Celestial Blue

Dead Reckoning with The IMU Strapdown Algorithm

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Introduction

Throughout history, the ability to navigate to different locations has been incredibly important. Whether it be crossing an ocean, landing on the moon, or walking to the nearest coffee shop down street, some type of navigation algorithm must be used. The IMU Strapdown Algorithm is a way of performing dead reckoning, which is a term used to describe navigating without any external reference like stars or GPS by integrating position relative to some known initial point. An inertial measurement unit (IMU) is a sensor which can detect linear acceleration and angular velocity along all three axes. With acceleration, angular velocity, and timestep in between samples, position, velocity and orientation can be calculated at every sample. The strapdown algorithm has applications in military, space, and consumer electronics.

Background

While the exact origin of dead reckoning (short for deduced reckoning) is unclear, the technique seemed to have originated in 15th century Europe. At this time, the main mode of transport over long distances was sailing ships. It was also at this time when the first transatlantic voyage attempts started. On these long voyages, knowing your exact position was incredibly important in order to avoid dangerous sections of the sea and to ensure that the ship arrives to the correct destination. At this time, the sextant, which is a device that uses the stars to calculate position, had not yet been invented. This left sailors with only two measurement devices: a compass and a rope. The compass could inform a navigator of the heading of the ship, and rope could be knotted and lowered into the water to determine the speed by counting the number of knots that had gone through the sailor's hand after the rope is thrown overboard. By constantly measuring velocity and heading, the ship's position could be plotted relative to its initial position [1]. The technique of navigating relative to initial position without external references is known as dead reckoning. Instead of providing heading and the magnitude of velocity, the IMU strapdown algorithm will provide orientation in 3D space, and acceleration which can be integrated twice to determine position. With all this information, an estimation of a vehicle's position, velocity, and orientation (attitude), can be calculated at every IMU timestep.

Motivation

While dead reckoning seems to be a good method of navigating without the use of an external reference, in the modern day, we have access to many external references. The most common external position reference is Global Navigation Satellite Systems (GNSS). The United States uses a constellation called GPS. GPS works by harnessing the doppler effect to triangulate position when three or more satellites are fixed to a receiver. The most advanced GPS receivers can calculate position with sub meter accuracy. The existence of high accuracy external position references begs the question of the necessity of dead reckoning algorithms like the IMU strapdown algorithm. There are three major motivations. The first is the vulnerability of GPS receivers to GPS spoofing cyberattacks [2]. GPS spoofing is when an adversary emits a counterfeit GPS signal to confuse the receiver or even lead it to the wrong location. Resiliency to GPS spoofing is especially important for highly assured military or human rated systems where a spoofing attack could lead to catastrophe. It is for this reason that some assured military systems do not use GPS as their main external reference. The second reason to use IMU strapdown for dead reckoning is the relatively higher data sampling rates of IMUs. The fastest GPS receivers generally can output data on the order of 10 Hz [3]. The fastest IMUs can sample at upwards of 10,00 Hz. Additionally, there is a power limitation with GPSs. Calculating latitude, longitude, and altitude in a high precision GPS receiver can require a huge amount of power relative to an IMU reading [4]. For power constrained applications, it often makes sense to take infrequent GPS readings in conjunction with an IMU to navigate. GPSs and IMUs outputs can be fused using a sensor fusion algorithm like Kalman filtering. The third reason that IMU dead reckoning is still useful is because GPS only provides positional data, whereas IMU strapdown provides position, velocity, and attitude information. There are many applications in velocity and attitude data are extremely important, especially for vehicles that fly. In summary, IMU dead reckoning is still useful even with highly accurate external references because it can protect against GPS spoofing, it offers more frequent data updates than GPS, and it provides velocity and attitude information.

The Algorithm

$$\dot{\mathbf{r}} = \mathbf{v}$$

$$\dot{\mathbf{v}} = \mathbf{T}^{I}_{B}\mathbf{a}_m + \mathbf{g}(\mathbf{r}) - \Omega \times (\Omega \times \mathbf{v}) - 2\Omega \times \mathbf{v}$$

$$\dot{q}^{B}_{I} = \frac{1}{2}\begin{bmatrix} 0 \\ \omega_m \end{bmatrix} \otimes q^{B}_{I}$$

Figure 1. The IMU strapdown algorithm

For sake of brevity, the exact details of every part of the IMU strapdown algorithm will not be discussed, however, a strong overview will be provided. The first term equates the time derivative of position, $\dot{r}$, to velocity. This is a definition. The time derivative of position is velocity. The second term equates the time derivative of velocity (acceleration), with the sum of four terms. The first term uses a transformation matrix to convert the acceleration reading from the IMU into the inertial reference frame. The second term, g(r) takes position as an argument and returns the gravity vector in the inertial frame. g(.) is the gravity model. It describes gravity as a function of position. The two terms which both contain Ω, describe the centripetal acceleration with respect to a rotating object (the earth) and the Coriolis acceleration. The final equation in the IMU strapdown algorithm is the time derivative of the attitude representation. Attitude, or vehicle orientation describes the vehicles orientation in 3D space. It is typically representing using a mathematical object called a quaternion. In the context of aerospace, a quaternion is a 4-vector which represents an axis of rotation and a magnitude of rotation. This final equation tells us that the time derivative of the attitude representation is related to the product of the previous attitude representation and the angular velocity reading detected by the IMU. After all these derivatives are calculated, a linear interpolation can be used to integrate position, velocity, and attitude.

Applications

There are a massive variety of applications of the IMU strapdown algorithm so only a few applications will be covered. One of the most notable applications is in spacecraft guidance. Spacecraft that are travelling to deep space beyond range of the satellite constellations need to know their orientation and position. These spacecraft still use external references like star sighting, however in between reference updates, the trajectory must be known. Another common application is in submarines. GPS does not penetrate the deep waters that submarines navigate through and there are no worldwide beacon-based ocean floor navigation networks. Submarines use incredibly advanced ring laser gyro (RLG) IMUs to navigate for months with no external reference.

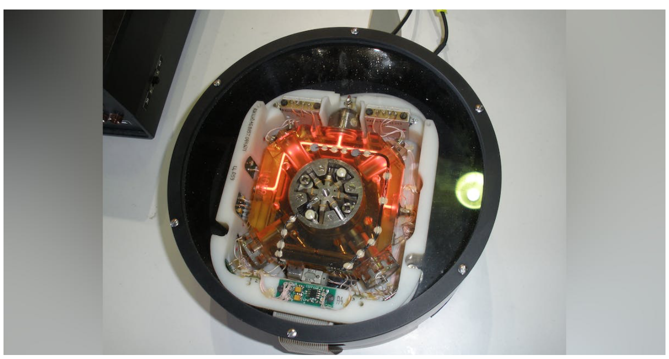

Figure 2. Northrop Grumman Ring Laser Gyro for Submarine Navigation [5]

The last application that will be discussed in this note is IMU use in aircraft. Larger commercial aircraft all have a system called an Air Data Inertial Reference Unit (ADIRU). This system in conjunction with angle of attack and airspeed sensors is used to determine the both the planes position, velocity, and attitude. Knowing these metrics to a high degree of accuracy is incredibly important for precision landings and avoiding stalls.

Conclusion

While it is no longer used to cross the Atlantic ocean in sailboats, dead reckoning is a navigation technique that is still used on some of humanity's most advanced vehicles. The IMU strapdown algorithm is the core algorithm that translates IMU output into position, velocity, and attitude information. This algorithm was a key technological development that enabled the first moon landings and it will continue to be relevant in humanities future exploration of the sea, the sky, and space.

References

1. Posner Memorial Collection. "Dead Reckoning | Timeand Navigation." *Timeandnavigation.si.edu*, 2012, timeandnavigation.si.edu/navigating-at-sea/navigating-without-a-clock/dead-reckoning.

2. McAfee. "What Is GPS Spoofing?" *McAfee*, 7 Dec. 2022, www.mcafee.com/learn/what-is-gps-spoofing/. Accessed 9 May 2023.

3. Titan Sports. "TITAN | Titan 2 plus GPS Sensors." *Www.titansensor.com*, www.titansensor.com/titan_2p.html#:~:text=More%20speed%2C%20more%20satellites%2C%20better%20data.&text=vs%2010%20Hz-. Accessed 9 May 2023.

4. Wei, Y. and Li, Y.: IMPACT OF SENSOR DATA SAMPLING RATE IN GNSS/INS INTEGRATED NAVIGATION WITH VARIOUS SENSOR GRADES, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVI-3/W1-2022, 205–211, https://doi.org/10.5194/isprs-archives-XLVI-3-W1-2022-205-2022, 2022.

5. Keller, John. "Navy Asks Northrop Grumman to Build AN/WSN-7 Ring Laser Gyro." *Military+Aerospace Electronics*, 8 Oct. 202AD, www.militaryaerospace.com/sensors/article/14038770/shipboard-navigation-ring-laser-gyro.