The Development of a Geo-Referenced System for Machine Controlled Construction Equipment

Nicholas Muth
Department of Civil Engineering
Ryerson University
Toronto, Canada
nmuth@ryerson.ca

Mike Chapman
Department of Civil Engineering
Ryerson University
Toronto, Canada
mchapman@ryerson.ca

***Abstract*—This article outlines the motivation and methodology for a reliable, stand-alone, real-time, geo-referencing system for construction equipment. The system consists of a fully integrated Differential Global Positioning System (DGPS)/Inertial Navigation System (INS) Kalman Filter to geo-reference the main body of the construction equipment. Inertial Measurement Units (IMU) attached to each operational joint will provide joint angle information between each link. The IMU information is used in the Denavit-Hartenberg Convention (DH), describing the position of the end-effector in 3D space with respect to the geo-referenced main body of the equipment. There are distinct advantages to this type of approach. It is a more complicated, yet cost-effective, system because lower grade IMUs can be made to perform as more stable IMUs by constant re-calibration using DGPS measurements in a tightly coupled Kalman Filter. It is an autonomous system, unaided by line-of-sight survey based equipment. Finally, it creates a unified model approach for geo-referencing multi-sensor systems that can be applied without accounting for a different set of parameters for each sensor. Preliminary results of a decomposed Kalman Filter to estimate DGPS baselines show a Root Mean Square Error (RMSE) of ±0.003m for variation in successive baseline estimations of stationary receivers.**

Keywords-Geosensor networks; Tracking moving objects; Application of geosensor networks; Localization and tracking using satellites; Movement sensors; Position sensors

I. Introduction

Construction is an integral part of our overall economy and is of economic significance to many industry sectors and stakeholders. Intense competition, shortages of skilled labor and constant technological advances continue to force rapid change in the construction industry and in support of machine control and Construction Automation (CA) [1].

In order to achieve machine control, considerations must be made regarding equipment operating procedures, construction safety, efficiency, position and navigation. Therefore, machine controlled construction equipment must have the ability to:

- Reference itself in the same coordinate system as the design of the project.
- Navigate in real-time.
- Operate with precision and reliability.
- Position the end-effector accurately.

The research proposed here aims to advance the use of machine control by developing a robust and reliable real-time geo-referencing system for construction equipment focused on the study of an excavator. The geo-referencing system will be a stand-alone system based on the integration of DGPS [2] and INS [3]. The goal of the research is to create a system with centimeter level accuracy in order to achieve Quality Level A standards for precise horizontal and vertical control of utilities, set by the American Society for Civil Engineers *Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data* [4].

The motivation for research is the potential benefits of a high precision geo-referencing system, including:

- *Safety on the construction site*
- *Optimization of construction tasks*
- *Precision construction/limited accuracy checks*
- *Real-time updating of preliminary survey, design drawings and as-built surveys*

In order to complete the research, the project will be separated into four components. The ***first*** and ***second component***-developing a GPS/INS integrated positioning system to geo-reference the construction equipment body center and relative location of the end-effector with respect to the body center-will be combined in the ***third component*** to create a unified model approach for geo-referencing a multi-sensor system. The ***fourth component*** will be testing system accuracy using one of two approaches: point-to-point comparison of the end-effector position with known locations and comparison of the Digital Elevation Model (DEM) [5] of the construction task with the design of the construction task.

The article has five sections. Section II outlines the current research in real-time geo-referencing systems in the construction environment and the available commercial systems. Section III outlines the methodology of the system including system components (instrumentation, sensors and hardware) and the integration algorithm and architecture for geo-referencing. Section IV outlines work to date, preliminary results of the tightly coupled Kalman Filter decomposed to estimate DGPS baselines and affects this has on the DGPS/INS system. The article concludes with Section

V, by outlining the need for this type of system and stating the overall accuracy goals for geo-referencing.

II. BACKGROUND – GEO-REFERENCING SYSTEMS

The majority of research into absolute, real-time positioning systems has been in Aerial Mapping and Terrestrial Mobile Mapping. The focus of the research is on GPS/INS integration and the argument of centralized versus decentralized integration architecture, which is very well balanced and considered application specific [6].

Aerial navigation is concerned with six degrees of freedom, three position (X, Y and Z) and three orientation (Pitch, Roll and Yaw) components; the same six components needed to geo-reference construction equipment. However, the accuracy of aerial navigation research, in many cases, relies on post-processing even though it is implemented in real-time. One would assume that vehicle navigation is applicable, however, in vehicle navigation it is common to find research on low-order vehicle positioning; navigation that deals with the location of the vehicle, but limits the orientation to two position components (X and Y) and one orientation component (Yaw/Heading) .

A terrestrial multi-sensor GPS/INS system for vehicular mobile mapping conducted by El-Sheimy [7] is worth mentioning due to promising results. The GPS/INS centralized system produced centimeter level accuracy in height.

The majority of studies dealing with positioning construction equipment is in the field of machine control and is based on relative, not geo-referenced, systems. However, large survey companies such as Leica and Trimble, are leading the way in production of off-the-shelf positioning systems for construction equipment. The latest developments include the Leica Powerdigger 3D™ and the Trimble GCS900™.

Powerdigger 3D™ uses a combination of GPS with a pitch, roll and direction sensor to geo-reference the excavator main-body, while the GCS900 ™ system uses a combination of two GPS receivers, a pitch and a roll sensor. Both systems are considered 'black box' integrated, meaning there is no information on the integration algorithm or architecture. There is also no information on the system link between GPS/INS on the excavator body and the end-effector, including the precision of the sensors, the expected accuracy of the ***stand-alone*** system, system testing or field tests.

III. METHODOLOGY

The intent of the research is to design a geo-referencing system based on GPS/INS integration and multiple sensors applicable to several earth-moving machines. However, the focus will be on excavators as they have the most complex range of motion (as many as six degrees of freedom).

The research will be separated into four components:

A. Geo-Referencing the excavator body center.
B. Relative positioning of the Excavator end-effector with respect to the center of the Excavator.
C. Geo-Referencing of the Excavator end-effector.
D. Testing system accuracy.

A. Geo-Referencing of the Excavator Body Center

This section deals with the selection of the instruments, integration algorithm and integration architecture for geo-referencing.

1) Instruments

GPS and INS are the main technologies chosen because of their opposing characteristics. For example, the GPS data latency and signal loss can be accounted for by the high sample rate and high short term stability of INS. Consequently, the INS accumulation of error over time can be accounted for by the high long term stability of GPS. It is this relationship that is the motivation for these sensors to be combined in a geo-referencing system.

Differential GPS (DGPS) using dual frequency receivers will be the specific GPS technique because it can provide many advantages (correcting for several common errors and resolving carrier phase ambiguity) and the centimeter level accuracy desired for this type of positioning.

2) Hardware

Two GPS receivers (base and rover) will be employed; the rover will be fixed to the excavator and the base station set over a known point near the rover. The INS must orient the equipment in three dimensions. This requires three accelerometers and three gyroscopes. The DGPS and INS can be combined in a 'black box' or the hardware of each system run independently and combined on the software level. The research will employ the latter technique because the former makes it difficult to modify the system.

3) Integration Algorithm and Architecture

The integration algorithm will be the Kalman Filter (KF) [8]. It is chosen for its optimum performance, versatility, and ease of implementation obtaining state estimates of a dynamical system in the presence of noisy input sensors. Thus it is the integration algorithm of choice for navigation sensor data.

There are two basic implementation architectures for the KF based on the extent that GPS and INS data aid the others function-tightly coupled and loosely coupled; with no coupling understood as no data feedback from either system.

Tightly coupled, also known as fully integrated or centralized systems, is the chosen architecture because these systems have the best potential accuracy. It requires raw/uncorrelated sensor data. The DGPS will be the main source of navigation because it provides geo-referenced coordinates and will provide constant recalibration of the INS sensors to combat the drifting or unbounded errors of INS over time. The INS, operating at a much higher frequency output, will provide the orientation of the system, as well as, supplement DGPS latency, DGPS outages and smooth transitions between less frequent DGPS measurements.

 ISBN: 978-1-61208-297-4

The result is a non-linear implementation, since both DGPS and INS are non-linear systems. One of the limiting conditions of the KF is the assumption that the system model is linear. Therefore, a method of linearizing the process about some known reference is needed. This is accomplished by implementing an Extended KF (EKF) [9]. The approach has very complex measurement equations, but requires only *one* KF, and thus, is straightforward from the processing point of view.

B. Relative Positioning of Excavator End-Effector

This section deals with the positioning of the excavator end-effector with respect to the excavator body. This includes the types of sensors that will be used to accomplish this, the errors associated with the sensors and a method to propagate the errors to analyze the effect on positioning.

The problem of positioning the end-effector with respect to the equipment main body can be thought of as the positioning a rigid body so it is considered a forward kinematics problem between the relationship of the individual joints of the construction equipment and the position and orientation of the end-effector.

The forward problem is to determine the position and orientation of the end-effector, given the cumulative affect of the joint variables-in an excavator they are simple revolute joints, or the angles between the links (boom, stick and bucket of excavator). The advantage is a single degree-of-freedom of motion for each joint.

Kinematic analysis rigidly attaches a coordinate frame to each link; each coordinate frame must then be related and/or *transformed* in a sequential manner to the inertial frame of reference (excavator center/coordinate frame O_0) as seen in Figure 1. Homogeneous Transformation Matrices (HT) [10] offer the ability to locate any point on construction equipment with respect to the inertial frame and therefore will be used to transform each coordinate frame.

1) The Denavit-Hartenberg Convention

The Denavit-Hartenberg Convention (DH) [10] will be implemented to reduce the number of parameters in the HT from the original six (3 rotations and 3 translations) to four (link length, link twist, link offset and joint angle) by systematically choosing the coordinate frames.

2) Sensors

In order to be a viable option for the private sector, the geo-referencing system must be cost effective and accurate to 1-2cm. For a large excavator (10m boom length) this would require stable sensor accuracy ≤ 0.1° arc seconds. This would require high accuracy/stability, high cost IMUs. However, by implementing a centralized KF with constant re-calibration of IMUs, low-grade, high drift rate IMUs can mimic high-grade, low drift rate IMUs. Micro Electronic Mechanical Systems or MEMS sensors built to measure angle/tilt/rotation will be used due to their size (40 to 100mm) and shock limits up to 1000*g*, which is adequate for construction environments.

3) Propagation of IMU Errors

One of the innovations of the relative positioning of the end-effector is the propagation of errors of measurement devices. IMU sensors will be used at each joint with each containing errors. These can be propagated through the network of the excavator to see the effect on geo-referencing, as well as testing the significance of using more/less precise measuring devices.

C. Geo-Referencing the Excavator End-Effector

This is accomplished by developing a unified approach for geo-referencing a multi-sensor system, in this case, composed of DGPS/INS and IMU sensors. The unified approach provides a very important model for sensor fusion in that the model can be applied to sensor data without the need to account for a different set of parameters for each sensor.

The model will be derived for an excavator, but with slight modifications to the transformation matrices, $T_{ee}^{eqp}(t)$ in equation (1), the model be can be used for any type of construction equipment. When the navigation component is supplied by an integrated DGPS/INS system, the equation for the model is of the form (the major steps of equation are shown in Figure 1):

$$r_{ee}^{m} = r_{GPS/INS}^{m}(t) + R_{eqp}^{m}(t)[T_{ee}^{eqp}(t) + a^{eqp}] \qquad (1)$$

where m is the mapping/absolute reference frame; eqp is the INS equipment body reference frame; ee is the excavator end-effector reference frame; r_{ee}^{m} is a vector of target point coordinates to be positioned in the absolute reference frame; $r_{GPS/INS}^{m}(t)$ is a vector of the coordinates of the INS center in the absolute reference frame, (estimated by the DGPS/INS integration); $R_{eqp}^{m}(t)$ is the rotation matrix from the INS body frame to the absolute reference frame (estimated by the DGPS/INS integration); $T_{ee}^{eqp}(t)$ are the transformation matrices between the INS body frame and the excavator end-effector (there is a transformation matrix for each joint); a^{eqp} is the translation vector between the INS center and excavator center (constant).

D. Testing System Accuracy

Testing of the system is set to begin in early summer 2013 and will be completed using two methods: point-by-point comparison and Digital Elevation Model (DEM) comparison.

Point-by-point testing will be a comparison of the coordinates of known control points (surveyed by a total station) with those geo-referenced by the excavator.

DEM testing will provide a more dynamic test of the system, closer to the accuracy one would expect from actual operation. It is intended that a human operator will complete

 ISBN: 978-1-61208-297-4

a simple excavation task using a Graphical User Interface (GUI) showing the position of the end-effector as compared to the construction design. After the excavation is complete, a topographic survey will be completed creating a DEM. The DEM, construction design and the actual trajectory measured by the excavator will be compared to quantify human error and assess the accuracy of the system.

In all cases, the excavator will be under human operation.

The success of the accuracy test will be based on the highest accuracy standards. In this case, the American Society of Civil Engineers (ASCE) *Standard Guidelines for the Collection and Depiction of Existing Subsurface Utility Data* [4]-one of the major benefits of this research is construction safety (geo-referencing with respect to safety hazards, i.e., existing underground utilities) and real-time updating of construction records-therefore, the accuracy of the system should strive for the highest quality, or Quality level A, that calls for a vertical accuracy of 15mm [4].

IV. RESULTS

To date, a tightly coupled Kalman Filter (KF) has been developed to integrate the DGPS/INS for geo-referencing the excavator body center. Although a complete DGPS/INS data set, to test the KF, has not been attained, a DGPS data set has been attained. To gain preliminary results, the KF was decomposed to test the DGPS baseline estimation accuracy only.

The DGPS KF utilizes an Extended KF (EKF) design to deal with the non-linearity of calculating the DGPS baseline estimation. The baseline components are estimated using both Course Acquisition (C/A) and Precision (P) code pseudorange and carrier phase observations. Preliminary results show a Root Mean Square Error (RMSE), for variation in successive baseline estimations of stationary DGPS receivers, of ±0.003m with maximum variations of ±0.008m, ±0.005m and ±0.010m in the North, East and Down directions, respectively.

Although the DGPS data is fundamental in the determination of the velocity and position of the excavator center, in order to position the end-effector, orientation of the excavator center, using INS data, must also be solved. Nevertheless, the preliminary results are promising given that in a tightly coupled KF DGPS data is used in comparison with INS to solve the errors of the INS orientation, velocity and position, and consequently, constantly calibrate the INS sensor data.

V. CONCLUSION

The article outlined an ongoing research study in the field of geo-referencing machine controlled construction equipment, the role of geo-referencing in machine control and the benefits it can provide to the overall construction environment.

Geo-referencing using GPS/INS integration has been left to the fields of aerial mapping and terrestrial mobile mapping. Although there has been much research on the integration of GPS/INS using KF, optimal integration architecture is mainly application specific based on motion of the object, processing complexity, flexibility, desired accuracy, integration level, etc. Not only is there a need for the development of a geo-referencing system based on GPS/INS integration, but there is a need to develop optimal integration architecture for construction equipment.

The goal of the research is to develop a stand-alone, robust, reliable, real-time geo-referencing system with centimeter level accuracy, specifically designed for a construction environment. Promising preliminary results for the decomposed Kalman Filter, estimating DGPS baseline components, suggest accuracy goals, on par with ASCE *Standard Guidelines for the Collection and Depiction of Existing Subsurface Utility Data* Quality level A-calling for 15mm vertical accuracy, are achievable.

REFERENCES

[1] Q. Ha, M. Santos, Q. Nguyen, D. Rye, and H. Durrant-Whyte, “Robotic excavation in construction automation,” IEEE [Robotics & Automation Magazine]. 2002, vol. 9, is. 1, pp. 20-28.

[2] B.W. Parkinson and P.K. Enge, “Differential GPS,” in Global positioning system:theory and applications, vol. II, B.W. Parkinson, and J.J. Spilker Jr., Eds. Washington, D.C.: AIAA, 1996, pp. 3-50.

[3] K.R. Britting, “Inertial navigation systems analysis,” New York: Wiley, 1971.

[4] American Society for Civil Engineers(ASCE) Code and Standards Activity Committee, “Standard guideline for the collection and depiction of existing subsurface utility data,” ASCE Standard, 2003, ASCE/CI 38-02 [Library of Congress Catalog Card No: 2002034155].

[5] D.F. Maune, “Digital elevation model technologies and applications: the DEM users manual,” Bethesda, Maryland: American Society for Photogrammetry and Remote Sensing, 2001.

[6] J. Skaloud, “Problems in direct-georeferencing by INS/DGPS in the airborne environment,” In an invited paper to an ISPRS Workshop [Workshop-direct versus indirect methods of orientation, WG III/1, Barcelona], November, 1999.

[7] El-Sheimy, “The development of VISAT - a mobile survey system for GIS applications,” PhD Thesis, Department of Geomatics Engineering, University of Calgary, 1996.

[8] R.E. Kalman, “A new approach to linear filtering and prediction problems,” Transaction of the ASME—Journal of Basic Engineering. March. 1960, pp. 35-45.

[9] H. W. Sorenson, “ Kalman filtering: theory and application,” H.W. Sorenson, Eds. IEEE Press, 1985.

[10] R.S. Hartenberg and J. Denavit, “Kinematic synthesis of linkages,” New York : McGraw-Hill, 1964.

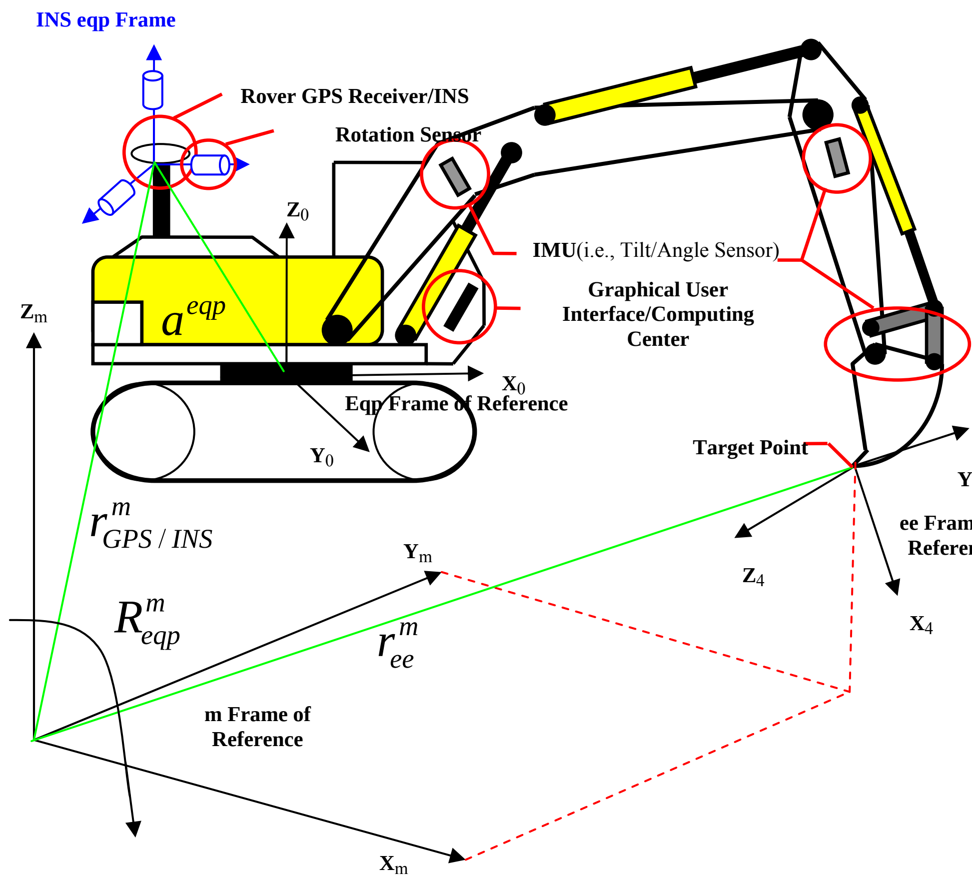

Figure 1. Elements of Geo-Referencing System