What is the Problem

Autonomous Guided Vehicles (AGV's) are smart vehicles that can guide themselves. That is, no user action is required to navigate the vehicle from one place to another. AGV's are typically found in large warehouses or storage places were packages are moved from one place to the other. In a typical situation, an AGV is commanded to go to some location, pick-up a package, bring it to another location and unload the package. Loading and unloading can be done autonomously or by hand, depending on the type of the AGV.

Figure 1: example AGV

Basically, an AGV is a platform with one or more steerable wheels, one or more electro motors driving the wheels and a guidance computer, controlling the motor(s). To guide the AGV, the guidance computer needs input from sensors. Most AGV's are equipped with so-called "wheel-encoders" that provide information about the angular movement of the wheels. Given the known diameter of the wheels, the wheel-encoders give basic information about the velocity (or more precise: position increment) of the AGV and the steering angle of the steering wheels. This information is numerically integrated by the guidance computer and results in the position and heading of the AGV. This type of processing of wheel-encoder information is called odometry.

Due to several reasons, the true position and true heading can only be estimated. Some of these reasons are the possible slipping of the wheels, incorrect wheel diameter (depending on weight of the cargo), lag of steering angle etc. A thorough discussion of these errors is beyond the scope of this paper. The main result of these errors is that the estimated position and heading drift away from the true position and heading. Because of this drift, AGV's can never rely on odometry alone and always need additional sensor systems to correct for the drift.

Several types of additional sensor systems exist:

- A system that detects some line or pre-installed path on the floor. This system may be an optical system (for instance a small camera that detects a line on the floor; see example picture in Figure 2), an electromagnetic system (detecting the magnetic field of a current carrying wire), an rfid-detection system, detecting small rfid-tags placed on the floor or similar systems. All these systems can be grouped in the class of line-following systems.

Figure 2: AGV guided by a line on the floor

- A second group of systems measure the movement of the AGV relative to a multiple of pre-installed beacons. Lasers may for instance be used to measure the distance and/or angle of the AGV relative to some reflectors at known locations (see example picture in Figure 3; the laser unit is indicated by the green circle). Likewise, radar type systems can be used to measure the distance to some radar reflectors and radio systems can be used to measure the distance to radio beacons.

Figure 3: AGV guided by a laser

- A less common type of system uses magnetic beacons that are installed in the floor in a grid-wise manner. Whenever the AGV passes and detects such a magnetic beacon it knows it is in the very close vicinity of the magnetic beacon. This information can also be used to correct the errors caused by the odometry system.

Although the combination of an odometry system and an additional sensor system is in general sufficient for the main task, navigating in a confined and well-defined space (so-called zone), there still are situations where the additional sensor systems fail to provide usable data and the combined systems fail to operate.
Some example situations are:

- The AGV needs to travel from one zone to another, and between these zones no laser reflectors, guidance line or grid beacons are present. In such a situation, the AGV simply cannot travel between the two zones. If a package needs to be transported from one zone to another it must be handed over from one AGV, navigating in the first zone, to another AGV, navigating in the second zone. Often this handing over is done manually and it is very time consuming.
- In case of a laser guided AGV, one or more laser reflectors may not be visible. This occurs for instance when a person, another vehicle or some construction is obstructing the laser beam. In such a situation, the AGV must stop and wait for the obstruction to clear, as it cannot rely on odometry alone.
- Likewise, for a grid-guided AGV, a multiple of magnetic floor beacons subsequently may not be detected. Although it will only rarely occur, the AGV must stop permanently for safety reasons.

A general solution, using inertial sensors with AGV's

Using inertial sensors to assist the guidance system is not new. Examples of inertial sensors are accelerometers and gyroscopes. Accelerometers measure the acceleration of the AGV in one or more direction (x,y or z). Gyroscopes measure the angular rate of the AGV around one or more axis (x,y or z). Numerical integration of the measured angular rate yields the attitude (roll, pitch and/or heading) of the AGV. Inertial sensors are typically high bandwidth sensors. The attitude information derived from the gyroscopes is only accurate for a relative short period of time, depending on the quality of the gyro. This is caused by systematic sensor errors that are also numerically integrated resulting in the so-called attitude drift. The gyros can be used to assist the guidance system by providing an accurate heading and allowing a longer travel without reference information.

Often, AGV manufacturers provide an inertial sensor package as an option. Typically, high quality gyros (and/or accelerometers) are offered. These high-quality gyros have very low systematic sensor errors and very low angular drift accordingly. As a down-side, the high-end inertial packages are also of high cost, making this option less affordable to relative low-budget AGV's.

Miniature, low-cost, MEMS gyros are also available. These gyros however, have huge angular drift rates and the heading provided by the gyro may quickly become inaccurate after some time. Initial drift-rate (after power-on) of low-cost MEMS gyros may be in the order of several thousand deg/hr. At best, after some compensations, MEMS gyros have a residual drift of well over 100 deg/hr.

GNC Solutions has developed a novel technology called DriftLess+ that can estimate and compensate the offsets of gyros, accelerometers and other sensors. This technology allows AGV's to autonomously travel a long distance without any other supporting sensor system. This technology is described in more detail in the next section.

Use of the DriftLess+ technology

DriftLess+ is an innovative technology to estimate and compensate the offsets of sensors that can measure a vector quantity. That is, it can improve any sensor of which the output depends on the physical orientation of the sensor. Examples of such sensors are accelerometers and gyroscopes, but also magnetometers, gravimeters etc. can be improved using this technology. Offsets on the outputs of gyroscopes and accelerometers are often the main source of error, causing the so-called drift in attitude, velocity or position estimation. By minimizing the offsets of the sensors this drift is also minimized, hence the name of the technology.

The DriftLess+ technology is a new and improved version compared to the initial technology as published in 2013 by TNO [1]. The basic principle of the technology is given by Figure 4. Two sensors, some rotation mechanism and a signal processing unit are all combined in one unit. One or both sensors are rotated mechanically and the output of the sensors is processed. The signal processing estimates the offsets of both sensors and corrects them.

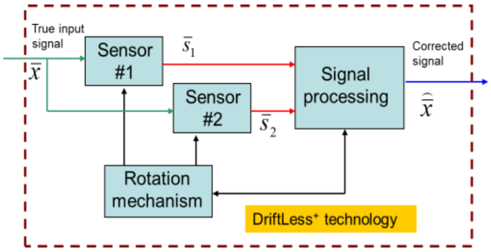

Figure 4: basic principle of the DriftLess+ technology

Each sensor by itself can have a multiple of sensing axis. Sensor 1 can for instance have only one sensing axis, two sensing axes or more. Likewise, sensor 2 can have only one sensing axis, two or more. Of each sensing axis, the offset can be estimated. Depending on the number of sensing axes and the number of output offsets to be estimated, one or more sensors or sensing axis need to be rotated mechanically. As an example, sensor 1 and sensor 2 can each have two sensing axes. In this example, only one sensor need to be rotated and the other sensor can be kept stationary with respect to the unit.

After turning on the unit, the sensors are rotated back and forth in a slow fashion. Typically, the rotation period is in the order of ten seconds but may depend on the type and properties of the sensors used. Immediately after turning on, the sensor output offsets are estimated and compensated for. After a short time, typically one minute, all offsets are fully compensated. The offset estimation continues during operational use of the unit. Therefore, if offsets change, for instance as a result of temperature change, they will automatically be estimated and compensated for. As a result, all offsets and offset changes (i.e. turn-on offsets, DC-offsets, in-run offset variations etc.) are automatically compensated for. The unit acts as a new sensor with virtually no remaining offsets.

A prototype unit DL2D5X5 has been made based on this new technology. This unit is a full 3D-sensing unit, but only two of the three axes are compensated by the DriftLess+ technology. The offsets of the third axis are not compensated for. A functional block diagram of the unit is given in Figure 5. The unit has one fixed low-cost 3D gyroscope/accelerometer chip and one 3D gyroscope/accelerometer chip that is rotated. The unit further has one small motor to mechanically rotate the second chip. A small microprocessor controls the unit and processes the signals. The unit communicates to a host system using a standard serial RS232 communication link. A photo of the prototype unit is shown in Figure 6.

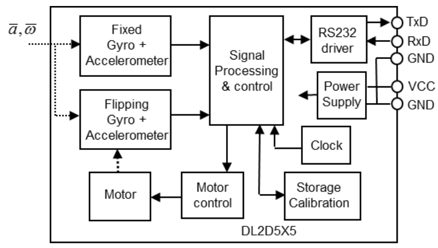

Figure 5: block diagram of DL2D5X5

Figure 6: photo of the DL2D5X5 prototype unit

A series of these prototype units have been thoroughly tested. The offsets of the gyroscopes are compensated to a level of less than 5 deg/hr. That is, all offsets are compensated, but a small residual offset remains. An example of the offset estimation is shown in Figure 7. The noisy lines are the x- and y-gyro outputs under stationary conditions. For clarity, these signals have already been low-pass filtered to remove most of the high frequent noise. The drawn lines are the offsets estimated by the signal processing algorithm.

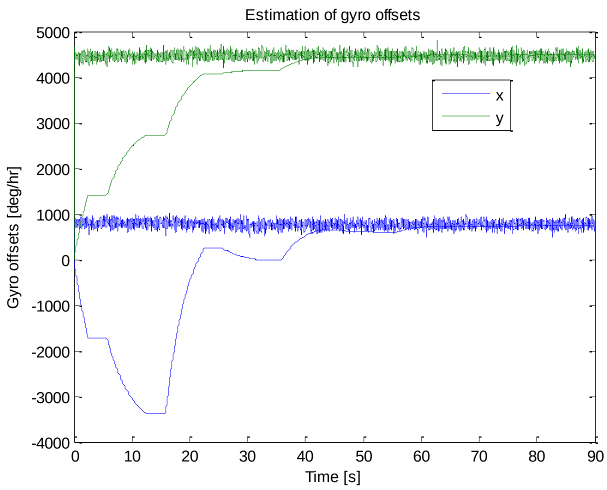

Figure 7:example estimation of gyro offsets

As the gyros are kept stationary, their outputs should be zero, except for known components of the Earth rotation rate. The figure therefore clearly shows the huge turn-on offsets of almost 1000 deg/hr for the x-axis gyro and approx. 4500 deg/hr for the y-axis gyro. After one and a half minute, the offsets are estimated to a 5 deg/hr level.

It is very common to use the Allan Variance (AV) to quantify the noise and offset variations of gyroscopes and accelerometers [2]. A typical AV curve of gyroscopes is given by the red dashed line in Figure 8. In general, for gyroscopes, the graph of the AV tends to go down as averaging time increases. This part of the curve is

mainly dominated by the white noise on the output of the sensor. The AV graph of an ideal sensor, having only white noise on its output is given by the green dashed line in Figure 8. After some averaging time, the graph of the typical sensor (red-line) tends to go up again. This part of the curve is mainly due to the presence of in-run offset changes. As the DriftLess+ technology, ideally, compensates all gyro offsets, the curve of a DriftLess+ compensated gyro should resemble the green dashed line in Figure 8.
The Allan Variance of a number of units have been calculated and fitted in a model. The results are shown in Figure 8. The black solid line is the average of the model and the dashed black lines are 1 sigma standard deviations. Offset variations are kept within a few deg/hr, even at long averaging times. A fixed residual offset remains, which is typically in the order of a few deg/hr.

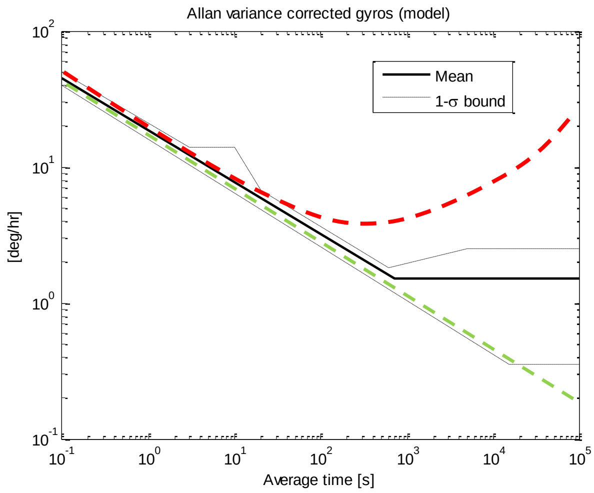

Figure 8: model of Allan Variance of gyros

It should be noted that the AV does not visualise fixed offsets or temperature depending offsets, as the AV measurements are usually done at constant temperature. It is one of the clear advantages of the DriftLess+ technology that any offset change, including offset changes due to temperature, are estimated and compensated for.
Compared with other MEMS sensors these results are excellent. Other MEMS gyroscopes for example have remaining offsets of over 100 deg/hr at best at constant temperature conditions. The accelerometer offsets are estimated by the DriftLess+ technology to a level of 0.5 mg.

Being based on low-cost sensors, the DL2D5X5 sensor is an affordable IMU (Inertial Measurement Unit, a combination of accelerometers and gyroscopes) that outperforms most MEMS-type IMU’s. In terms of residual gyro offsets, this unit approached the quality of some low-end laser and/or fiber-optic gyros, but only at a fraction of the costs.

Application areas are numerous. A few examples are:
Heading measurement and or wheel slip detection of AGV’s

- Attitude/pose tracking in augmented reality systems.
- Attitude tracking or stabilisation of camera’s.
- Roll/pitch measurements of ships, ROV’s etc.
- Attitude/movement compensation of airborne radar systems [3][4].

The current prototype can be further customized for a final application.

Practical tests

Specifically for testing purposes, a small trolley was made. Some practical tests were conducted with this trolley. For these tests, the trolley was controlled manually, not automatically. Therefore, the trolley was strictly speaking not an AGV. The purpose of these tests was to calculate the trajectory based on odometry and IMU information and compare these calculated trajectories with the actual location. This would result in the navigation error.

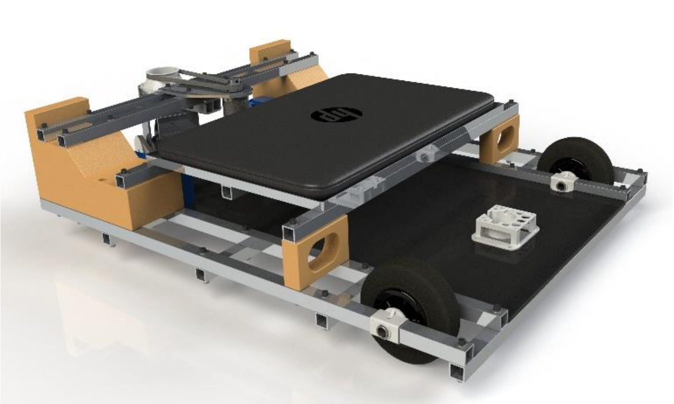

Figure 9: small trolley made for testing purposes

Figure 9 shows the test trolley. Essentially, it is a small platform with two non-steerable wheels at the back and one steerable wheel at the front. The front wheel was driven by two small stepper-motors. One of the motors was used to accelerate the trolley, the other motor was used to steer the front wheel. Functionally, this is fully equivalent to using two normal DC-motors and two wheel-encoders. An interface was made to control the stepper motors by a laptop. The laptop and interface were both placed on the trolley. Also, a DriftLess+ corrected IMU unit was mounted on the back of the trolley, approximately above the rear axis. The IMU was directly connected to the laptop. Further, a wireless joystick was used to command the laptop to start the trolley, accelerate, decelerate or steer it.

With a sampling frequency of approximately 100 Hz, both the steering angle was retrieved and the increment of the front wheel. The DriftLess+ IMU measured the angular rate of the trolley with a sampling frequency of 500 Hz. After numerical integration, the heading of the trolley was derived. The odometry information was fused with this heading information, yielding the position and velocity of the trolley.

Tests were conducted in a test-facility. The map of the facility is shown in Figure 10. At four locations, indicated by the letter “X” the trolley was stopped. At these locations, markers were placed on the floor with exact known positions. Using a digital camera, the position of the trolley relative to these markers was recorded. Analysing the camera pictures afterwards, the actual position of the trolley was found. This was compared to the position output by the navigation system based on odometry and IMU data and resulted in the navigation error.

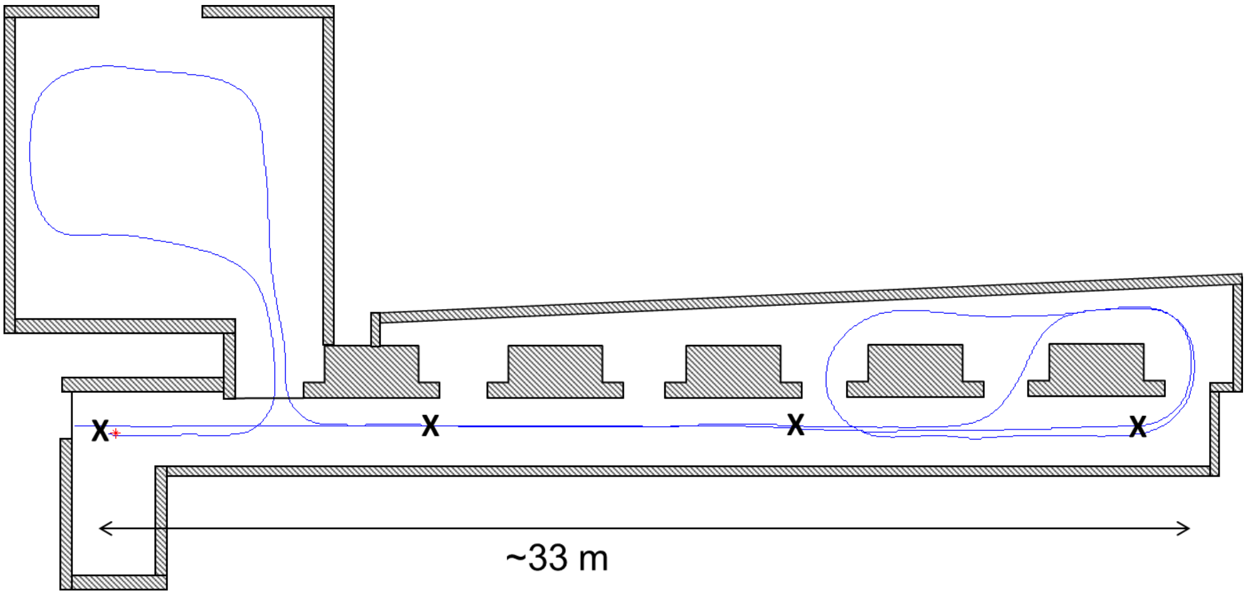

Figure 10: top-view map of the test facility

Each test trajectory started at the left of the corridor, made a 180-degree corner around a concrete column at the end of the corridor and returned to the starting position. Some trajectories included additional loops or included a loop in the room at the left. A typical trajectory with additional loops is shown in Figure 10. The first stop position, at approximately 10 m, was used to calculate the initial heading of the trolley. Total distance travelled (DT) of most trajectories was approximately 75 m. Other trajectories had a DT up to 100 m.

Some results in terms of navigation error are shown in Figure 11. The blue stars correspond to the navigation error in the x-direction (horizontal axis in the above map). This error component is mainly caused by the odometry errors and is therefore a function of distance travelled (and indirectly a function of time) and amounts to approximately 0.2% DT. The green stars correspond to the navigation error in the y-direction (vertical axis in the map). This error component is mainly due to gyro errors, in combination with odometry errors. On the average, the y-error is less than 10 cm.

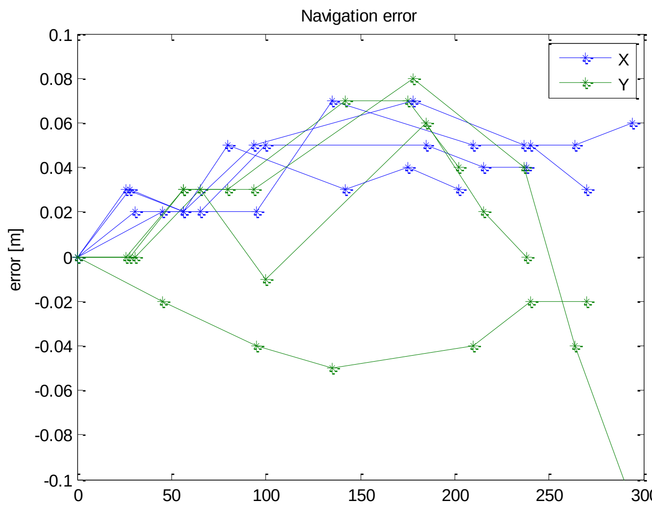

Figure 11: navigation error results of tests done with the trolley

The average velocity of the trolley was very low: less than 0.3 m/s. This was mainly caused by the trolley being stopped eight times at predefined locations (marked by the X in the map above) to take a photo of the actual location of the trolley (as described above). Further, the maximum velocity of the trolley was limited to 0.8 m/s.

Actual AGV's usually have larger velocities and therefore take less time to travel the distance. As gyro drift mainly depends on time, results are therefore more pessimistic then optimistic. Navigation errors may become much lower than 10 cm if the average velocity increases.

Additionally, a large number of tests have been conducted on a rough surface, composed of small pavement stones. This type of pavement can be expected when for instance a trolley travels between two buildings. The results are comparable to the results on the smooth surface.

Conclusions

- Using low-drift gyros the heading of an AGV can be accurately tracked. In combination with odometry, the AGV can navigate without the information of supporting sensors like laser, line detection etc. Low-drift gyros are usually very expensive. The DriftLess+ technology minimizes the drift of low-cost gyros creating an affordable alternative.
- With the DriftLess+ technology, the AGV can continue to navigate and bridge a long distance, even in the absence of usable supporting information. This makes the AGV more versatile and more efficient to use. The AGV does not have to stop if for instance laser beams are blocked.
- As longer distances without usable supporting sensor information can be bridged, the number of beacons that must be installed may even be lowered, resulting in lower installing and maintenance costs.

About us

GNC Solutions is a small company in The Netherlands, devoted to bringing to the market, innovative solutions in the field of Guidance, Navigation & Control (GNC). GNC Solutions is founded by Marcel Ruizenaar, inventor of several smart navigation related technologies.

Author
Marcel Ruizenaar is the founder of GNC Solutions bv. For almost 29 years, he worked for a research institute, mainly in the field of navigation. He invented and patented several innovative navigation concepts.

Glossary

3D	
AGV	Autonomous Guided Vehicle
AV	Allan Variance
DC	Direct Current, also use to indicate static/fixed (non varying) signals
DT	Distance Travelled
GNC	Guidance, Navigation & Control
Hz	Hz, unit of frequency (=cycles per second)
IMU	Inertial Measurement Unit, a combination of accelerometers and gyroscopes
MEMS	Micro Electro Mechanical System, usually chip-sized
mg	Milli-g. 1 g is the unit of gravity. 1 mg= 1/1000 of Earth gravity
RFID	Radio Frequency Identification.

ROV Remotely Operated Vehicle

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[2] Naser El-Sheimy, Haiying Hou, and Xiaoji Niu, "Analysis and Modeling of Inertial Sensors Using Allan Variance", in IEEE Transactions on instrumentation and measurement, Vol. 57, No. 1, January 2008.

[3] Marcel Ruizenaar and Rob Kemp, "DriftLess, an innovative method to estimate and compensate for the biases of inertial sensors" in proceedings of the ENC-GNSS 2014, the European Navigation Conference, Rotterdam, The Netherlands, April 15-17, 2014.

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