RTK Networks for competitive advantage in Machine Control and Site Positioning

Ryan KEENAN, Sweden, and Björn BEUTELSPACHER, Switzerland

Key words: GNSS, machine control, network RTK, productivity, telematics.

SUMMARY

As technology advances and the number of construction applications requiring high-precision position attributes increases, contractors increasingly require spatial data services with higher accuracy and availability. Moreover, spiralling machine fuel, labour and material costs are increasing the focus towards productivity tools and construction accuracy. Positioning equipment manufacturers have responded by developing advanced machine control systems capable of using positional information from a variety of sources, including conventional terrestrial total-stations, single- and dual-grade lasers, and increasingly real-time GNSS positioning.

Increasing numbers of construction projects thus depend on continually-available positioning signals, and the latest development in ubiquitous, network RTK – whereby the temporal and spatial errors affecting GNSS signals over a specific region, are estimated through sophisticated algorithms in order to generate real-time error corrections unique to the network area. These RTK-GNSS networks are thus able provide high-quality, high-accuracy and high-reliability coordinates and corrections via various communication channels and protocols, for use across entire metropolitan regions, and construction project areas. As a result, networks of RTK stations have caught the attention of contractors and consultants for their scalability, flexibility, stability and reliability whilst supporting spatial services.

Leica Geosystems, a pioneer in both network RTK positioning and machine control systems, has recognised the clear benefits that positioning infrastructure brings to improving the operational performance as well as the usability of reference networks to provide the competitive advantage for 3D machine control applications. This paper outlines these advantages as well as the fiscal benefits that can result from taking full advantage of the power of RTK networks.

RTK Networks for competitive advantage in Machine Control and Site Positioning

Ryan KEENAN, Sweden, and Björn BEUTELSPACHER, Switzerland

1. INTRODUCTION

An engineering design can only be of benefit to its 'digital architects' and machine operators when the data it contains is accurate and reliable – a true representation of the real world environment it will portray. In terms of spatial accuracy, the specifications for engineering projects can range from large scale mapping at the metre level for asset management and environmental applications, through decimetre and centimetre for cadastral surveying and engineering construction, up to millimetre level for high-precision engineering and deformation monitoring tasks (Keenan et al, 2005). Consequently at all times, the accuracy of the position information, also termed spatial accuracy, is the defining characteristic of the design's worth or value and a key requirements for demanding machine control applications. The currency of the data can be described as its temporal accuracy – the time at which the attribute had a specific spatial accuracy.

One technology that is helping contractors to meet the spatial accuracy demands is that of RTK networks. The motivation for combining multiple GNSS reference stations into a real-time network (RTN) is to model and correct for distance-dependent errors that reduce, in proportion to the distance from a rover to its nearest reference station, the accuracy of conventional RTK-derived position. The most significant sources of error affecting precise GNSS positioning are the ionosphere, troposphere and satellite orbits. These three error sources can be categorized in two groups: dispersive and non-dispersive. The ionosphere is a dispersive error because the magnitude of the resultant error is directly related to the frequency of the ranging signal (L1, L2, L5), and its influence on GNSS is well understood. The ionosphere, which is subject to rapid and localised disturbances, is the main restrictor to the density of stations in a reference network. Conversely as they are not frequency-dependent and have an equal effect on all ranging signals used by current (and proposed) GNSS, the troposphere and orbit errors are classified as non-dispersive.

After the error modelling has been performed, correctors are generated that account for these error sources and they are then represented in the form of real-time network RTK (nRTK) corrections transmitted to users so that they may derive rover positions with a higher accuracy than with conventional RTK. There has been much published about RTK networks, including Euler et al (2001) and Brown and Keenan (2005), with detailed discussion about the various methodologies and performances of such important infrastructure (Newcastle University (2008), Leica Geosystems (2008), and Janssen (2008)). Leica Geosystems has been heavily involved in the development of the RTCM 3.0 network RTK messages from the outset (Euler et al, 2001), and is fully committed across all GNSS products to the official internationally accepted standard for network RTK corrections.

Several independent reports have identified the massive potential that machine control (MC) and network RTK technologies have for the coming years, such that "the value of precision GNSS systems used for industrial applications such as machine control in agriculture and civil engineering shall exceed that of precision GNSS for traditional uses such as surveying and science for the first time." (Position One, 2008). During 2008-12, Machine Control applications for precision GNSS are forecast to grow at a Compound Annual Growth Rate (CAGR) of 23-28% whereas the growth in non-machine Control applications is forecast at 16-21% CAGR. Moreover the expanding global base of precision GNSS users (estimated at more than 300,000 in 2008) is encouraging government and the private sector to invest in precision GNSS infrastructure. The growth of infrastructure and its associated data services will be a significant feature of the precision GNSS landscape in 2008-2012. Indeed, precision GNSS data services, such as real-time networks, are forecast to be the fastest growing component of the value chain with a CAGR of 33-38%." (Position One, 2009). A research report from Berg Insight (2010) states that at the end of 2009, 1.4 percent of the mobile network connections worldwide were used for wireless machine-to-machine (M2M) communications, as featured in typical telemetry systems, and this figure is projected to reach 3.1% by 2014 – over 180 million connections.

This paper discusses the competitive advantages - both functionally and fiscally - that a RTK network brings to machine control, engineering and asset management applications requiring high-precision real-time positioning.

2. MOTIVATION FOR REAL-TIME NETWORKS IN MACHINE CONTROL

Ongoing worldwide construction of infrastructure requires the establishment (or updating) of a reference coordinate control framework to support positioning during construction. Every country that has been, or is, embarking on a redefinition of their national reference frame has done so making use of GNSS technology, typically in the form of an active reference station network (RSN) and the approach is applicable to engineering projects also.

A network of such continuously operating GNSS reference stations (CORS) is more efficient than a traditional terrestrial triangulation and traverse network. Although they are typically more precise than GNSS systems for site surveying, the limitations of opto-electronic total stations for dynamic machine control applications make them unsuitable as the sole 3D MC positioning system as follows:

- Limited distance of operation, due to the strength and accuracy of EDM measurements.
- Susceptibility to obstructions (either site, vehicular or personnel).
- Risk of damage to and theft of total station equipment on-site.
- Continual disturbance of site control monuments.

As the CORS can be set-up at convenient locations over the area where they are needed, the geometry of the RTK network is not as critical as with traditional networks, and the achievable accuracy is higher and more consistent. By default, the information (whether data, corrections or final positions) supplied by RTN is provided in a consistent global satellite datum, typically WGS84 (in some cases ITRF2000 or later). This datum and its parameters are well-known, many national coordinate reference frames are derived from it, and GNSS surveying systems are well equipped to cope with this datum, and transformations based upon it. Once the datum is defined within the network, all surveying results in the project are based on this datum. Consequently, with the establishment of a real-time control network system, construction tasks can be accelerated because of the improved survey control, active control can be provided given that the majority of traditional survey control points on-site may be seriously damaged, and networked RTK correction services can support all contractors.

Recent developments in networked RTK rover solutions, such as Leica Geosystems' SmartRTK featuring atmospheric decorrelator technology and observation optimisation techniques (Takac and Lienhart, 2008), are further improving the homogenous positioning accuracy and precision of GNSS solutions yielding more fixed rover positions. These advances have been facilitated by using the MAC network RTK approach, as realised in the RTCM v3.1 standard for differential services (RTCM, 2007).

2.1 Functional Benefits of RTK Networks

The operational benefits of these technologies are well-chronicled by various organisations including Ordnance Survey GB and Oregon Department of Transportation, but for reference purposes shall be summarised here as follows.

Table 1: Functional Benefits afforded by RTK Networks

BENEFIT	DEFINITION AND EXAMPLE
Accuracy	Positional accuracy – *the degree of closeness of calculated positions to the truth position* – is improved as the distance-dependent component (ppm) is reduced significantly through network processing, providing more homogenous positioning accuracy at different distances from the stations.
Reliability	The reliability of ambiguity fixed RTK rover positions is improved, even when operating at long ranges and under difficult ionospheric conditions. Permanent stations, fixed communication lines, and redundant server architecture ensure near 100% uptime 24/7. Conversely, local bases are subject to communication outages and have no redundancy in case of failure.
Availability	*The proportion of time a system is in a functioning condition,* such as providing continuous and reliable RTK corrections and data services to all users. The network software is designed for distributed server architecture, with automatic data archival and hardware redundancy.
Stability	Networks are monitored continuously for station movements, thus ensuring that they truly define the correct reference datum.
Scalability	The ability for the technology to accept increased workload without impacting performance Supporting GPS & GLONASS, and future systems such as GALILEO and COMPASS.
Flexibility	Centralised RTN software can support multiple users and applications

	simultaneously, including conventional RTK & DGPS, and networked services – nRTK & nDGPS, as well as new applications.
Compatibility	The most powerful network software system incorporates data from legacy base stations, as well as providing standardised RTCM correction information at various rates in various formats. Supports various communication protocols such as cellular (including GMS/GPRS, CDMA & HSPA), radio (UHF & VHF), TCP/IP (NTRIP).

2.2 Fiscal Benefits of RTK Networks for Machine Control

These benefits directly relate to the reduction of operational expenditure and are summarised here.

2.2.1 Productivity

Getting the job done quicker normally equates to spending less time performing the job; translated into machine control terms, it typically means achieving grade specifications with fewer passes. Fewer passes means less driving and ultimately lower machine costs, and faster completion times. Typical 3D machine control (MC) systems such as Leica Geosystems' PowerGrade 3D using RedLine GNSS positioning technology, can operate in 'Indicate' or 'Auto' modes; the former provides visual signs to cut or fill according to the design. The latter involves the MC system automatically controlling the machine hydraulics to ensure that the blade is always 'on grade'. The use of 'Auto' systems can lead to consistently high levels of productivity as they aren't subject to operator fatigue.

2.2.2 Reduced Labour

A major component of any construction project costs is labour, and no less so for MC applications – whether it is machine operator, vehicle driver or site surveyor. With the use of 3D machine control systems, the need for field surveyors to 'check grade' is greatly reduced, thus saving considerable labour costs. With a fully calibrated machine, the bucket or blade's cutting edge essentially becomes a real-time 3D coordinate measuring tool. For certain applications, once the machine has been calibrated successfully, the need for grade-checkers can even be eliminated because of machine control. No longer must machines idle unproductively while a surveyor travels across the project to check the grade and provide feedback to the operator as to whether another pass is needed. These benefits clearly affect productivity and efficiency on site, while reducing costs (fuels, setting out, equipment rental and costs etc).

2.2.3 Materials

As the prices of most raw materials have increased steadily over the last years, the significance of achieving grade to tighter specifications than ever before has focussed the application of 3D machine control to help minimising production costs. For example, tightening the specification of sub-grade by 1cm on a 10m wide carriageway would save approximately $100m^3$ of material per kilometre of highway. Factor in the relevant costs of different materials used in the particular construction process, and this adds up to considerable additional savings of the overall project costs.

2.2.4 Fuel and Servicing Costs

Now a regular headline worldwide, the variable costs of fuel, motor oil and servicing are major expenses in project costs. Even with the U.S. Energy Information Administration's optimistic Reference Case projection, the price of crude oil could increase by over 30% in the next 20 years (Reference International Energy Outlook 2009), and diesel fuel costs likely higher because of refining costs. For mega-projects such as mines and earthworks, that involve considerable numbers of machines, transportation may count for up to 50% of total operational costs (Leica Geosystems, 2010). Having an overview of all these machines wherever they are on-site, and the ability to monitor their fuel consumption and engine performance, brings many advantages to optimise their utilisation and productivity.

2.2.5 Safety

The term 'safety of life' is well-known in the navigation markets of aviation, shipping and transportation, and as a result of legislation, is becoming commonplace in construction projects. Consider the mountain of insurance paperwork with having one or more grade-checkers injured whilst working around large earthmoving machines. For those tasks where a site surveyor must be in the dirt (i.e. setting out), then making use of a RTN can be more efficient than using local bases because of the higher availability of RTK corrections and services from the network. With faster initialisation times thanks to the network, grades can also be checked quicker, the surveyor spends less time around the machines and machine idle times can be reduced.

Another major advantage of providing high accuracy positions to MC systems is to monitor their moment in critical areas such as when working near high-pressure fuel main or expensive optical fibers. Being able to warn the machine operators of the danger of striking such utilities provides a safer working environment while also a potentially large cost saving to the contractor. This technology is also being coupled with cable detection equipment such as the Leica EziDig system, and when used in conjunction with nRTK can also provide a means of remotely mapping buried services directly from a MC system.

2.3 Demands of Machine Control and Site Positioning

The benefit of making design models available to the machine operators is that they provide the most efficient basis for visualizing the target designs from within the machine. Operators are then informed about the different grades and features of the project, allowing them to decide how best the materials should be modified according to local conditions in order to achieve grade. Two major challenges to this are those of data fidelity (correctness) and data access; fidelity 'on grade' can be achieved through use of the RTK networks, and design model access through the use of telemetry systems. The machine control market segments of precision agriculture and mining should not be forgotten in terms of their demands of precise positioning and data transfers.

Increased productivity with lower costs

Agriculture technologists were quick to identify and embrace the technology of precision GNSS specifically to help lower operational costs and improve yield management, specifically the process of understanding, anticipating and influencing crop growth in order to maximize output from a fixed, perishable resource. With the relevant measurements and information, farm managers can take informed decisions in a multi-billion dollar industry that is trying to produce maximum yield (crop & profit) with minimal OPEX (fuel, machines, fertilizer). For agronomy, a main aim is for improved repeatability of the measurement so that users, such as farmers, can realize precise “pass-to-pass” navigation for applications requiring a high level of precision such as tractor auto-steering. Just like in MC applications, reducing the number of passes means lower vehicle and fuel costs, leading to increased profitability.

RTK corrections are typically provided over radio to these Precise Ag users, however there is a rapidly growing demand and availability of access to network RTK corrections over cellular links. Agricultural dealers and network providers are now investing considerably in marketing their network services to agricultural operators. One example is SmartNet Australia, distributing network RTK corrections to key growing regions (SmartNet Australia, 2010).

Remote Connectivity

One major benefit of centralised RTK services for site positioning, is that of telemetry – the connectivity from a remote location to a field computer inherently afforded by the RTK communications device. This connectivity can be classified in three forms:

1. between Office and Field (O2F) – typically a field surveyor,
2. between Office and Machine (O2M) and
3. between machines (M2M).

A prime example of remote connectivity adding more benefit to the customer experience is Leica’s VirtualWrench. This is the Ag industry's first web-based remote service (O2M) and diagnostics tool available exclusively to Leica Geosystems authorized technicians to remotely support Leica mojoRTK systems in farm machines.

Telematics as a leading-edge real-time field technology, has greatly impacted the mining industry to increase site productivity and machine uptime, whilst lowering the associated operational costs. Given the increased demand for natural resources, having the ability to fully integrate high-precision guidance all into a single fleet management solution makes extremely good sense in order to optimise production control. With the adoption of scalable GNSS-based mine management solutions (incorporating telemetry systems), mine operators are empowered to use their assets optimally and to demonstrate their production competitiveness within the mining industry.

3. DATA FUSION AND APPLICATION FUSION

Bringing together RTK correction information via the telemetric communication links to improve spatial accuracy, is only one part of the overall solution – the other is optimizing resources who use that accuracy. The importance of GNSS position information from 3D machines must not be forgotten when considering Telematics applications – even though telematics and fleet management type applications use position as secondary attribute metadata rather than the main output. Production control in terms of 3D MC, is defined as the ability to review the current status of engineering operations, analyse the unproductive procedures, and action optimisations. One such production control application is the Viewserve Construction suite, which is well-established in Scandinavia for providing specific tools for construction managers to have both a real-time overview and historical analysis of fleet activities affording them informed decisions in order to improve site productivity.

There are three main steps within the Process Cycle of Production Control using Telematics, as indicated in Figure 1.

Figure 1: The Process Cycle of Production Control using Telematics (after Viewserve, 2010)

1) Measurement:
- Automatic collection of data (position & sensor) from vehicles (machines & fleet).
- Normally no interaction required of drivers.
- Position and sensor data – such as mass transportation - displayed via a web portal.

2) Analysis:
- Use Viewserve reports to analyse data, raising alarms of outages.
- Management reports.
- Identify areas of productivity improvement.

3) Action:
- Identify measurable KPIs relevant to the tasks.
- Take adequate actions to reach KPIs.
- On-site management (training and information to drivers) – e.g. reassignment to another area.

Advantages of Production Control Systems

Monitoring, supervising and coordinating construction works helps to ensure achievement of the project's planned progress. Using a common example of Idle time Analysis, where a fleet of machines is idling for around 10 minutes per hour, the implementation of production control system could help to reduce the amount of time lost during excessive idling, and reduce operational costs.

Table 2: Production Control Idle Time Analysis showing Cost Savings*

Running	Running Costs	Initial Idle	Projected	Total Idle time	Total Idle time

hours per week	per week per machine	time & Costs per week	Reduction in Idle time per hour	cost Savings per hour	Cost Savings per week	
60	$2,400	10 hours / $400	1 minutes	$0.67	$40	2%
			2 minutes	$1.33	$80	3%
			3 minutes	$2.00	$120	5%
			5 minutes	$3.33	$200	8%

**Calculation based on average hourly costs of $40 (including: diesel/fuel and oil consumption, cost of operator, cost of service hours, spare parts and normal usage) and average of 10 minutes idle time per hour. Based on vehicles consistently using the same route.*

As can be seen, the nature of production control lends itself very well to a continuous iterative review process – with the reports generated by a production control system, the fleet manager is now able to make informed decisions and initiate the necessary actions that would allow to:

- decrease idle time and thus fuel consumption,
- decrease wear and tear on the machine – by identifying vehicles using excessive fuel/oil,
- identify bottlenecks and areas of improvement,
- increase productivity and efficiency,
- reduce operational costs, and
- continuously monitor and review vehicle behaviour via the Viewserve portal.

While these costings will vary depending on machine type, labour costs and operating behaviour amongst others, the general trend of reducing the operational expenditure thanks to more informed reporting and decision-making is clear (Talend, 2009).

4. CONCLUSIONS

The use of GNSS within the construction arena is not new, however the recent (and current) financial crisis has put new focus on the productivity improvements that can be gained from the fusion of high-precision GNSS positioning together with machine control systems.

It is clear that the combined value of Reference Station Networks to the machine control community is immense, not only in terms of providing spatial accuracy and reliability in support of multiple users and applications, but also for profitability. Reference Station Networks and their services provide the geodetic coordinate control needed for high-precision positioning as well as supporting a wide variety of applications, especially data transfer, telematics and production control. With the proliferation of machine control systems, particularly the visualisation of design data and data telemetry systems, the applications of fleet management and production control, become empowered to provide resource efficiency, optimised productivity and operational awareness leading to maximum site output.

The standardised use of 'always on' internet-connected communication devices on machines – whether construction, agriculture, mining or fleet – has facilitated the adoption of telematics within these markets & applications, so much so that O2M connectivity is now the norm, rather than the exception. The usage of these communication devices clearly demonstrates the functional benefits – higher accuracy via receipt of network RTK corrections, reliable transfer and exchange of design & job files, tracking and remote support. In addition, fleet owners and project managers are able to see the current status of production derived from these measurements. By analysing the information afforded by these combined systems, managers can make informed decisions and operational changes that will directly improve productivity and efficiency. This in turn corresponds to increased profitability and even bonuses for early completion of projects.

On small projects with relatively low numbers of machines, the payback of capital costs for technologies of machine control, nRTK, office-field connectivity and fleet management, would typically in the period of a couple of years. Large and mega-projects involving multiple machines and vehicles working over larger areas, may yield such productivity improvements to achieve payback in much shorter periods.

Hopefully the speculated rates at which construction projects involving Machine Control will proliferate in the future will ring true. Positioning is a key activity within machine control, agriculture and mining, that demands the accuracy, reliability and availability that RTK networks can provide. The robustness of RTN means that they will flourish as commercial organisations seek to enhance data fidelity and information management across their projects. Such a network's permanence as fundamental infrastructure means that it not only supports the creation of structures such as buildings, bridges and mines, but also their maintenance life cycles, update and expansion - establishing the RSN infrastructure now will reap dividends later by ensuring a swift return on investment.

Machine control systems operating within RTK networks will neither become ubiquitous overnight nor eliminate the need for grade-checkers and setting-out engineers on every site. However their synergism with site management software will allow those embracing nRTK machine control systems to compete successfully both operationally and profitably by efficiently controlling resources and equipment for optimised productivity.

REFERENCES

BROWN, N., KEENAN, R.: *Leica Geosystems White Paper: Take it to the MAX*, 2005, downloaded from http://www.leica-geosystems.com, last accessed on 03 January 2010.

EULER, H-J., KEENAN, R. C., ZEBHAUSER, B. E., WÜBBENA, G.: *Study of a Simplified Approach Utilizing Information from Permanent Station Arrays*, in Proceedings of the 14th International Technical Meeting of the Satellite Division of The Institute of Navigation ION GPS 2001, Salt Lake City, Utah, USA, September 11-14, 2001.

KEENAN, C.R., WANG. C., LUI, V., VAN CRANENBROECK, J., WU. L.: *Digital Cities*, in Proceedings of the International Symposium on GPS/*GNSS*, Hong Kong, PR China, 2005.

LEICA GEOSYSTEMS: *System 1200 Newsletter Series 52-54*, 2008, downloaded from http://www.leica-geosystems.com, last accessed 07 January 2010.

NEWCASTLE UNIVERSITY: *Report for TSA - An examination of commercial network RTK GPS services in Great Britain*, download at http://www.tsa-uk.org.uk, November 2008.

JANSSEN, V.: *A Comparison of the VRS and MAC principles for network RTK*, in Proceedings of IGNSS Symposium 2009, Surfer's Paradise, Australia, 2009.

POSITION ONE: *POSITION REPORT – GNSS Precise Positioning Markets 2008-2012*, October 2008.

POSITION ONE: *POSITION REPORT – GPS/GNSS Networks and Services,* March 2009.

RADIO TECHNICAL COMMISSION FOR MARITIME SERVICES (RTCM): RTCM Standard 10403.1 For Differential GNSS Services – Version 3 with Amendment 1, *RTCM Paper177-2006-SC104-STD*, Developed by the RTCM Special Committee No. 104, Amended May 21, 2007.

TAKAC, F. LIENHART, W.: *SmartRTK: A Novel Method Of Processing Standardised RTCM Network RTK Information For High Precision Positioning*, in Proceedings of ENC GNSS 2008, April 22-25, Toulouse, France, 2008.

TALEND, D.: *GNSS for Heavy Construction*, GIM International, Vol. 23, Issue 10, October 2008.

Links:
http://www.berginsight.com, last accessed on January 10, 2010.
http://www.eia.doe.gov, U.S. Energy Information Administration, last accessed on January 10, 2010.
http://www.leica-geosystems.com, last accessed on January 10, 2010.
http://www.mojortk.com, last accessed on January 10, 2010.

http://www.ordnancesurvey.co.uk/oswebsite/gps/commercialservices/index.html, last accessed on January 10, 2010.
http://www.theorgn.org, last accessed on January 10, 2010.
http://www.smartnetaus.com, last accessed on January 15, 2010.
http://www.viewserve.com, last accessed on January 09, 2010.

BIOGRAPHICAL NOTES

Dr. Ryan Keenan has a Bachelor of Engineering Honours degree in Civil Engineering Surveying from Nottingham Trent University and a PhD in GPS Geodesy & Navigation from UCL (University College London), England. The title of his doctoral thesis was Stochastic Modelling for High-Fidelity Differential GPS Quality Measures. Since 2001, Dr. Keenan has been employed within the companies of Leica Geosystems and Hexagon Measurement Technologies, working in various projects involving high-precision GNSS, in particular Network RTK methodologies and applications, and most recently for 3D machine control applications. He is a co-inventor of the master-auxiliary correction-differences concept for the standardization of message information from RTK networks, which is now realized in the official RTCM V3 network RTK correction standard known as MAC.

Björn Beutelspacher has a Diploma in Engineering from the University of Applied Sciences Surveying and Geoinformatics in Stuttgart, Germany. His diploma thesis, entitled "Analysis of GPS measurements with the network solution SAPOS., had focus on accuracy, reliability and cost-effectiveness, including analysis on how the occupation time of static GPS measurements influences accuracy and reliability. He is currently working as an Application Engineer for GNSS Systems in Machine Control, at Leica Geosystems, Heerbrugg, Switzerland.

CONTACTS

Dr. Ryan Keenan
Hexagon Machine Control Division, c/o SBG AB,
Elektronvägen 1, SE-141 49 Huddinge,
SWEDEN
Tel: +46 8 562-80821
Fax: +46 8 711-2098
Email: ryan.keenan@hexagon-machine-control.com
Web site: http://www.leica-geosystems.com