. Ilham Arun Faisal, Tito Waluyo Purboyo and Anton SiswoRaharjoAnsori, A Review of Accelerometer Sensor and Gyroscope Sensor in IMU Sensors on Motion Capture, Journal of Engineering and Applied Sciences 15 (3): 826-829, 2020

7. Liam Herlihy, Erik Golen, Leonid Reznik, Sergey Edward Lyshevski, Secure Communication and Signal Processing in Inertial Navigation Systems, 2017 IEEE 37th International Conference on Electronics and Nanotechnology (ELNANO)

8.JamesDeBruin, Dynamically tuned gyroscopes in stabilized electro-optical sights, Acquisition, Tracking, and Pointing XIII 3692, 94-100, 1999

9. Jeffrey S Cain, Douglas A Staley, Glenn R Heppler, John McPhee, Stability analysis of a dynamically tuned gyroscope, Journal of guidance, control, and dynamics 29 (4), 965-969, 2006

10. Vittorio M. N. Passaro ,AntonelloCuccovillo , Lorenzo Vaiani , Martino De Carlo and Carlo Edoardo Campanella, Gyroscope Technology and Applications: A Review in the Industrial Perspective, 7 October 2017

11. Mark Bowser, James Hammond, Michael Perlmutter, Christopher Reynolds, Remote Fiber Optic Gyroscopes for a Broad Range of Applications, Proceedings of Position, Location and Navigation Symposium-PLANS'96, 553-558, 1996

12. Yuri B. Shtessel, WING MISSILES STABILIZATION BASED ON SLIDING MODE CONTROL, The First IEEE Regional Conference on Aerospace Control Systems,, 574-578, 1993

13. MORRIS M. KURITSKY, MURRAY S. GOLDSTEIN, Inertial Navigation, Autonomous robot vehicles, 96-116, 1990

14. Daniel Tazartes, An Historical Perspective on Inertial Navigation Systems, 2014 international symposium on inertial sensors and systems (ISISS), 1-5, 2014

15. J. Kitching, S. Knappe, E. Donley, “Atomic sensors – a review,” IEEE Sensors Journal Vol. 11, No. 9, September 2011, pp. 1749-1758.

16. Oliver J Woodman, An introduction to inertial navigation, University of Cambridge, Computer Laboratory, 2007

17.Richard P Troiano, James J McClain, Robert J Brychta, Kong Y Chen,Evolution of accelerometer methods for physical activity research, British journal of sports medicine 48 (13), 1019-1023, 2014