High-Precision Crane Guidance

Shipyard Giants

Giant cranes moving in busy container yards require precise positioning to operate efficiently and safely. To accomplish this, the University of New Brunswick has developed ultra high-precision GPS RTK software that works in conjunction with dual-frequency GPS receivers and wireless data modems installed on the cranes. The software monitors a crane's deviations from its tracks and feeds the data to the crane's auto-steering system.

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Photographs taken by Dongcheol Jeong,
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Metal banging, engines roaring, machines whizzing, and sirens wailing — these are the sounds that fill the air at Korea International Terminals' Kwangyang Port, a busy container terminal. Constantly moving above this hubbub are gigantic cranes — rail-mounted quayside cranes for loading/unloading containers from ships and rubber-tired gantry cranes (RTGCs) for stacking/unstacking containers in the container yard.

The movement of these cranes is carefully choreographed by the crane control system — a key component of the port's management system. The control system was developed to improve container-handling productivity and operational safety. It comprises the anti-sway system, which helps operators accurately position a crane's "spreader" to grab containers; the position detection system, used to identify and cross-check the positions of stacked/ unstacked containers; and the auto-steering system, which keeps the wheels of an RTGC moving along a track — either a painted line or an electrical guide wire — and prevents it from hitting containers or other cranes in the tightly packed yard.

For that purpose the auto-steering system must consistently identify the line mark and calculate the corresponding deviations of the RTGC's front and rear wheels. The most efficient and reliable way to accomplish this is by using real-time kinematic (RTK) GPS technology.

RTGC Auto-steering Technologies

In an automated system, a programmable logic controller (PLC) is usually the central part of a process control system which comprises a group of electronic devices and equipment. With execution of a program stored in program memory, the PLC continuously monitors the status of the system through signals from input devices. Based on the logic implemented in the program, the PLC determines which actions the output devices need to execute.

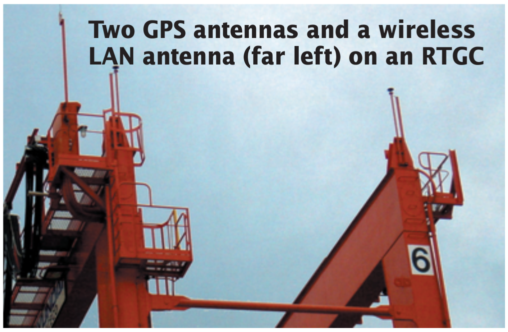
In an RTGC auto-steering system, the calculated deviations of the front and rear wheels are fed into the PLC so that it can adjust the speed of the left and right wheels to keep the crane on track. (Operators turn the crane's wheels only to make ninety degree changes to its direction of movement and only when the crane is stationary at special low-friction turning pads.)

Conventional Approaches. Several technologies for identifying the line mark — such as the induction-loop, transponders, and charge-coupled device (CCD) cameras — have been adopted for RTGC auto-steering systems. Although these technologies have been employed successfully, there is a growing concern that they may not provide the greatest possible system reliability and economic efficiency. Induction-loop and transponder systems have a limited effective range of about 10 centimeters. If a crane exceeds this range for some reason, there is no way to get it back on track easily. Furthermore, these systems require

A rubber-tired gantry crane (RTGC) moving along its track.

An RTGC unloading a truck at Korea International Terminals' Kwangyang Port

frequent maintenance. CCD systems are highly dependent on environmental factors (such as surface reflection and line mark condition) which cannot be overcome completely by the system's hardware and software. Also, CCD systems suffer the same limited range problem as the induction-loop and transponder systems and both the CCD hardware subsystem and the line marks require continuous maintenance to guarantee the performance of the auto-steering system.



Two GPS antennas and a wireless LAN antenna (far left) on an RTGC

GPS-Based Approach. An auto-steering control system which is independent of environmental factors requires a technology not based on physical line marks in the container yard. This can be accomplished by an electronic map with virtual lines and a GPS receiver to precisely locate an RTGC on the map. The control system can then compare the crane's position as reported by the GPS receiver with the virtual lines and steer the crane accordingly.

GPS Auto-steering

The GPS-based auto-steering system recently installed at Kwangyang Port consists of three major components: GPS hardware (dual-frequency receivers and antennas), RTK processors (industrial panel PCs and RTK software), and a 2.4 GHz wireless local area network (LAN) base unit, access point, and station adapters. It includes one GPS hardware unit for the base station and two remote units on each crane. It also includes one RTK processor unit for the base station and one for each crane. The base unit of the wireless LAN is installed at the base station while each crane has an individual station adapter. To improve the performance of wireless LAN communication, if necessary, additonal access points can be installed in the container yard.

A fully operational and safe RTGC auto-steering system requires GPS RTK software with high levels of accuracy, integrity, continuity, availability, and computational efficiency.

Accuracy. For this application, the horizontal accuracy requirement of GPS positioning solutions is 1.5 centimeters at a 95 percent confidence level. This enables the integration of GPS with the auto-steering control system and is almost the highest real-time accuracy level currently attainable from GPS. While this accuracy level is generally achievable in short-baseline and static applications, it is very challenging to achieve it in kinematic mode due to the dynamics of a moving platform and the problem of multipath (produced by the crane itself, and any lighting towers or other cranes in the vicinity). Therefore, in order to attain the required accuracy we had to devise a robust quality control scheme.

Integrity and Continuity. For the system to be safe, the GPS RTK software must include a self-diagnosis routine able to detect failures when the positioning accuracy degrades beyond what could be expected from the

RTGC tracking a line mark. The length of an RTGC's typical run is about 500 meters and its frame spans about 23 meters.

GPS observations the system is using. For that purpose, two parameters — integrity and continuity — should be considered rigorously. The risk associated with equipment latency or design failure is specified by an integrity parameter while the risk associated with unscheduled function interruptions is specified by a continuity parameter.

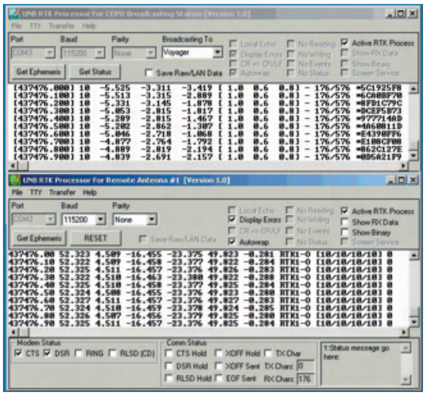
Availability. In general, the system's availability parameter depends on the visible GPS constellation (that is, the number of satellites available at the site at a particular time with a given mask angle profile). This parameter affects the GPS data processing software design to some degree because processing the GPS observations with our approach requires that at least five satellites commonly observed by both base and remote receivers be available at the site all day.

Computational Efficiency. Since the system works in real time and, furthermore, must be capable of measuring the deviation of an RTGC with an update interval of less than 150 milliseconds, data processing speed needs to be fast enough to handle observations obtained at a 10 Hz data rate. In this case, the latency of data communication (for example, data communication between a GPS receiver and a PC or between the wireless LAN and a PC) is crucial, as is the computational efficiency of the GPS data processing software. The communication capacity of the wireless LAN, the performance (in terms of stability) of the GPS receivers, and the serial interface of the PCs can all contribute to the latency problem. Meanwhile, the real-time capability of the system depends to a large degree on the computational efficiency of the GPS data processing software. In GPS RTK software, the most time-consuming process is integer ambiguity resolution, which typically searches a huge number of ambiguity candidates. It is important to keep the system latency as short as possible to minimize the auto-steering response time. A longer response time results in larger wheel deviations.

UNB RTK Software

To enable an RTGC to operate in automatic mode, a team of researchers at the University of New Brunswick (UNB), in Fredericton, Canada, have developed ultra high-precision GPS RTK software (see **Figure 1**), which satisfies the performance requirements discussed earlier.

This software is able to provide navigation solutions in real time at a 10 Hz update rate commensurate with the dual-frequency data rate (see **Figures 2 and 3**). The hori-



Port: COM3 ▾ Baud: 115200 ▾ Parity: None ▾ Broadcasting To: Voyager ▾ ☐ Save Raw/LAN Data ☐ Local Echo ☑ Display Errors ☐ CR => CR/LF ☑ Autowrap ☐ No Reading ☐ No Writing ☐ No Events ☐ No Status ☑ Active RTK Process ☐ Show RX Data ☐ Show Binary ☐ Screen Service

```
[437476.000] 10  -5.525  -3.311  -3.419 [ 1.0  0.6  0.8] - 176/576  =5C1925F8
[437476.100] 10  -5.513  -3.315  -2.889 [ 1.0  0.6  0.8] - 176/576  =6CA0BF70
[437476.200] 10  -5.331  -3.145  -1.878 [ 1.0  0.6  0.8] - 176/576  =8FD1C79C
[437476.300] 10  -5.053  -2.815  -1.817 [ 1.0  0.6  0.8] - 176/576  =DCEF5B73
[437476.400] 10  -5.289  -2.815  -1.467 [ 1.0  0.6  0.8] - 176/576  =977714AD
[437476.500] 10  -5.202  -2.862  -1.307 [ 1.0  0.6  0.8] - 176/576  =4A60811D
[437476.600] 10  -5.046  -2.718  -1.068 [ 1.0  0.6  0.8] - 176/576  =E4390FF6
[437476.700] 10  -4.877  -2.764  -1.792 [ 1.0  0.6  0.8] - 176/576  =E100CF00
[437476.800] 10  -4.889  -2.819  -2.194 [ 1.0  0.6  0.8] - 176/576  =862C127E
[437476.900] 10  -4.839  -2.691  -2.157 [ 1.0  0.6  0.8] - 176/576  =005A21F9
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Port: COM2 ▾ Baud: 115200 ▾ Parity: None ▾ ☐ Save Raw/LAN Data ☐ Local Echo ☑ Display Errors ☐ CR => CR/LF ☑ Autowrap ☐ No Reading ☐ No Writing ☐ No Events ☐ No Status ☑ Active RTK Process ☐ Show RX Data ☐ Show Binary ☐ Screen Service

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437476.00 52.323 4.509 -16.455 -23.375 49.823 -0.281 RTK1-0 [10/10/10/10] 0
437476.10 52.322 4.509 -16.458 -23.377 49.822 -0.284 RTK1-0 [10/10/10/10] 0
437476.20 52.325 4.511 -16.457 -23.376 49.826 -0.283 RTK1-0 [10/10/10/10] 0
437476.30 52.322 4.510 -16.463 -23.380 49.822 -0.288 RTK1-0 [10/10/10/10] 0
437476.40 52.325 4.510 -16.458 -23.377 49.825 -0.284 RTK1-0 [10/10/10/10] 0
437476.50 52.324 4.508 -16.455 -23.376 49.823 -0.280 RTK1-0 [10/10/10/10] 0
437476.60 52.327 4.511 -16.457 -23.376 49.827 -0.283 RTK1-0 [10/10/10/10] 0
437476.70 52.324 4.510 -16.459 -23.378 49.824 -0.285 RTK1-0 [10/10/10/10] 0
437476.80 52.326 4.507 -16.456 -23.379 49.825 -0.280 RTK1-0 [10/10/10/10] 0
437476.90 52.325 4.511 -16.457 -23.376 49.825 -0.284 RTK1-0 [10/10/10/10] 0
```

Modem Status: ☑ CTS ☑ DSR ☐ RING ☐ RLSD (CD)
Comm Status: ☐ CTS Hold ☐ XOFF Hold ☐ TX Char ☐ DSR Hold ☐ XOFF Sent TX Chars: 0 ☐ RLSD Hold ☐ EOF Sent RX Chars: 176

FIGURE 1 University of New Brunswick RTK software graphical user interface

zontal positioning accuracy guaranteed at essentially a 100 percent confidence level is better than 2 centimeters. The system tuning time for stochastic modeling is normally set to 5.3 seconds. As soon as a stochastic model is available, the software can resolve GPS ambiguities using only current epoch measurements. Therefore, the typical ambiguity resolution time of the software is 5.3 seconds, corresponding to the stochastic model tuning time. Ambiguity resolution typically requires a minimum of six common satellites. When this number drops to five, as a constraint, a priori or recursively calibrated information such as the heights and speeds of the RTGC is automatically incorporated by the software with the GPS measurements in order to improve the performance of the ambiguity resolution process.

The kernel of this RTK software is UNB's OMEGA (Optimal Method for Estimating GPS Ambiguities) ambiguity search engine and the quality control routine which the first author conceived and developed. Typically, OMEGA is able to find the first- and second-best ambiguity candidates out of a potential 10^{18} candidates within 0.1 second using a 486/50 PC. Unlike conventional approaches — such as a sequential least-squares estimator or Kalman filter, which uses the prediction values of the measurements for quality control — the quality control routine of this RTK software utilizes only the current epoch's measurements. Therefore, this approach attains high performance even when a receiver platform is maneuvering. Moreover, the quality control routine can handle cycle slips in low-quality measurements, so that we do not have to discard the measurements obtained at low elevation angles and from weak signals with low signal-to-noise ratios. As a result, this approach tends to increase observation redundancy and improve system performance in terms of integrity, continuity, accuracy, and availability.

Typically, the aggregate latency of our system, considering all factors, is less than 60 milliseconds.

GPS receiver (right) at base station

Auto-steering Test

After setting up the hardware and software for this application, we tuned the PLC and GPS RTK software on site to determine the system parameter values. In general, such tuning should be carried out on site before conducting routine crane operations because the performance of the auto-steering system depends on the following conditions:

- the gradient of the yard
- the RTGC's balance (unequal weights on its wheels can affect its travel path unless compensated)
- condition of an RTGC such as mechanical structure, tire pressure, chain tension, etc.

As a result of system tuning, the PLC was able to control the speed of each wheel to keep the crane on a track (that is, a constant offset of 50 centimeters from the line mark) within a given tolerance (for example, ±10 centimeters). Moving the crane at different speeds, we monitored the behavior of the system, as **Figure 4** shows. The sinusoidal pattern of wheel deviation is typical in auto-steering mode. The results of the test run were compared with the positions predetermined by conventional optical surveying equipment at several check points. This confirmed that the system was successfully tuned (that is, wheel deviation from a constant offset of 50 centimeters was within ±3 centimeters in Figure 4). We also conducted a continuous test run, as **Figure 5** shows, to simulate actual crane operations in auto-steering mode.

The Future

We demonstrated the performance of the Seoho prototype auto-steering system at Kwangyang Port in May 2002, achieving excellent results. This system is state-of-the-art and owes its unique capabilities mostly to the RTK software. Its development led to several remarkable achievements in GPS-based machine control, including:

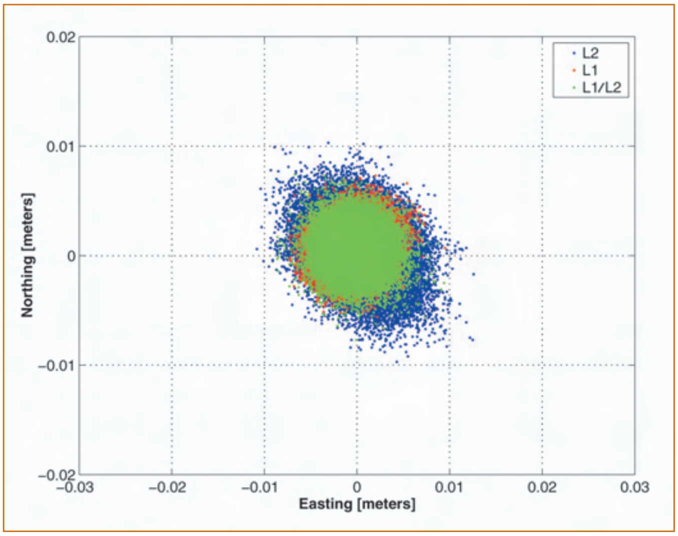

FIGURE 2 Example of the horizontal scatter of UNB RTK positioning solutions over one hour for a stationary receiver

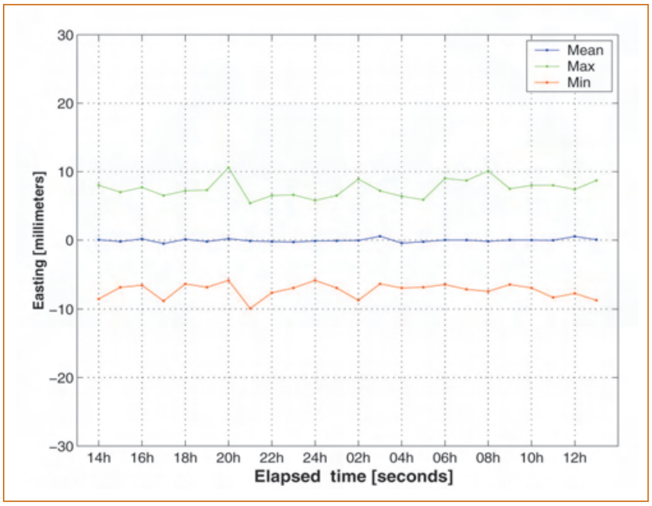

FIGURE 3 Example of the repeatability of RTK positioning solutions (easting component) over 24 hours. Each hour's data was processed separately and the mean, maximum, and minimum values computed.

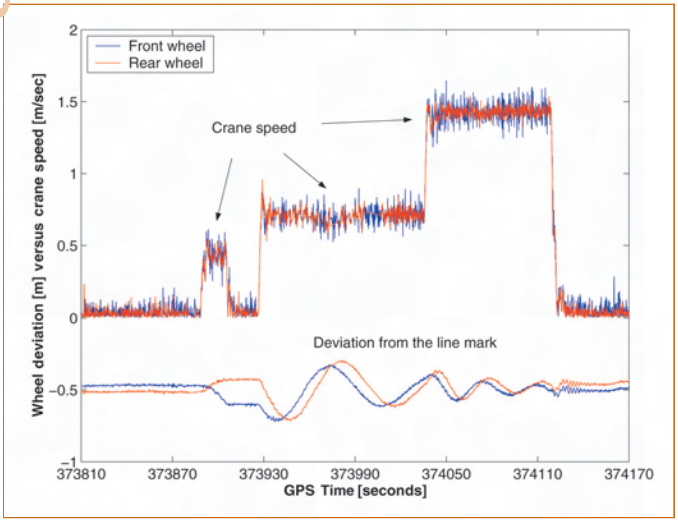

FIGURE 4 Auto-steering test run to determine the system control parameters. Wheel deviation and crane speed were estimated using GPS RTK solutions.

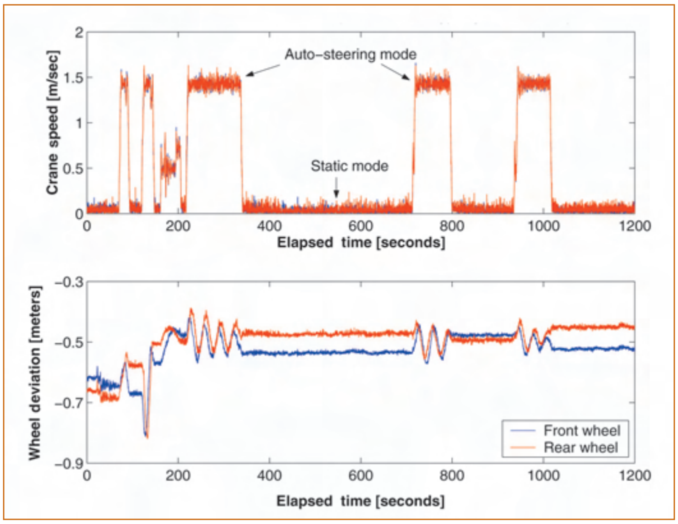

FIGURE 5 Continuous auto-steering test run to simulate actual crane operations.

- a real-time kinematic system using GPS dual-frequency carrier phases with high availability (available more than 99.9 percent of the time over the whole day even when satellite constellation geometry is sub-optimum)
- centimeter-level (better than 2 centimeters at virtually a 100 percent confidence level) ultra high-precision navigation system
- high navigation solution update rate (10 Hz update rate commensurate with the dual-frequency data rate).

Currently, we are carrying out alpha and beta testing in different environments, including Kwangyang Port, jointly with the manufacturer of the crane control system. The manufacturer plans to replicate the system at other container ports and we hope to expand their efforts to explore the capabilities of the RTK software in new GPS applications.

Manufacturers

The *GPS-RTK auto-steering system* described in this article was developed by **Seoho Electric Co., Ltd.**, of Anyang, Korea. It uses the *NCT-2000D GPS receiver* produced by **NavCom Technology** of Redondo Beach, California; the *BreezeNET DS.11 Wireless Bridge* and *BreezeNET PRO.11 Wireless LAN* by **Alvarion** of Tel Aviv, Israel; and the *JPC Industrial Panel PC* by **Jeongil Intercom** of Anyang, Korea. The *RTK software* described was developed by the **University of New Brunswick**, in Fredericton, Canada. Test results in Figures 2 and 3 were obtained with OEM4 receivers manufactured by **NovAtel Inc.** of Calgary, Canada.

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