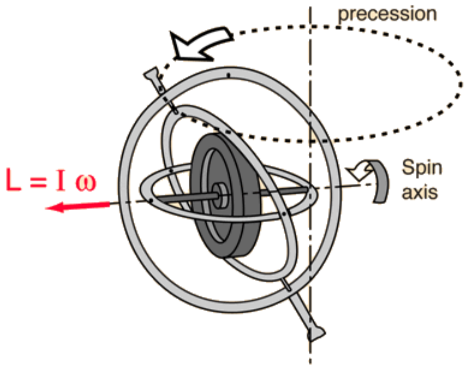
INERTIA GUIDED MUNITION - SMART BULLET CONCEPT

THEORY OF GYROSCOPE

Gyroscopes have been known for thousands of years, and their mathematical expressions have been understood for over 200 years, yet their working principle is still not fully explained. The behavior of a gyroscope is counterintuitive, requiring hands-on experiments to truly feel and learn its actual behavior. We know that it is based on Newton's Laws and that gravity has no effect on gyroscopic forces, which is why it works in space and the upper atmosphere. To this day, it lacks a complete explanation in classical physics. Gyroscopes have been used for navigation in air and sea, as well as in camera or sensor gimbals. Due to the vulnerability of current GPS tracking technology, inertia-based navigation is gaining ground in military installations. Recent developments in gyroscope manufacturing technologies—like fiber optic, micromechanics, and silicon sensors—have dramatically reduced sensor size (https://www.anellophotonics.com/). This also means there are fewer applications for kinetic gyroscopes beyond educational and toy purposes."

This presentation focuses on an inertial guidance system based on kinetic gyroscopes and the control electronics required to operate them. The kinetic gyroscope is the main component in the 'smart bullet' concept, as all other parts of the system are well-known and developed to an industrial level. Despite the fact that there is still no complete explanation of how gyroscopes work, their mathematical basis is well understood, and their movements can be calculated using the following equations:



The angular momentum (L) of a rotating mass is:

$L=m*r^2*\omega = I*\omega$

where m is the mass, r is the radius and ω is the angular velocity.

When a torque is applied to a spinning gyroscope, instead of tilting directly in the direction of the applied force, its axis of rotation tilts in a direction perpendicular to the applied force. Because the precession rate is inversely proportional to angular momentum and angular velocity, precession can be minimized by increasing velocity, mass, or radius. When the applied torque is high, it may be necessary to compensate for the precession effect. This can be achieved using multiple gyroscopes or by making gradual trajectory adjustments with fins. However, this is often unnecessary, as fast sensors and rapid signal processing provide constant position feedback and correct minor directional errors caused by the precession effect. The formula for the precession rate under the influence of an external torque is given by:

$\omega p = \tau / (I * \omega)$

where ωp is the precession angular velocity, τ is the external torque, I is the moment of inertia of the gyroscope ($I = m * r^2$), and ω is the angular velocity of the gyroscope. The applied external force is momentary and is removed after the trajectory adjustment has been made.

PRINCIPLE OF OPERATION

The main strategy is to detect the target as soon as possible and continuously update its location and speed using various sensors. In some cases, the target coordinates are preset during the initialization phase. After trajectory adjustment, the rocket motor's thrust vector is immediately redirected to the new location. However, due to the missile's mass, it continues to follow a curved path in accordance with Newton's Laws. This path can be calculated using basic parameters (speed, weight, longitudinal angular momentum, and thrust vector). Weather conditions can disturb the path, but it is constantly corrected with new sensor data. The gimbal turning time is the duration required to receive new data and initiate a new adjustment, and this speed depends on the gimbal motor's efficiency. As soon as the new trajectory data is calculated, the missile is directed to the newly estimated collision point by adjusting the gyroscopes. To turn quickly, high-speed signal processing is required to interpret sensor data into gimbal commands. The faster the gimbal moves, the quicker the calculation can be completed. This is a crucial requirement for hypersonic missiles but less important when intercepting slow-moving drones.

The simplified targeting procedure is depicted in Fig. 1.

- •t0: Time when the target is detected
- •t1: Time when the target's direction and speed have been analyzed
- •t2: Time when the missile has been turned to the new position
- •t3: Time of impact

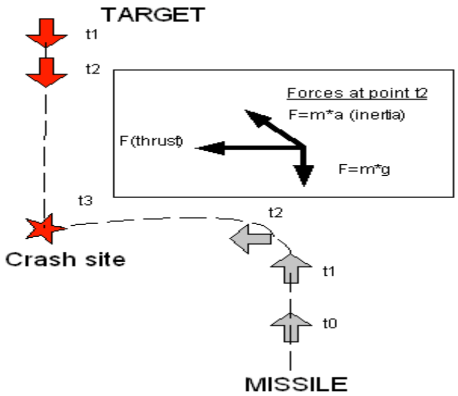


FIG 1

The time interval t2 – t1 is the duration required to turn the missile. This is also the time needed to analyze new sensor data. This sequence is constantly repeated to hit the target.
When the missile is pointing to the new location, inertial forces continue to move the missile forward, but this movement is gradually overtaken by the motor thrust force.

To hit the target, it is important to detect and analyze the target's trajectory quickly, but the following information is also needed for the calculations:

- •Missile total mass
- •Missile longitudinal angular momentum
- •Missile's inertia (rotational angular momentum) for precession corrections
- •Gimbal turning force and access time (turning speed measured in degrees per millisecond)
- •Air drag is considered constant and is subtracted from the rocket's total thrust
- •Weather conditions are not analyzed but can be incorporated into the flight plan during the initialization phase
- •If a random trajectory is used at the final approach, a special algorithm ensures the target can be hit at all times

There are multiple methods to detect a target depending on the target type and speed requirements:

1.High-speed CMOS camera: This is the most common and inexpensive way to detect a target. Using multiple CMOS cameras simplifies the mechanical construction compared to a single camera on a gimbal.

2.Optical Time-of-Flight (ToF) sensors: These can improve detection in bad weather conditions due to their modulated signal but are more expensive than cameras, especially at longer ranges.

3.LIDAR sensor: This method can use different frequencies for maximum penetration. Due to its scanning principle, it is slower than ToF sensors. When longer wavelengths (e.g., 1550 nm) are used, LIDAR can penetrate through some clouds, but the sensor price is higher compared to sensors in the visible range.

4.RF signal detection: When the target has a GPS or other radio frequency communication device, it is possible to detect the signal direction using multiple RF antennas and measure the phase difference between them.

5.Audio signals: With multiple inexpensive microphones, it is possible to determine the signal direction from the target by comparing the phase differences of incoming signals. Microphones can also be used to recognize the target from a library of sound profiles, which helps filter the sound to improve the signal-to-noise (S/N) ratio.

6.IR radiation: This is a very common method when the target is hot, such as hypersonic missiles or tanks. IR detection is not recommended for low-cost devices, as IR cameras are expensive due to the sensor's strict operating condition and construction requirements.

7.GPS: This is not recommended due to its vulnerability to electronic warfare. It can be used conditionally for guidance, but an onboard database with terrain data is preferred.

8.Accelerometer and altimeter: These would enhance accuracy, but rough data can also be obtained from gyroscopic data.

MECHANICAL CONSTRUCTION

The main difference from existing missiles is the length and the absence of control fins. Smaller fins could help stabilize the trajectory, but if the gyroscope's angular momentum is high, they are not necessary. A shorter length improves maneuverability. As radius is the most significant parameter in the angular momentum formula, the radius of the rotating mass should be maximized, leading to a short and wide form factor.

It is also important to maximize longitudinal angular momentum by placing all heavy components in the center. For this reason, the explosive material is integrated into the rotating mass. The extra kinetic energy from the rotation of the explosive mass can also increase destruction at the target.

Sensors, computers, and other lightweight elements can be placed in the front cone. During the initialization phase, the docking or launching station will provide a high-current supply to the motors to load a predetermined inertia level into the gyroscopes. Flight data will also be loaded through this connection.

TYPICAL VARIATIONS TO GYROSCOPE CONFIGURATION

The inertial guidance unit with integrated explosives is controlled by the main computer, which also manages all other missile functions, such as ignition of the rocket motor, target recognition, trajectory calculation, target proximity detection, and other crucial features. There is no need to control the rocket motor, as inertial guidance provides reasonably accurate location data even when rocket thrust is unstable. Reasonable location accuracy can also be calculated from gyroscope movements. Feedback data from the sensor system provides reliable target information and can compensate for any deviations in the trajectory. When higher accuracy is required, a micro-electromechanical system (MEMS), silicon photonic integrated circuit (IC), or fiber optic sensor can be added.

The gyroscope is placed at the center of mass to reduce longitudinal angular momentum and enable faster turning. Furthermore, the gyroscope's mass is maximized to increase rotational angular momentum, making it easier to turn the missile relative to the gyroscope and reducing the precession effect. These are the reasons why it is beneficial to integrate everything into the center. If the space is limited to a specific value, such as 155 mm ramjet driven munition, the gimbal mechanism should be placed at the center of the gyroscope, with the mass concentrated on the outer rim, where the highest momentum is achieved. To further reduce the size, it is advantageous to place the x- and y-axis gyroscopes at the same center point. This structure increases angular momentum but requires a very sturdy gimbal mechanism and powerful motors to operate it. This principle is also useful when gyroscopes are separated, each with its own position access mechanism.

In one version, a single gyroscope is assembled within a moving frame supported by a two-axis gimbal arrangement (pitch and yaw). The rotating mass is shaped as either a sphere or a disc. Angular velocity is sustained using stator coils attached to the frame and magnets embedded in the rotating mass, forming a brushless DC motor. The coils are connected via a flexible cable to the control PCB, which houses the DC motor drivers. This configuration enables the gyroscope's angular momentum to be maintained throughout the entire flight duration. The motor must also support a high acceleration rate when powered by a high-current supply during the initialization phase. The time required to accelerate the motor's spin is termed the 'initialization delay,' which varies depending on the use case. In scenarios with a short range, high-quality bearings, and a substantial rotating mass, it may be feasible to leave the gyroscope unpowered after launch, allowing the rotor speed to gradually decrease. With RPM feedback, adjustments can be made to the gyroscope formulas, such as the precession rate ($\omega p=\tau/(I\cdot\omega)$), based on the measured RPM value.

The detonator for the explosive core of the gyroscope can be placed close to the stator coils or on the opposite side of the mass. Using connecting rings, it is possible to transmit the detonator impulse from the main computer. It is also possible to place the detonator capacitor here, but as it is a lightweight component, it is better to place it outside, reserving this space for heavier components to maximize angular momentum. The detonator action can also be wireless. To allow maximum gimbal movements, all wiring is implemented with a flexible circuit, which includes at least the following connections:

- Power supply to feed the motors, 3–12 V (overridden at startup by an external high-power supply to initiate the gyroscopes)

•12 leads to the motors if motor control is external; otherwise, only 2 wires to switch on if the control circuit is integrated into the motor coils

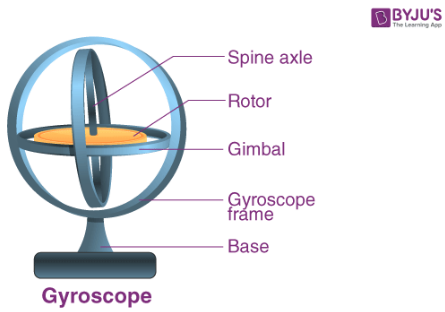
•Detonator signals (2)

•Optionally, RPM signals to the main CPU from the gyroscopes (optionally using a wireless Hall sensor)

GIMBAL CONTROL MECHANISM

The gimbal is connected to the chassis by two curvilinear rods: one in front for yaw and the other in the back for pitch, positioned 90 degrees apart from each other. In the standard arrangement, the turning angle is approximately 150 degrees, but with specialized mechanics, it can reach up to 180 degrees. However, it is easier to return to the original position using fins if inertial guidance is employed. This means that after a rapid maneuver, the control system begins to restore the original position through gradual directional corrections. This approach provides greater gimbal movement flexibility when the next very fast, excessive turn request occurs. It is beneficial to place the gimbal at the center of mass to achieve low axial inertia, which also enables the missile to turn quickly. This may require calculations to balance other components, such as the rocket motor, electronics, and batteries.

The motor assembly is attached to the curvilinear rods, which are hinged to the gyroscope's frame. The motor is either a stepper motor or a DC brushless motor.



The gimbal is moved to the required position using stepper motors or high-torque DC motors when high speed and/or high torque is needed. A stepper motor offers precise movements and does not require position feedback, while a high-torque DC motor can act quickly but needs position feedback, typically provided by optical or magnetic devices. The choice of motor type depends on the missile's mass, the required turning speed, and the turning angle requirements. The gimbal's x- and y-axis motors are fixed to the chassis, and there is ample space to place motor control electronics close to the motors, thus reducing wiring requirements. A 4-wire flexible cable can supply power and serial data to the motor control electronics.

All critical mechanical connections to the gimbal must be secured against high acceleration forces. The key areas to monitor are: the bearings of the gyroscope axle and the curvilinear rod connections to the gimbal frame (4 pieces). These connections bear the full force from the gyroscope's mass (F= m * a) during the initial acceleration phase. Turning-induced acceleration can also be significant, with a force vector different from that during launch, potentially loading the gyroscope axle vertically. In cases where expected turning commands are primarily downward—such as when targeting an object over a hill or building—it is beneficial to make an initial direction adjustment in the opposite direction to gain more range for a rapid downward turn. This is a typical scenario in smart mortar launches. It's important to note that, without gyroscope adjustments, the missile's behavior is ballistic, which can reduce the available turning angle if not properly managed.

An alternate structure consists of two separate gyroscopes: one for pitch and the other for yaw. This construction is mechanically simpler but offers greater resistance to precession. The gyroscope position control actuator is similar to the gimbal version but allows some flexibility for variations. This structure also increases longitudinal angular momentum, as it is challenging to place both gyroscopes in the same location.

STRUCTURAL VARIATIONS AND DEFENSE POLICIES IN DIFFERENT USE CASES

Although the gyroscope principle is a universal physical phenomenon scalable to different masses, there are typical variations depending on the use case:

1. Handheld Devices for Drones or Other Slow-Moving Targets
    - The ability to aim reduces the required range and turning angle.
    - Initial target settings are provided by remote fire control.
    - Fast target recognition using localized AI is required.
    - The diameter of the 'bullet' is limited to a maximum of 50 mm.
    - A tungsten shell may be needed to increase inertia.
    - Various types of explosives or destructive devices are possible (e.g., sticky glue, net, napalm).
    - Intelligent swarm defense is enabled through communication (e.g., UWB, frequency hopping) between bullets.
    - Initialization delay must be considered.
2. Mortar-Type Devices to Destroy Stationary or Slow-Moving Targets
    - A rocket-propelled ballistic trajectory is well-predicted and loaded into memory during initialization.
    - A random trajectory option can be used to evade counterstrikes.
    - Camera- and IR-based sensors are employed.
    - Maintaining gyroscope motor power can be omitted due to the short range, though initialization is still required.

SAAB THOR 120 mm MORTAR AMMUNITION

3. Air-to-Air Missiles

- •Very fast movements are required to defeat fin-driven missiles and fighter jets.
- •The initialization delay is problematic when installed under the wings.
- •The form factor differs from the Sidewinder type, with a shorter length preferred to enable rapid movements.
- •A high-power kick-start is needed to accelerate the gyroscopes prior to launch.
- •AI-based target recognition is utilized.

4. Hypersonic Missiles

- •Extremely fast computing is required.
- •Fast movements, generated by high angular momentum, are necessary.
- •The target is easily detected by IR radiation.
- •Radar- and satellite-based target detection is utilized.

SUMMARY

Kinetic gyroscopes with high angular momentum can substantially improve missile maneuverability and hit accuracy. Compared to traditionally used control fins, a gyroscope-assisted missile can turn orders of magnitude faster because air density has no effect on the turning. Integration with the latest microelectronics and silicon sensor technology reduces the overall size and cost in mass production. Incorporating explosive material into the rotating gyroscope's mass further reduces the missile's size and enhances maneuverability. With the exception of the gyroscope gimbal mechanics, all components are industrially manufactured and currently used in existing missile

products. The gimbal is a well-known mechanical structure but requires redesign specifically for this application due to rigidity requirements stemming from the high acceleration stresses encountered during flight. The electromechanical design of the gimbal leverages cutting-edge technologies used in robotic assemblies, such as flexible circuits and dedicated embedded microcontrollers.

A faster response to intercepted threats is crucial in modern warfare. This principle is scalable, from handheld devices to ICBMs, constrained only by the miniaturization limits of the gimbal structure. Some size-constrained designs, such as 155 mm munition, may need to limit gyroscope size due to ramjet motor requirements. Similarly, designs requiring very large turning angles may necessitate a larger gimbal to accommodate excessive turning commands. However, this method is generally flexible and adaptable to various configurations, including a single gyroscope, two separate gyroscopes, two gyroscopes within a gimbal, or three gyroscopes for maximum directional stability.

It is important to note that adopting this inertia guidance method into existing designs is based on well-known physical phenomena and requires only electromechanical engineering and customization for different use cases. However, the software required to utilize fast sensor data and fast movement controls should not be neglected as it could constitute a substantial part of the NRE cost.