Utilizing the Internal Gyroscope for Reliable Inertial Navigation
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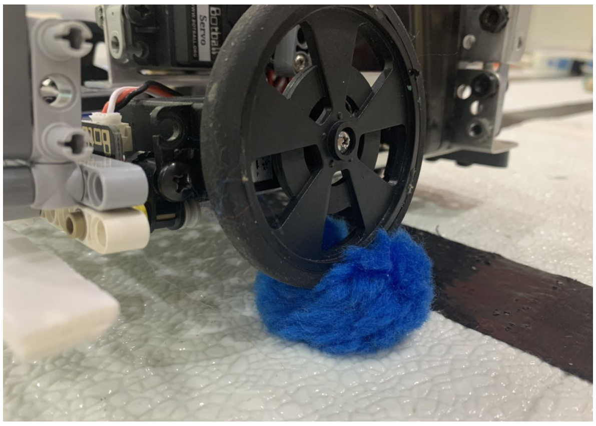
Abstract – This paper shows an approach on how to significantly improve the maneuvering reliability of a wallaby-controlled robot by using its internal gyroscope and various supporting algorithms. Stable movement is an extremely desirable feature of robots in Botball, because of the various obstacles present on the game table, as well as possible interference from the opponents, which can hit the robot and set it off-course. A robot equipped with an implementation of the gyroscope system can accomplish tasks such as turning accurately for 90 degrees, driving in a straight line, and correcting its orientation after colliding with obstacles.

1. Introduction

Robots are typically constructed with two motors on its base, each attached to two wheels, that administers its movement around the game table. The motors themselves are usually controlled by functions such as mav( ) and mrp( ), sometimes in conjunction with correction methods such as line following, wall-bumping, etc. This setup is widely used because of its simplicity, but it has several drawbacks.

It is hard for the robot to move in a straight line, even if the robot is oriented correctly at the start, and the two motors are set to the same velocity. This is because the two motors may have a very slight speed differential, and one wheel would spin faster than the other, causing the robot to deviate left or right. Normally, with some help from line-following and other correction procedures, this problem can be overcome, but sometimes it is necessary for a robot to enter an area that has no lines to follow, in which the conventional methods of navigation would become too unreliable to use.

Accurate turning is also difficult to accomplish by using this simple system, and sometimes a significant deviation would appear if you execute many seemingly perfect 90 degrees turns in series. Using the mrp( ) function can slightly improve the situation, but the back-EMF based tick counting system for the motors still suffers from precision issues, and its readings varies for different motors.



The presence of obstacles on the game table poses a further threat to the robots. Most of the time, a properly installed bumper can push away dangers in the robot's way, but sometimes, deformable objects, such as pom balls, can be squashed and slide under the bumper. The wheel would slip if a pom goes beneath it, and this causes the robot to deviate off course. Interference from the opposing team can also similarly affect the robot's movement.

The problems mentioned above inspired the author of this paper to develop the gyroscope-based inertial navigation system to improve the robot's reliability and stability.

2. Data Stabilization

Ideally, the readings from the gyroscope on all axis should be zero when the robot is static. However, this is rarely the case, because the gyroscope is affected by vibrations, ambient temperature, and various other uncontrollable environmental factors [1], which results in a reading that oscillates around -10 to +10. This raw reading cannot be used directly for integration because the integral would accumulate these false values and become unusable. In order to solve this, an integer conversion is used first to rectify the readings, and an average over 10 iterations is taken. This is demonstrated through the following code snippet:

```
A1=0;
for(i=0; i<10; i++){
    // force conv into integer
    A = (int)(gyro_x()/5)*5;
    A1 = A1 + A;
}
A = A1 / 10; // take avg
```

3. Offset Parameters

The gyroscope's reading is sometimes off by a constant amount [2], and its cause is similar to the reasons mentioned above. This constant offset would accumulate and cause the integral to grow over time even if the robot is static, and it would falsely predict that the robot rotated. To solve this, an offset parameter is subtracted from the average reading taken previously. This parameter can be adjusted manually, or it can be calculated by taking the average of the gyroscope's reading over 100 iterations. The following code snippet shows how the offset parameter is used in an integration step:

```
void move_gyro(int speed, double tt)
{
    ...
    while(1){
        // read gyro...
        angle += (average_va - move_f) * t2;
        // adjust motor...
        if(done)
            break;
    }
}
```

A different offset parameter is used for calculating the degrees turned when the robot rotates. In order to ease the programming process, we multiply the target angle by the offset, and compare this value to the one returned by the integral, as the integral uses an arbitrary unit that isn't degrees. This way, instead of passing an arbitrary value into the function, we can now simply write rotate(90) to turn 90 degrees. The angle_f offset parameter is tuned manually by seeing if the robot can return to its original orientation by rotating 720 degrees, using a series of rotate(90) calls. This process accumulates the small deviation in each rotation that would otherwise be unnoticeable.

```
void rotate(int aa){
    ...
    int angle = 0;
    aa = aa * angle_f;
    while(1){
        // read gyro...
        // integration...
        if(angle>aa)
            break;
    }
}
```

A third offset parameter is used to account for the reading difference returned by the gyroscope for clockwise and counterclockwise rotations. This difference was discovered by accident when the author observed that a perfectly calibrated clockwise 90 degrees turn will always result in a constant amount of excess rotation when -90 (anticlockwise turn) is passed to the rotation function. This negative offset is calibrated manually, with the same procedure (rotate 720 degrees and observe the deviation) that's used previously.

```
void rotate(int aa){
    if(aa>0){   // clockwise turn
        if(angle>aa)
            ...
    } else {    // anticlockwise
        if(angle<aa*nrOffset)
            ...
    }
}
```

The value of nrOffset is typically set to 0.99 based on the author's experience, but may need to be adjusted for different wallaby controllers.

4. Fixed Time Step Integration

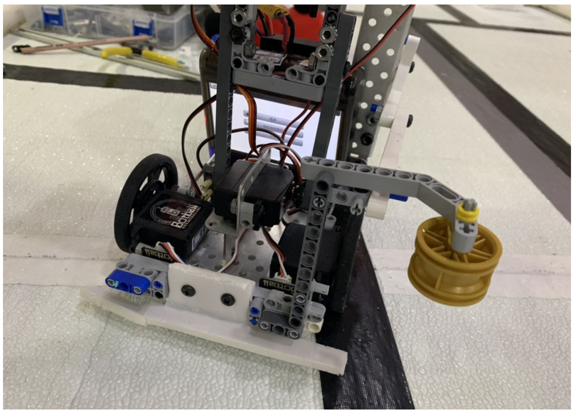
Integration is the central component in the gyroscope navigation system. To calculate displacement over a period of time, the following integral is used [3]:

$$\int_a^b v(t)\,dt$$

This integral calculates the displacement in the time period from a to b, and it involves finding the antiderivative of the v(t) function. However, in practice, we can't find the antiderivative of the gyro_x( ) function, so it is usually implemented as a finite sum to approximate the integral, with Δt being a finitely small value, typically 1 millisecond:

$$\sum_{i=a}^{b} v(i) \cdot \Delta t$$

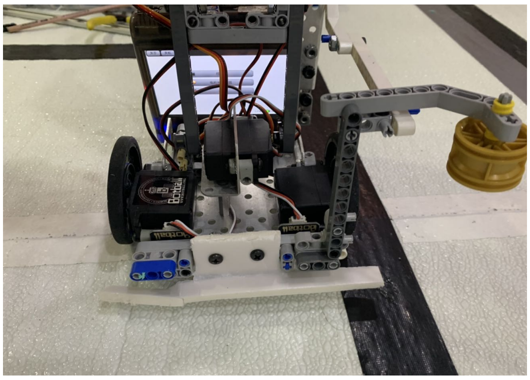
Of course, when implementing the above idea in code, the velocity function (gyro_x) does not take a time parameter input; instead, it just reports the angular velocity reading at the moment. However, because the wallaby is running on Linux instead of an RTOS (real time operating system), every iteration of the loop isn't guaranteed to have a fixed time step of 1 millisecond, as the CPU has to spend time dealing with other tasks given to it by Linux [4]. The constantly changing elapsed time would add a lot of errors to the integral, which ultimately leads to an inaccurate estimation of the degrees turned by the robot. The following picture shows the deviation created when the robot executes eight 90 degrees rotations in series.



In order to enforce a fixed "frame rate" for the loop, a timer is incorporated into the code to calculate the elapsed time.

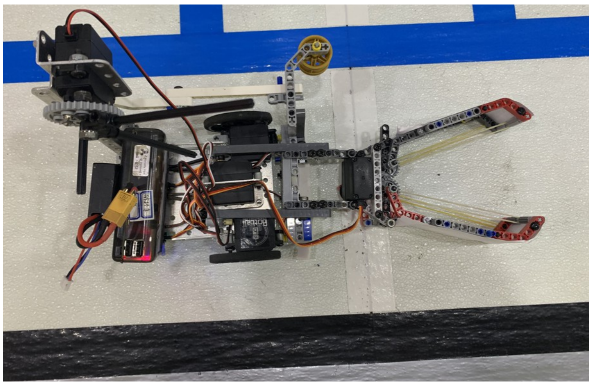
```
t0 = seconds();
while(1){
    ...
    // calculate elapsed time
    angle += A*(seconds()-t0);
    t0 = seconds();
    ...
}
```

The seconds( ) function provided by the wallaby library only has a resolution of 0.001 seconds, and it will return a value of zero if less than 1 millisecond has elapsed. This allows the integral to only accumulate the value given by gyro_x once per millisecond, and give us a precise approximation of the degrees turned. The robot is able to return to its original position (parallel to the tape) after eight 90 degrees turns.



5. PID Controller

Based on the angular deviation returned by the integral, the robot needs to adjust its two motor's power to correct the change, and maintain a straight path. A simple system would adjust the motor speeds by a constant amount in order to correct the deviation. However, this method responses poorly when there's a sudden large change in angle, and it will wobble rapidly when the deviation is close to zero. The horizontal sway caused by the wobble can sometimes set the robot off course by as much as 5cm (with reference to the black tape).

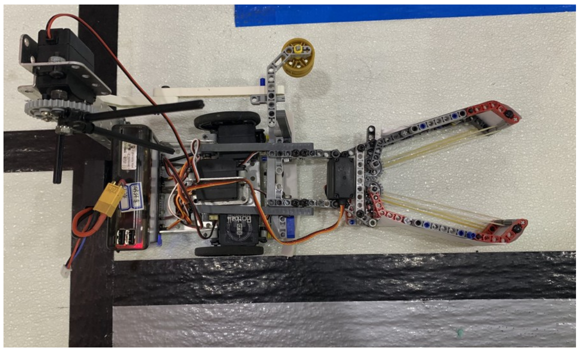


To address this problem, a PID controller is used to adjust the motor speeds. The P controller gives proportional output based on the current error. This controller provides stable operation, but never reaches the steady state (it oscillates above and below it). The I controller integrates the steady-state error over a period of time until the error reaches zero. This eliminates the wobble issue, but it needs time to react. The D controller finds the rate of change of the error with respect to time and it anticipates errors that could occur in the future. With all three together, the PID controller can smoothly adjust the motor's power based on the error. [5]

In this case, a PD controller, which is a special instance of the PID controller, is used to control the robot's motors, because rapid response is needed in order for the robot to compensate large changes quickly, and the extra stability of the I controller is not needed. This is achieved by setting the I term to zero, so it is ignored.

```
int P = 0.8, I = 0, D = 0.5;
while(1){
    ...
    E[1] = E[0];
    E[0] = angle;
    E[2] = E[0]-E[1];
    // calculate new speed
    speed_n = P*E[0] + D*E[2];
    // adjust the motors
    motor(1, speed+speed_n);
    motor(2, speed-speed_n);
    ...
}
```

After adding the PID controller, the motor's speed change is much smoother, and the issue of wobbling and horizontal sway is eliminated. The robot managed to closely follow the black line while it referenced nothing but the gyro system.



6. Motor Braking

After the movement functions completes their jobs, the motors needs to stop. The conventional method of setting the motor's speed to 0 by using mav( ) will power down the motor, but the robot will still slip forward slightly (for about 0.5mm to 1cm) because of its momentum. Because the two wheels have different friction, this slipping action would cause the one wheel to move forward more than the other, effectively rotating the robot slightly, which defeats the purpose of having a gyroscope based accurate turning system. The built-in freeze( ) function provided by the wallaby library doesn't seem to do anything to brake the motors. In order to counter this, we would force the motor to turn in the opposite direction for 10 milliseconds, then immediately shut it down. This provides a strong braking force that immediately sets the robot to a stop, and prevents any unwanted forward movement.

```
if(done){
    // reverse speed for 10ms
    motor(1, 40);
    motor(2, -40);
    msleep(10);
    motor(1, 0);
    motor(2, 0);
    break;
}
```

7. Conclusion

The gyroscope system is an invaluable piece of equipment that has made its way into many aspects of our life, such as in smart phones, watches, drones, and cars. In the case of the Botball competition, the gyroscope system, alongside its various supporting algorithms, provides a robust and reliable way of navigating robots. It is resistant to deterrences such as obstacles and accidental collisions, and it eliminates problems created by wheel slipping or motor speed differential. Utilizing the gyroscope can open up a plethora of new possibilities in terms of robot design, programming, and game strategies for Botball participants.

References

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