Accurate Navigation of Industrial Mobile Robots

Georges Blaha and Stephen R. Gerig

Envirospace Software Research, Inc.
P.O. Box 3723
Indialantic, Florida 32903

ABSTRACT. The present paper treats the topic of accurate navigation of mobile robots in small areas, such as industrial facilities. The navigational system described uses a combination of an INS and state-of-the-art sensors collocated on board the robot. Under certain conditions, this combination enables the robot to determine its position at a millimeter level, and its orientation at an arcsec level.

1. BACKGROUND

Industrial inspection, maintenance, and other tasks require the use of teleoperated or autonomous mobile robots when the environments in which such tasks must be performed are hazardous. The navigation of these robots can be provided by an integrated navigational system, where the on-board "primary navigator" can be an inertial navigation system (INS). The primary navigator needs to be periodically updated and re-initialized by a "secondary navigator".

This paper focuses on the secondary navigator along with its contribution to accurate navigation. The high degree of achievable accuracy is based on a state-of-the-art electronic and optical measuring system, and advanced scientific computer processing. The optical measuring system aids the primary navigator, such as an INS, which must be initialized, updated at some time-intervals, and, due especially to gyro drifts, re-initialized at much longer time-intervals.

The concept and design of updates and (re-)initializations of an INS by the optical measuring system Geodimeter as a secondary navigator have been developed at Envirospace Software Research, Inc. as a follow-on research subsequent to [Blaha and Gerig, 1992]. This research represents an important step toward developing a prototype of a specific integrated navigational system, the INS/Geodimeter system. Such a system is described, from the conceptual point of view, in the balance of the present paper. The same subject has been previously discussed in [Blaha and Gerig, 1993]; the latter contains, for example, an additional topic where the re-initialization model is treated in an alternate approach based on nonlinear least-squares adjustment.

2. COMPONENTS OF THE NAVIGATIONAL SYSTEM

The INS/Geodimeter navigational system is composed of three subsystems, all residing on board the robot, which are listed as follows.

INS. This subsystem is assumed to be the strapdown rather than the gimbaled type of INS. The strapdown system with the ring laser gyro (RLG) uses optical principles as opposed to mechanical ones used by the gimbaled system; many moving parts, as well as lengthy processes (associated especially with the initialization), are eliminated. The three mutually perpendicular INS axes, referred to as the body axes, have a known configuration relative to the robot.

Geodimeter. This subsystem provides the INS with accurate updates and extremely accurate (re-)initializations. The updates can be made while the robot is in motion; the re-initializations can be made only when the robot is stationary. In the present system, the Geodimeter consists of the measuring

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unit (MU) and targets (reflective prisms). The MU is fixed on the robot, while the targets are fixed in the facility, at points whose positions are accurately known. More detail on the Geodimeter is given in the next section.

Computer. This subsystem, assumed to be a single-board computer, runs the program that implements the Kalman filter. The Kalman filter plays a pivotal role in the functioning of the navigational system. It provides, from the present and past observations, realtime optimal estimates of the present position and orientation, as well as the estimates of errors in these quantities, and the associated variance-covariances. It also determines the times when the Geodimeter should be activated for updates or re-initializations.

3. GEODIMETER AS THE SECONDARY NAVIGATOR

The state-of-the-art technology used as the secondary navigator for updating and (re-)initializing the INS on board a mobile robot is the surveying system Geodimeter. It consists of a measuring unit (MU) and a set of reflective prisms as targets. The measurements are performed by means of a beam of infrared light emitted by the MU and reflected back to it by a target. To receive a proper reflection, the MU must aim at the target to within about 10 arcminutes, half the angular diameter of the emitted beam; the target may be aimed at the MU very coarsely. The Geodimeter instruments of the 400-series feature MUs with a servo, which can be commanded through an RS-232 serial port to aim at a target.

These instruments have been successfully tested in the U.S. and abroad. For example, in tests by the U.S. Army at Ft. Belvoir, Virginia, they met military specifications. They can be operated on a moving or unstable platform, and can be operated at any attitude. The model Geodimeter 460, due to its design and to cost-benefit considerations, is currently the best choice as a secondary navigator on board a mobile robot. A successor to the Geodimeter 460, the Geodimeter System 4000, was successfully tested by Envirospace Software Research, Inc.; the MU was stationary at a known ground point, and a prism station was mounted on a moving vehicle (see [Blaha and Gerig, 1992]).

The MU is directed to a given target by means of the INS, which provides sufficiently accurate position and orientation of the MU's optical axis. Thus, the MU is capable of aiming at the target well enough to receive the necessary reflection. The optical center of the target is found by realtime internal analysis of the return beam of infrared light, which makes possible an accurate determination of the total vector from the MU to the target. Additional specifications are listed as follows.

Total vector. The Geodimeter supplies a total vector from the MU to the target, in the sense that all three vector components are determinable in a given frame. This is possible because the MU's measurements to the target comprise the distance as well as two angles in two mutually perpendicular planes. The frame in which the total vector is determined is the INS body frame, since the axes of the MU are aligned with the INS body axes. (Any small deviations in the alignment, as well as the linear offset between the centers of the MU and the INS, are accurately determined beforehand.)

Frequency of measurements. Observations from the MU to a target can be made at a rate up to one observation every 0.4 second.

Accuracy. In the tracking mode, used when the robot is in motion, the ranging accuracy is 10mm+5ppm and the angular accuracy (in both angles) is 2 arcsec. In the standard mode, used when the robot is stationary, the ranging accuracy is 2mm+2ppm and the angular accuracy is 1 arcsec. (The improvement stems from the fact that at a stationary position, the measurements are automatically repeated several times.)

4. (RE-)INITIALIZATIONS OF THE INS

Before a mobile robot begins to operate, the on-board INS must be accurately initialized. The INS should be re-initialized when the INS errors have increased to the point that they render the need for updates intolerably frequent. This is especially true of the gyro drift errors, described in Honeywell's technical manual for Modular Azimuth Position System (MAPS). The standard error in azimuth is 2.4 arcmin (the probable error is 1.6 arcmin), but only within 2 hours of an azimuth alignment or realignment.

An important feature of the presented (re-)initialization concept is that the on-board MU is capable of updating extremely accurately both position and orientation of the INS in one procedure. The robot must be stationary for a few seconds, allowing the MU to measure to three or more targets. If *only* three targets are utilized (as a minimum), they must not be collinear, but should preferably be close to the vertices of a right triangle.

The adjustment model with three targets known in the $\{X,Y,Z\}$ navigation frame (fixed in the facility) gives rise to three vectors expressed in the $\{x,y,z\}$ body frame (fixed with respect to the robot). These vectors are to be observed by the MU as total vectors from the MU to the targets. The orientation of the body frame with respect to the navigation frame is defined by three orientation angles estimated by the INS, denoted α, β, and γ, which, in the re-initialization model, are considered as unknown parameters.

The re-initialization model contains nonlinear relationships among the observables and the parameters. The present setup features 6 model equations containing 9 observables (3 observables for each of the 3 vectors) and 3 parameters (angles α, β, and γ). If the model is augmented by other known targets, the number of equations and observables will each increase by 3 per target, but the number of parameters will be unchanged.

The actual observations (realizations of the model observables) are adjusted according to the method of least-squares. The most common application of the least-squares adjustment is to the parametric model, in [James, 1992] referred to as the "explicit-in-l" model. The least-squares adjustment can also be applied to a more general model, in [James, 1992] referred to as the "implicit model", which includes the re-initialization model.

The implicit model is symbolized by

$$F(L,X) = 0,$$

where L represents the observables and X represents the parameters. The model is customarily linearized. The least-squares resolution, including the variance-covariance matrices of adjusted observations and adjusted parameters, can be found in standard adjustment literature, e.g., in Chapter 12 of [Vanicek and Krakiwsky, 1986].

The above description is supplemented by a simple example with three targets. The simplicity stems from features such as the zero values of α, β, and γ, which, however, do not detract from the re-initialization concept. The three targets are located at the vertices of a right triangle, whose one side is parallel to the X-axis and another to the Y-axis, and the MU is coplanar with the three targets. The length of the sides adjacent to the right angle is 20m; the distances from the vertices of the triangle to the MU are 25.5m, 29.2m, and 15.8m. All measurements are considered to be error-free in this example, where only the variance-covariance propagation is of interest.

According to the accuracy specifications in Section 3, the standard error (σ) for the measured distances is adopted as 2mm, and the σ for the measured angles is adopted as 1 arcsec (1"). Slight simplifications, making the weight matrix of observations to be block-diagonal, allow for a purely analytical resolution of the re-initialization adjustment. In particular, the model is linearized at the known error-free values, and then resolved by standard formulas as indicated above. After adjustment, the σ's in the INS orientation and position, respectively, are:

$$\sigma_\alpha = 1.4'', \quad \sigma_\beta = 1.4'', \quad \sigma_\gamma = 14'';$$
$$\sigma_X = 1.1\text{mm}, \quad \sigma_Y = 1.8\text{mm}, \quad \sigma_Z = 0.2\text{mm}.$$

The quality of the adjusted γ, X, and Y worsens only slightly upon a 20-fold increase in the angular σ's. This lack of response, indicating that the high quality of angular measurements is of little benefit, is imputable to the coplanarity of all four points (the MU and the three targets). If one of the targets is placed several meters above the plane of the other points, the σ's of γ, X, and Y will substantially improve. If a fourth target is added to the configuration, the increased redundancy will necessarily improve all of the σ's.

5. IN-MOTION UPDATES OF THE INS

The in-motion updates, like the stationary (re-)initializations, take advantage of the MU's capability to measure total vectors. A total vector measured from the MU to a target, along with the estimated orientation of the body axes and the known position of the target, constitutes an update. Since the MU is required to measure only to one target at a time, updates can be made in motion. However, they provide useful estimates in position but not in orientation; the latter is adopted as estimated by the INS.

The errors due to the INS and to the Geodimeter are statistically independent. The error in the robot's position due to the INS errors in orientation increases linearly with distance from the MU to the target. Such error further increases with time, due to the growth of the INS orientation errors. An optimal estimate of position is obtained, for each update, upon adjusting the observations (past and present MU and INS measurements) with the aid of the Kalman filter. Related applications, where the common link is the use of an RLG INS, were treated by [Blaha and Gerig, 1992] and [Eissfeller and Spietz, 1989].

The Kalman filter calculates the realtime values for the errors of position (from the error state-vector), as well as the associated variance-covariances. The calculated error values and the calculated variance-covariances are used to determine whether or not an update is needed. This determination is guided by the threshold accuracy to be maintained at all times. When the frequency for updating surpasses a stipulated tolerance (e.g., once every few seconds), the need for a re-initialization is indicated.

6. CONCLUDING REMARKS

This paper presents a concept for accurate navigation, by an integrated navigational system, of mobile robots performing inspection, maintenance, and other tasks in industrial facilities. A robot is navigated by a primary navigator, here an INS, which requires relatively frequent updates and infrequent re-initializations by a secondary navigator. The updates and the re-initializations make use of the Geodimeter as the secondary navigator, and advanced scientific computer processing. In industrial facilities measuring 20-50m across, a re-initialization has an accuracy on the order of 1mm in position and 1 arcsec in orientation.

The re-initialization model is "implicit", where the observables and the parameters are combined in nonlinear relationships. The model is customarily linearized, and the optimal values for the (corrected) observations and the parameters are obtained by the least-squares adjustment, which also furnishes the variance-covariances associated with these values. Due to the model's nonlinearity, the least-squares process is iterative in nature.

The updates can be performed while the robot is in motion. The output from the primary and the secondary navigators is optimally combined by means of the Kalman filter. In addition, the Kalman filter serves in determining when the secondary navigator is to be activated, and whether an in-motion update or a stationary re-initialization is to take place.

The presented concept enables the robot to be autonomous, where no data transfer from, or communication with, an outside source is needed. The capability of accurately positioning and orienting an autonomous mobile robot is important especially in hazardous environments. By virtue of the high-accuracy measurements provided by the secondary navigator, and advanced scientific computer processing, the primary navigator is not required to produce accurate data for extended periods of time, yet the navigational system can maintain the required accuracy in position and orientation at all times.

REFERENCES

Blaha, G. and Gerig, S.R., 1992. *A System for Updating an INS.* Final Report, F08635-91-C-0196, Envirospace Software Research, Inc., Melbourne Beach, FL. (Contract Monitor: H. Edward Brown, Robotics Lab., Tyndall AFB, FL.)

Blaha, G. and Gerig, S.R., 1993. "Navigation of Autonomous Mobile Robots." Paper prepared for the 4th International Conference and Exposition SPACE 94, ASCE, February 26 - March 3, 1994, Albuquerque, NM; to be published in the *Proceedings of SPACE 94: Robotics for Challenging Environments*.

Eissfeller, B. and Spietz, P., 1989. "Basic Filter Concepts for the Integration of GPS and an Inertial Ring Laser Gyro Strapdown System." *Manuscripta Geodaetica*, v. 14, pp. 166-182.

Geotronics, 1989. *Geodimeter System 400.* Combined Technical and Operating Manual. Geotronics of North America, Itasca, IL.

Geotronics, 1990. *Geodimeter 460: The Servo-Controlled Surveying Computer.* Technical Description. Geotronics of North America, Itasca, IL.

Geotronics, 1991. *Geodimeter System 4000: One-Man System.* Technical Description. Geotronics of North America, Itasca, IL.

Honeywell, 1989. *Modular Azimuth Position System.* Technical Manual. Honeywell Inc., St. Petersburg, FL.

James, D.E. (ed.), 1992. *The Encyclopedia of Solid Earth Geophysics;* "Adjustment Methods," pp. 21-26. Van Nostrand Reinhold Co., New York.

Vanicek, P. and Krakiwsky, E.J., 1986. *Geodesy: The Concepts.* 2nd ed., North-Holland, New York.