Navigation using Gyroscope and Accelerometer in Botball

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***Abstract*—Navigating without external references remains a significant challenge if external sources are unreliable due to effects such as GPS spoofing or unavailable in enclosed environments. In such situations, gyroscopes and accelerometers enable motion tracking through inertial references. This principle forms the basis of inertial navigation systems (INS), which are commonly used in modern aviation to maintain positional awareness and orientation independent of external signals. This paper investigates the feasibility of using the Wombat controller's low-cost IMU for Botball navigation through experimental evaluation of gyroscope bias and accelerometer-based position estimation.**

I. INTRODUCTION

Autonomous navigation without reliable external references is a significant engineering challenge. In modern aviation, Inertial Navigation Systems (INS) are crucial for maintaining positional awareness when signals like GPS are jammed, spoofed, or otherwise unavailable. These systems rely purely on internal sensors like gyroscopes and accelerometers.

This concept of inertial navigation is highly relevant not only for aerospace but also for autonomous educational robotics. In the Botball robotics program, autonomous robots must navigate precisely on a competition table. Since external positioning systems (like GPS) are not applicable indoors and traditional wheel odometry often fails due to wheel slip, internal motion tracking becomes a vital alternative.

However, while aviation utilizes highly accurate and expensive sensor arrays, educational robots like those in Botball rely on low-cost Micro-Electromechanical Systems (MEMS), such as the IMU integrated into the Wombat controller. This paper investigates the feasibility of using these low-cost gyroscope and accelerometer sensors for Botball navigation, analyzing their fundamental principles, practical limitations such as sensor drift, and evaluating to what extent a full INS approach is viable in this context.

II. FUNDAMENTALS OF GYROSCOPES AND ACCELEROMETERS

A. Gyroscope

Gyroscopes are used to measure rotational motion. The measurement of rotational speed is called angular velocity and is measured in degrees per second ($^{\circ}\,\mathrm{s}^{-1}$) or revolutions per second (RPS). Gyroscopes usually measure angular velocities about the x- (roll), y- (pitch) and z-axis (yaw).

The values measured by the sensor will contain some error or deviation. These errors are called bias and can be measured when the gyroscope is stationary. Instead of measuring an angular velocity of $0\,^{\circ}\,\mathrm{s}^{-1}$ it will show a tiny error. The measured sensor bias is highly affected by the temperature, for this exact reason most gyroscopes are fitted with a temperature sensor to correct temperature-dependent bias. [1]

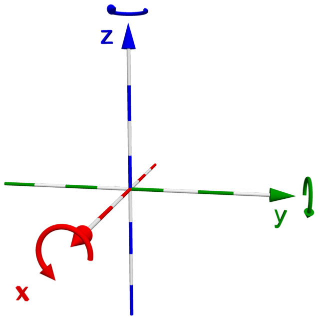

Fig. 1. Right-handed coordinate system (x to front), by Watchduck, licensed under CC-BY-SA-4.0, via Wikimedia Commons

B. Accelerometer

Accelerometers are used to measure the linear acceleration experienced by an object. Acceleration indicates the rate of change of velocity in $\mathrm{m\,s^{-2}}$. When an object changes direction, speed or transitions between stationary state and moving state, an accelerometer detects this acceleration. Like gyroscopes, accelerometers also commonly measure along the x-, y- and z-axis. [2]

The acceleration measured by these sensors can be integrated in order to determine velocity and position of an object. Since accelerometers do also have a bias, position and velocity errors increase over time and accuracy decreases. [3]

III. COMBINING GYROSCOPES AND ACCELEROMETERS FOR NAVIGATION

A. Principle of Inertial Navigation

An inertial navigation system combines motion sensors (accelerometers), rotation sensors (gyroscopes) and a computer which continuously calculates the position, the orientation and the velocity using dead reckoning[1] without the need for external references.

An INS needs to be initialized with a starting position and velocity. This information can be fed from a GPS information receiver, a human operator or in case of Botball from an always identical starting position. Once initialized the system does not require any further external references and is able to navigate relative to an initial reference frame. [4]

B. Role of Gyroscopes and Accelerometers Together

Gyroscopes are used to measure the angular velocity relative to the sensor frame. This is achieved by using the inertial reference frame as the initial condition and integrating the angular displacement, so the orientation of an object can be estimated at all times.

By using gyroscopes only, the orientation of an object is known, but to know the position of an object knowledge about the distance that is traveled is also required. The distance can be measured by using an accelerometer and integrating the linear acceleration to determine the velocity and integrating a second time to determine the position. [4]

C. Error Accumulation and Drift

Inertial navigation systems suffer from integration drift. This drift originates from small errors in the measurement of acceleration and angular velocity which are integrated and result in progressively larger errors. Since the current position is always calculated based on the last position, the experienced drift accumulates over time. To keep the position highly accurate, the position may get periodically corrected by input from another navigation system like GPS. If gyroscope and accelerometer are accurate enough and the use-case does not require near 100 % accuracy, the drift can also be considered irrelevant.

GPS—if reliable and available—is commonly used to correct the inertial navigation systems and keep them highly accurate. In areas where GPS is unreliable or unavailable INS can then be used to navigate providing sufficient accuracy. [4]

IV. AVIATION AS A REFERENCE SYSTEM

A. Use of Inertial Navigation in Aviation

Most modern commercial and military aircraft use inertial navigation systems to have redundancies when GPS is unavailable or unreliable. GPS or other signals often get jammed[2] or spoofed[3] in and above war zones or conflict areas by the military. GPS or other signals might also get obstructed or influenced by environmental conditions. In these scenarios an aircraft's systems and the pilots can no longer rely on external references. Instead, they need to be able to rely on their inertial navigation system for accurate position data.

B. Combination of INS and GPS

One advantage of combining INS and GPS is redundancy, in the event that one of the systems fails. When both systems work as expected the GPS can also be used to periodically correct the INS and therefore reduce the drift. Inertial navigation systems are well suited for short-term use on their own and supplemented by GPS long-term accuracy is ensured.

V. PRACTICAL IMPLEMENTATION

The following code listings demonstrate the core algorithmic steps of inertial navigation as implemented on the Wombat controller.

A. Attitude Estimation using Gyroscope

Attitude estimation is achieved by numerically integrating the angular velocity measured by the gyroscope over time. The raw integer values returned by `gyro_z()` must be scaled by a factor of $\frac{250}{512}$ to obtain angular velocity in °, as the Wombat's sensor maps $\pm 250\,^{\circ}\,\mathrm{s}^{-1}$ to the integer range ± 512.

Listing 1 shows a minimal implementation.

```
double angle_deg = 0.0;
const double dt = 0.01; // 10 ms sample
    interval

while (1) {
    double omega = gyro_z() * (250.0 / 512.0);
    angle_deg += omega * dt;
    msleep(10);
}
```

Listing 1. Angle estimation from gyroscope data

B. Position Estimation using Accelerometer

Position is estimated via double integration of linear acceleration. As each integration step introduces additional error, position estimates degrade significantly over time. The raw integer values returned by `accel_x()` must be scaled by a factor of $\frac{9.81}{1024}$ to obtain linear acceleration along the x-axis in $\mathrm{m\,s^{-2}}$, as the Wombat's sensor maps $\pm 9.81\,\mathrm{m\,s^{-2}}$ to the integer range ± 1024.

Listing 2 shows a minimal implementation.

```
double vel = 0.0, pos = 0.0;
const double dt = 0.01;

while (1) {
    double acc = accel_x() * (9.81 / 1024.0);
    vel += acc * dt;
    pos += vel * dt;
    msleep(10);
}
```

Listing 2. Position estimation via double integration

The double integration means that a constant bias b in the accelerometer results in a position error that grows quadratically as $\frac{1}{2}bt^2$, making long-term position tracking infeasible with low-cost sensors.

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[1] Dead reckoning is the process of calculating the current position of a moving object using a previously determined position. [5]

[2] Signal jamming is done by using a transmitter to create signals of the same frequency as the original signals and therefore interfering with them. This can make it difficult for signal receivers to receive any signal and therefore lead to rendering them useless. Jamming can happen either accidental or intentional. [6]

[3] Signal spoofing is done by generating a spoofed version of a signal and transmitting it. A receiver then is unable to tell which one is the real signal. [6]

VI. EXPERIMENTS & RESULTS

To evaluate the practical suitability of the Wombat's IMU for Botball navigation, three experiments were conducted.

A. *Static Gyroscope Bias Test*

The robot was placed stationary for 60 seconds while gyroscope readings were continuously logged at 100 Hz. Ideally, the measured angular velocity should remain at $0\,°\,\mathrm{s}^{-1}$. Fig. 2 shows the recorded angular velocity and the resulting accumulated angle error.

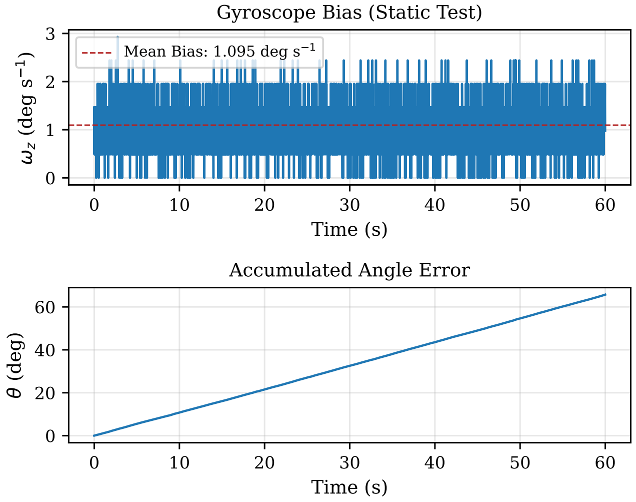

Fig. 2. Gyroscope readings during static test (top) and resulting accumulated angle error (bottom).

The mean bias was measured at $1.095\,°\,\mathrm{s}^{-1}$, resulting in an accumulated heading error of 65.708° after 60 seconds. In addition to the high bias, the measurements exhibit noticeable noise, which introduces short-term fluctuations in the angular velocity signal. Over time, this leads to a growing angle error.

B. *Dynamic Gyroscope Straight-Line Test*

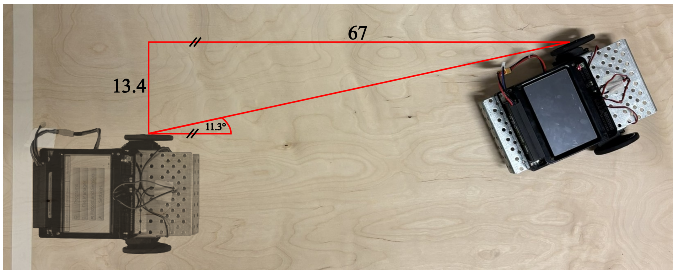

Fig. 3. Experimental setup after straight-line run, showing lateral deviation from the intended path.

The robot was commanded to drive straight for 8 seconds. The heading change estimated by the gyroscope was compared to the real lateral deviation (Fig. 3) measured manually using a tape measure.

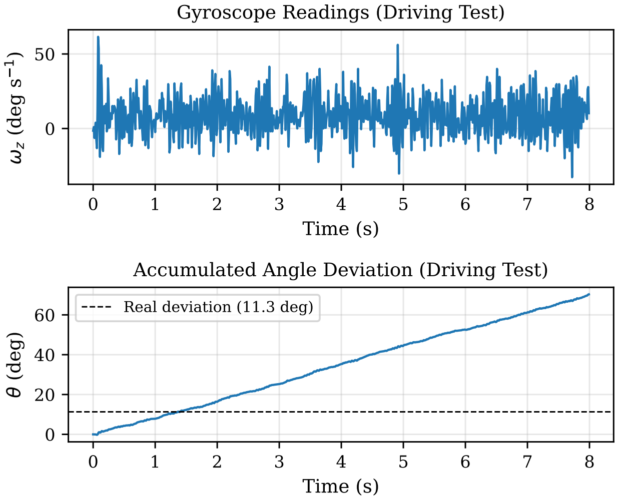

Fig. 4. Gyroscope readings during driving test (top) and resulting accumulated course deviation (bottom).

The static experiment illustrates (Fig. 4) the long-term drift caused by gyroscope bias, whereas the dynamic test shows that this effect already leads to measurable deviations over short distances.

Although the gyroscope provides a continuous estimate of angular velocity, even small biases accumulate over time and result in a deviation from the intended trajectory. In this experiment, the integrated angle error caused a lateral deviation of approximately 13.4 cm over a traveled distance of 67 cm.

This corresponds to a deviation of about 20% of the driven distance, highlighting that gyroscope-only navigation is not sufficiently accurate for precise path following in Botball.

C. *Accelerometer Distance Test*

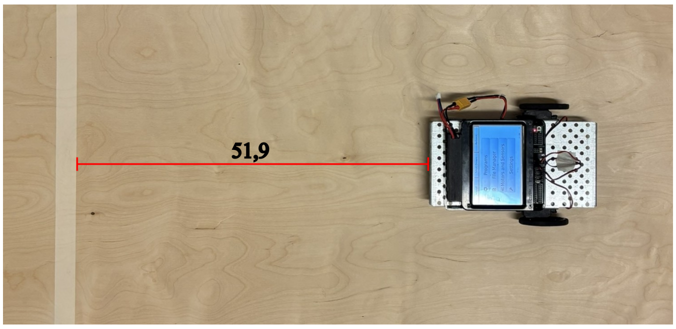

Fig. 5. Experimental setup after straight-line run, showing actual distance driven.

The robot was commanded to drive in a straight line until the estimated distance, obtained by double-integrating the accelerometer data, reached approximately 0.8 m. A piece of tape was used to mark the starting position, and the actual traveled distance was measured manually after the run.

Fig. 5 shows the experimental setup and the final position of the robot relative to the starting point.

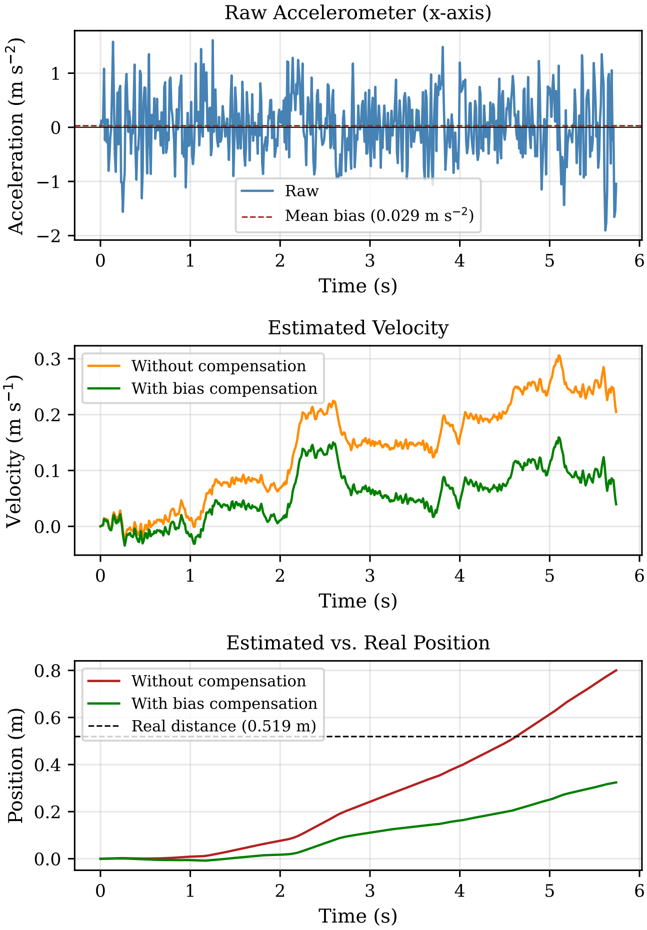

Fig. 6. Accelerometer readings during driving test (top), estimated velocity during driving test (center) and resulting position estimate (bottom).

The recorded accelerometer data and the resulting velocity and position estimates are shown in Fig. 6.

The raw acceleration signal exhibits significant noise and a measurable bias of approximately 0.029 m/s^2. When integrated, this bias leads to a steadily increasing velocity offset, which in turn causes a rapidly growing position error.

Without bias compensation, the estimated position diverges significantly from the real trajectory. Even with bias compensation applied, the remaining noise and inaccuracies result in a substantial deviation.

While the robot estimated a traveled distance of approximately 0.8 m, the actual measured distance was 0.519 m, resulting in an error of about 54 %.

This experiment clearly demonstrates that accelerometer-based position estimation is highly unreliable in this setup, primarily due to the double integration of measurement errors.

This error is systematic rather than random, as it is primarily caused by the constant bias of the sensor.

VII. Discussion

While professional inertial navigation systems in aviation serve as a benchmark for high-precision, long-term navigation, the results of these experiments demonstrate that a full INS approach is not feasible with the low-cost MEMS sensors of the Wombat controller.

The primary limitation is the significant sensor bias. The measured mean gyroscope bias of $1.095\,^\circ\,\mathrm{s}^{-1}$ led to a lateral deviation of approximately 20 % of the driven distance in dynamic tests. Unlike aviation-grade systems that use high-quality hardware and complex filtering to mitigate drift, the Wombat's sensors accumulate error too rapidly for reliable heading maintenance over longer periods.

The challenges are even more pronounced for position estimation. The experiment showed a distance error of about 54 %. This confirms the theoretical expectation that even a small constant bias b results in a position error that grows quadratically as $\frac{1}{2}bt^2$ due to double integration.

For practical Botball applications, this means that inertial sensing remains useful only for short-term, discrete tasks, such as executing controlled turns or maintaining a heading for a few seconds. To achieve reliable autonomous navigation across the entire competition table, a hybrid approach is mandatory, where the IMU is periodically corrected by external references like line sensors, walls, or starting positions.

VIII. Conclusion

Inertial navigation systems are a powerful concept and widely used in safety-critical applications such as aviation.

However, the experiments conducted in this paper show that the low-cost IMU integrated in the Wombat controller is not suitable for full inertial navigation due to significant sensor bias and error accumulation.

Nevertheless, the gyroscope can still be used effectively for short-term orientation tasks, such as executing controlled turns or maintaining a heading over short distances.

For practical Botball applications, a hybrid approach combining inertial sensing with external references is recommended to achieve reliable navigation.

References

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