Inertial Sensors Facilitate Autonomous Operation in Mobile Robots

By Mark Looney

Introduction

Ground-based robot systems must often handle "the dull, the dirty, and the dangerous" tasks, according to Seth Allen, project manager at Adept MobileRobots.[1] In other words, robot systems are typically used for missions where direct human involvement is too expensive, too dangerous, or just ineffective. In many cases, the ability of robotic platforms to operate autonomously is a valuable feature, using navigation systems to monitor and control their motion when moving from one location to the next. Accuracy in managing position and motion is a key factor in enabling really useful autonomous operation, and MEMS (*microelectromechanical system*) gyroscopes provide a feedback sensing mechanism that can be very useful in optimizing navigation system performance. The Seekur® robot system, shown in Figure 1, is an example of an autonomous system that employs advanced MEMS devices to improve navigation performance.

Figure 1. Adept MobileRobots Seekur system.

Robot Navigation Overview

A robot movement typically starts with a position change request from the central processor that is managing the progress of the robot's overall mission. The *navigation system* begins executing a position change request by developing a trip plan or trajectory. The trip plan considers available paths, known obstacle locations, robot capability, and any relevant mission objectives. (For example, delivery time can be critical for a specimen delivery robot in a hospital.) The trip plan is fed into a controller, which produces drive and direction profiles for navigational control. These profiles result in motion and progress with respect to the plan. The motion is typically monitored by a number of sensing systems, each of which produces feedback signals; the feedback controller combines and translates them into updated trip plans and conditions. Figure 2 is a basic block diagram of a generic navigation system.

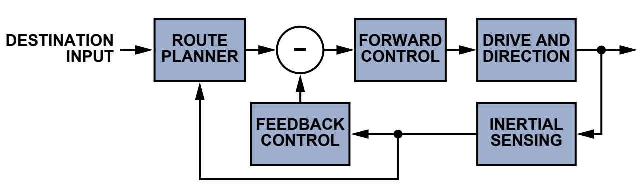

Figure 2. Generic navigation system.

The key steps in developing a navigation system start with a good understanding of each function, with particular emphasis on its operational goals and limitations. Each function typically has some clearly defined and easily executed aspects, but also offers challenging limitations that need to be managed. In some cases, this process can be iterative, where identifying and dealing with limitations enables new opportunities for optimization. The best way to describe this process is through an example.

Adept MobileRobots Seekur

The Adept MobileRobots Seekur[2] is an autonomous robot that uses an *inertial navigation system* (INS) similar to the one shown in Figure 3. This vehicle has a 4-wheel drive system, with independent steering and speed control for each wheel, providing the flexibility to move the platform in any horizontal direction. This ability is valuable for robotic vehicles in such emerging applications as warehouse delivery systems, hospital specimen/supply delivery systems, and military force augmentation systems.

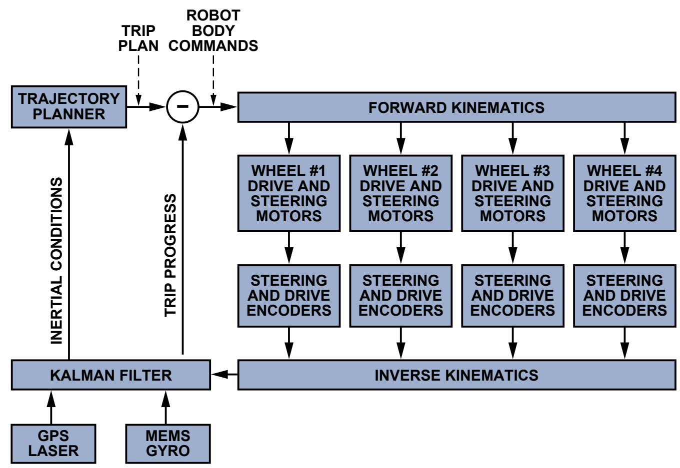

Figure 3. Adept MobileRobots Seekur navigation system.

Forward Control

Robot body commands, the main *error signals*, represent the difference between the trip plan provided by the trajectory planner and *trip progress* updates produced by the feedback sensing system. They are fed into the *inverse kinematics* system, which translates the robot body commands into steering and velocity profiles for each individual wheel. These profiles are calculated using *Ackermann steering relationships*,* which incorporate tire diameter, surface contact area, spacing, and other important geometrical features. Ackermann steering principles and relationships enable these robot platforms to create electronically linked steering angle profiles similar to those of the mechanical rack-and-pinion systems used in many automotive steering systems. Incorporating these relationships remotely, without requiring the axles to be mechanically linked, helps minimize friction and tire slip, provides the benefits of reduced tire wear and energy loss, and allows motion not possible with simple mechanical linkages.

Wheel Drive and Steering System

Each wheel has a *drive shaft* that is mechanically coupled to its drive motor through a gear box and—through another gear box—to an optical encoder, which is an input to the *odometry feedback* system. The *steering shaft* couples the axle to another servo motor, which establishes the wheel's steering angle. The steering shaft also couples to a second optical encoder through a gear box—which provides another input to the odometry feedback system.

*Patented by Rudolph Ackermann in *1817*(!)

Feedback Sensing and Control

The navigation system uses an extended Kalman filter[3] to estimate the pose of the robot on the map by combining data from multiple sensors. The odometry data on the Seekur is derived from the wheel traction and steering encoders—which provide the translation—and a MEMS gyro, which provides the rotation.

Odometry

The odometry feedback system estimates robot position, heading, and speed using optical-encoder measurements of drive- and steering shaft rotation. In optical encoders, a disk blocks an internal light source or allows it to shine on a light sensor via thousands of tiny openings. As the disk rotates, it produces a series of electrical pulses that are typically fed into a counter circuit. The number of counts per rotation is equal to the number of slots in the disc, which allows the number of rotations (including fractional) to be calculated from the encoder circuit's pulse count. Figure 4 provides a graphical reference and relationship for translating the drive shaft's rotation count into linear *displacement* (position) changes.

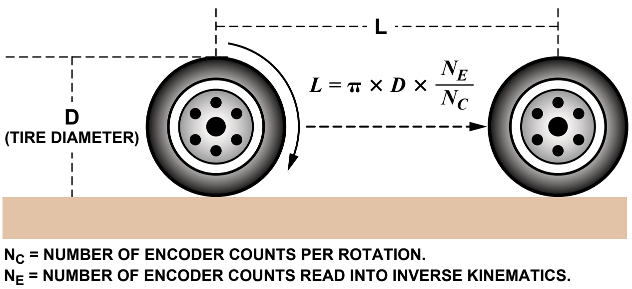

Figure 4. Odometry linear-displacement relationship.

The drive-axle and steering-shaft encoder measurements for each wheel are combined in the *forward-kinematics* processor, using the Ackermann steering formulas, which produce heading, turn rate, position, and linear velocity measurements.

The advantage of this measurement system is that its sensing function is directly coupled to the drive and steering control systems, so their state is accurately known. However, its accuracy in terms of the actual speed and direction of the vehicle is limited unless reference to a set of real-world coordinates is available. The primary limitations, or error sources, are in the tire-geometry consistency (the accuracy and variation of D in Figure 4) and breaks in the contact between the tire and the ground surface. Tire geometry is dependent on tread consistency, air pressure, temperature, and weight—all conditions that can change during normal robot use. Tire slip depends on turn radii, velocity, and surface consistency.

Position Sensing

The Seekur system uses various range sensors. For *indoor* applications, it employs a 270° laser scanner to build a map of its environment. The laser system measures object shapes, sizes, and distance from the laser source using returned-energy patterns and signal-return times. When in its mapping mode, it characterizes its workspace by combining scan results from many different positions in the workspace (Figure 5). This produces a map of object locations, sizes, and shapes, which is used as a reference for run-time scans. When used in conjunction with the mapping information, the laser scanner function provides accurate position information. If used by itself, it would bear limitations that include the stop time for scans and an inability to manage a changing environment. In a warehouse environment, people, lift trucks, pallet jacks, and many other objects change position often, which could potentially impact speed to a destination and, indeed, accuracy of achieving the correct destination.

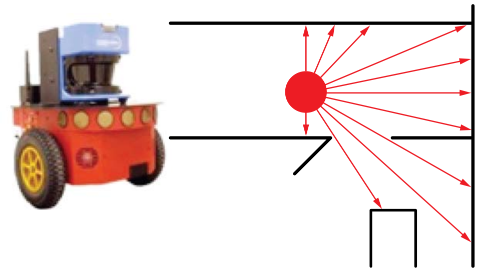

Figure 5. Laser mapping.

For *outdoor* applications, the Seekur uses *global positioning systems* (GPS) for position measurements (Figure 6). These systems use flight times of radio signals from at least four satellites to triangulate a position on the earth's surface. When available, they can provide levels of accuracy to within 1 m. However, these systems are limited by the *line of sight* requirements, which can be impeded by buildings, trees, bridges, tunnels, and many other types of objects. In some cases, where outdoor object locations and features are known (urban canyons), radar and sonar can also be used to supplement the position estimates during GPS outages. Even so, effectiveness is often limited when dynamic conditions exist, such as cars passing by or construction.

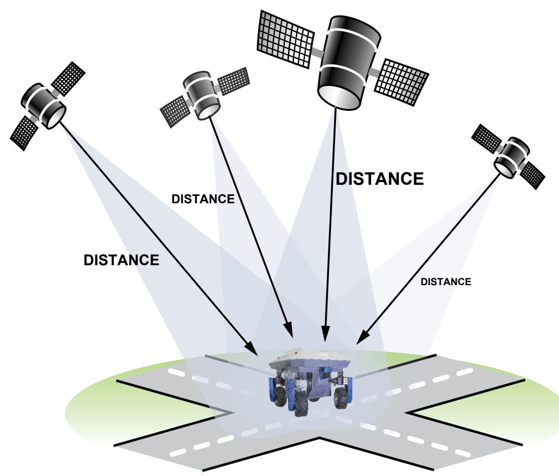

Figure 6. GPS position sensing.

MEMS Angular Rate Sensing

The MEMS gyroscope used in the Seekur system provides a direct measurement of the Seekur's rate of rotation about the yaw (vertical) axis, which is normal to the earth's surface in the Seekur navigational reference frame. The mathematical relationship for calculating a relative heading is a simple integration of the angular rate measurement over a fixed period (t_1 to t_2).

$$\theta_H = \int_{t_1}^{t_2} \omega \cdot dt$$

One of the key advantages of this approach is that the gyroscope, being attached to the robot frame, measures the vehicle's actual motion without relying on gear ratios, backlash, tire geometry, or surface contact integrity. However, the heading estimate does rely on sensor accuracy, which is a function of the following key parameters: bias error, noise, stability, and sensitivity. Fixed bias error translates into a heading drift rate, as shown in the following relationship that includes the bias error, ω_{BE}:

$$\theta_H = \int_{t_1}^{t_2} (\omega + \omega_{BE}) \cdot dt = \int_{t_1}^{t_2} \omega \cdot dt + \underline{\underline{(t_2 - t_1) \cdot \omega_{BE}}}$$

Bias error can be broken down into two categories: *current* and *condition-dependent*. The Seekur system estimates current bias errors when it is not in motion. This requires the navigation computer to recognize when no position change commands are being executed and facilitate data-collection bias estimate and correction-factor updates. The accuracy of this process depends on sensor noise and the amount of time available to collect data and formulate an error estimate. The *Allan variance curve* provides a convenient relationship between bias accuracy and averaging time, as shown in Figure 7, which captures the relationship for the ADIS16265—an *i*Sensor® MEMS device similar to the gyroscope currently used in the Seekur system. In this case, the Seekur can reduce the bias error to less than 0.01°/sec, averaged over 20 seconds, and can optimize the estimate by averaging over about 100 seconds.

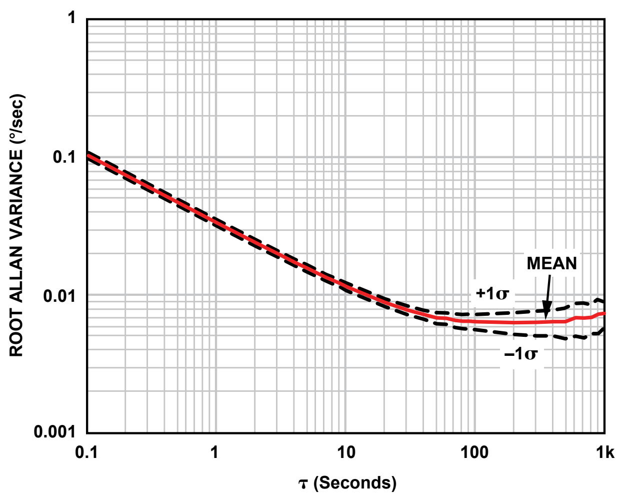

Figure 7. ADIS16265 Allan variance curve.

The Allan variance[4] relationship also offers insights into the optimal integration time ($\tau = t_2 - t_1$). The minimum point on this curve is typically identified as the *in-run bias stability*. The heading estimates are optimized by setting the integration time, τ, equal to the integration time associated with the minimum point on the Allan variance curve for the gyroscope in use.

Because they influence performance, *condition-dependent* errors, such as bias temperature coefficient, can determine how often the robot must stop to update its bias correction. Using precalibrated sensors can help address the most common error sources, such as temperature- and power-supply changes. For example, a change from the ADIS16060 to the precalibrated ADIS16265 may incrementally increase size, price, and power, but offers 18× better stability with respect to temperature. For a 2°C change in temperature, the maximum bias of 0.22°/sec with the ADIS16060 is reduced to 0.012°/sec with the ADIS16265.

The *sensitivity* error source is proportional to the actual change in heading, as shown in the following relationship:

$$\theta_H = \int_{t_1}^{t_2} (1+\varepsilon)\cdot\omega\cdot dt = \int_{t_1}^{t_2} \omega\cdot dt + \underline{\underline{\int_{t_1}^{t_2} \varepsilon\cdot\omega\cdot dt}}$$

Commercial MEMS sensors often provide sensitivity error specifications that range from ±5% to above ±20%, so they will need calibration to minimize these errors. Precalibrated MEMS[5] gyroscopes, such as the ADIS16265 and ADIS16135, provide specifications of less than ±1%—with even better performance in controlled environments.

Application Examples:
Warehouse Inventory Delivery

Warehouse automation currently uses lift trucks and belt systems to move materials for organizing inventory and fulfilling demands. The lift trucks require direct human control, and the belt system requires regular maintenance attention. In order to achieve maximum warehouse value, many warehouses are being reconfigured, a process that opens the door for autonomous robot platforms. Instead of a substantial construction effort to revise lift trucks and belt systems, a fleet of robots requires only software changes and retraining the robot's navigation system for its new mission. The key performance requirement in a warehouse delivery system is the robot's ability to maintain a consistent pattern of travel and maneuver safely in a dynamic environment, where obstacles move and human safety cannot be compromised. In order to demonstrate the value of MEMS gyroscope feedback on the Seekur in this type of application, Adept MobileRobots conducted an experiment to find out how well the Seekur would maintain a repetitive path, without (Figure 8) and with (Figure 9) MEMS gyroscopic feedback. It is important to note that this experiment was run without GPS or laser-scanning correction—for the purpose of studying the impact of MEMS gyroscopic feedback.

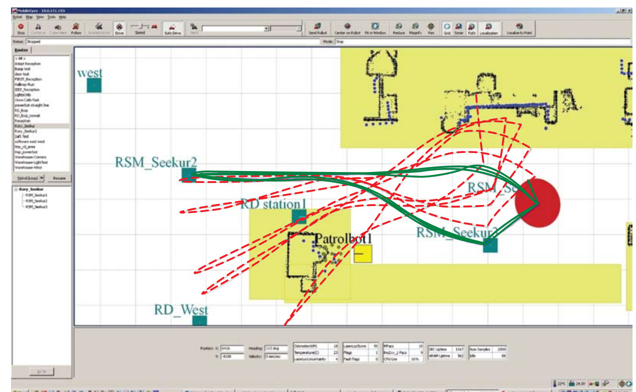

Figure 8. Seekur path accuracy, no MEMS gyroscope feedback.

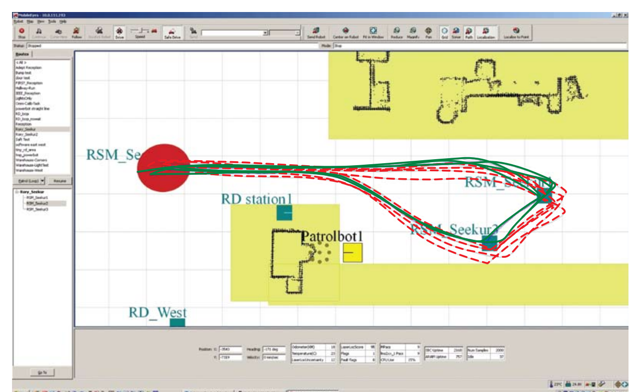

Figure 9. Seekur path accuracy, MEMS gyroscope feedback enabled.

The difference in maintaining the path accuracy is easy to see when comparing the path traces in Figure 8 and Figure 9. It is important to note that these experiments were run on early generation MEMS technology that supported ~0.02°/sec stability. Current gyroscopes enable 2× to 4× performance improvement at the same cost, size, and power levels. As this trend continues, the ability to maintain accurate navigation on repetitive paths will continue to improve—opening up additional markets and applications, such as specimen and supply delivery in hospitals.

Supply Convoys

Current DARPA initiatives continue to call for more robot technology to help in *force multiplication*. Supply convoys are an example of this type of application, where military convoys are exposed to opposing threats while forced to move in slow, predictable patterns. Accurate navigation enables robots, like the Seekur, to take on more responsibility in supply convoys, reducing human exposure to threats along their paths. One key performance metric, where the MEMS gyroscope heading feedback is particularly helpful, is in managing GPS outage conditions. The latest Seekur navigation effort, geared towards this environment, employs MEMS inertial measurement units (IMUs)[6] for better accuracy and their ability to incorporate future integration advances—for terrain management and other functional areas.

In order to test how well this system localizes—with and without the IMU—the error of an outdoor path was recorded and analyzed. Figure 10 shows the comparison of the errors—with respect to the true path (from the GPS)—of the odometry only with the errors when the odometry and the IMU are combined in the Kalman filter. The positional accuracy was nearly 15× better in the latter case.

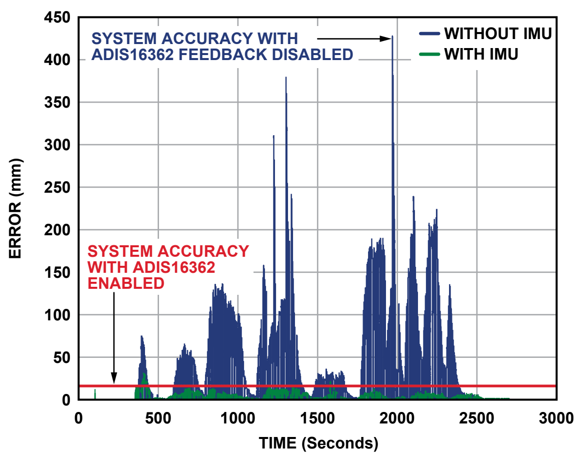

Figure 10. Seekur position error using odometry/IMU (green) vs. odometry only (blue).

Conclusion

Robot platform developers are finding that MEMS gyroscope technology provides cost-effective methods for improving directional estimation and overall accuracy in their navigation systems. The availability of precalibrated, system-ready devices enables simple functional integration, which leads to early success in the development process and allows engineers to concentrate on system optimization. As MEMS technology continues to improve gyroscope noise, stability, and accuracy specifications, it will continue to enable higher levels of accuracy and control, which will likely continue to open new markets for autonomous robot platforms. Next-generation development for systems such as the Seekur could move from gyroscopes to fully integrated MEMS IMU/6-degrees-of-freedom (6DoF) sensors. While the yaw-oriented approach is useful, the world isn't flat; many other applications, existing and future, can incorporate MEMS IMUs for terrain management and for additional accuracy refinement, with three gyroscopes enabling full alignment feedback and correction.

Acknowledgment

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References

(Information on all ADI components can be found at www.analog.com.)

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