Review of Positioning Services and User Requirements for Machine Guidance Applications in Australia

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Key words: Requirements, machine control, precision agriculture, GNSS/GPS

SUMMARY

Performance requirements for PNT end-user applications have been studied in the aviation and maritime context since the advent of GPS navigation. The Standard Positioning Service and Wide Area Augmentation Service cover the required navigation performance criteria of accuracy, availability, reliability, integrity and coverage in these industries. For applications requiring high accuracy navigation such as Machine Guidance in Civil Construction and Precision Agriculture, users rely on dual-frequency carrier phase augmentation techniques to achieve cm-level accuracies. Augmentation techniques in these environments have evolved from ad-hoc radio RTK operations for single owners, to subscription-based Network RTK covering regional areas, and global PPP delivered by L-band satellite communication. Additionally, the fully operational multi GNSS world promises future high-accuracy Commercial Services provided by GNSS operators such as Galileo, Beidou & QZSS as part of their basic operation. While several services are functioning in Australia, uniform performance standards for utilizing them have not been specified in high accuracy applications.

In an effort to standardize GNSS positioning services and end-user requirements, this paper provides a systematic review of the augmentation services available in Australia in the context of high accuracy PNT applications for Machine Guidance in Civil Construction and Precision Agriculture. A section is dedicated to defining the required navigation performance criteria for existing machine guidance and automation tasks, future application trends and developments. The results of this review aim to inform the end-user of available PNT solutions to meet high accuracy applications within Australia, where the country's geographic location, size & population density make a challenging environment for delivering consistent PNT services.

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1. INTRODUCTION

Research into applying GNSS navigation for guidance and automatic control of heavy machinery in the civil construction and agriculture sectors developed in the early 1990s into today's competitive commercial positioning and navigation market. The geospatial industry is now a well-established provider of PNT products and services to different sectors including various augmented GNSS solutions that provide positioning and navigation from centimetre (RTK, PPP) to meter level accuracies (DGPS).

As GNSS and complementary sensing technologies (IMU, LiDAR, Radar, Sonar, 3D-vision) become widespread, the application of automation and robotics to the construction, agriculture, mining and intelligent transport industries will continue to deliver increased benefits in terms of productivity and safety. In particular, the projected adoption rate of GNSS guided machines in the construction sector is estimated to reach 40% - 60% by 2030 (ACIL Allen Consulting 2013). The civil construction industry has shown progress in automation of construction processes, Civil Integrated Management (CIM), augmented reality, machine automation, telematics and asset and personnel tracking in the jobsite (Balaguer & Abderrahim 2008; Viljamaa et al. 2014) while automation for machines in mining and agriculture have been demonstrated in research and commercial operations (Billingsley et al. 2008; Corke et al. 2008; Australian Mining 2015). The research trends in automation and robotics are moving towards full automation of machine specific tasks and processes in these industries in which GNSS services play an important role in providing positioning and navigation in a single reference frame.

2. BACKGROUND

Using the GPS' Standard Positioning Service (SPS) or equivalent for other GNSS allows for a range of navigation applications of relatively low accuracy and integrity due to errors inherent in the position estimation. For applications where improved navigation performance is required, real-time augmentation systems are implemented to enhance accuracy, integrity, availability, reliability and coverage parameters. The different augmentation approaches to treating the GNSS signals and correcting for errors in the determination of position have been described as two spatial representations; OSR (Observation Space Representation) and SSR (State Space Representation). The methods of accessing these augmented services have been classified as Ground-based data links, Satellite-based data links or Internet delivery (Lachapelle et al. 2010).

2.1 Augmentation methods

In the Observation Space Representation (OSR) range corrections from error sources in the GNSS code and phase observations are computed in a reference station as a "lump-sum" correction. The solution in the OSR model, used in Differential GNSS, Wide Area DGPS, RTK and Network RTK techniques, is *relative* to the reference station's reference frame and its accuracy is baseline dependent, thus the solution is limited to an effective range applicable in a local or regional scale.

The State Space Representation (SSR) computes individual error sources from orbits, clocks, atmospheric delays, and biases as components of a state vector. Computing the individual magnitude of orbit and clock errors provides *absolute* positioning that is not spatially correlated and thus the solution is independent from reference station distance and can be applied in a wide-area or global scale. In the case of carrier phase processing, the computation of a solution is more intensive resulting in a longer time to converge on an accurate solution although research is being done to improve processing algorithms to provide faster initialisation times. PPP is based on the SSR model.

2.1.1 DGNSS

In the Differential GNSS (multiple terms refer to this technique; DGPS, dGNSS) technique a single reference station on a known location calculates the errors in the code and carrier phase smoothed pseudorange observables and delivers them to a user receiver as a correction message through a real-time data link. The accuracy of the solution degrades over distance from sub-meter within 100km to several meters with increasing distance from the base station. On the user end, low-cost, single frequency (L1) phase tracking receivers with external correction input are used.

DGPS has been applied for machine guidance in forestry, agriculture, mining and transport sectors where meter-level accuracy is sufficient for automation of the machine tasks. Reference stations are generally user-owned in a farm or mine site, or operated as part of networks owned by private or government agencies.

2.1.2 RTK and Network RTK

RTK is a more accurate relative positioning technique that calculates the differences in the carrier phase signal observations of L1 or L1/L2 frequencies (and L5 with triple frequency combinations) in a reference receiver on a known location and transmits the correction message to a rover receiver through a real-time data link. The phase measurements enable a cm-level accuracy position estimation using an integer ambiguity resolution technique within a 20km range. Network RTK improves this method by using networks of reference stations that can extend the range of the correction delivered through Internet Protocol to users within the area of the CORS network but still the accuracy is inversely correlated with distance (Janssen et al. 2012).

GNSS augmented by RTK and Network RTK is the main positioning technique for machine control applications in the civil construction industry where most tasks for earthmoving machinery are done within 2-5cm accuracy, although applications with smaller tolerances (paving, fine grading) are often complemented by laser and traditional survey methods. In agriculture, even though DGPS is widely used, some machine applications (strip tilling, inter-row seeding) can only be done with RTK-like methods providing cm-level accuracy. In mining, precise machine guidance rely on centimetre accurate RTK for cutting and excavation. The datum of the positioning solution can be local (in the case of mine sites operating user-owned bases with legacy local datums) or national (GDA94).

2.1.3 Wide Area DGPS

A differential method that can be combined with satellite orbits and clocks corrections is implemented in several regional public-access Wide Area DGPS (or Wide Area GNSS) services that provide meter-level accuracies to receivers using code measurements by transmitting corrections over a satellite-based data link in the case of Satellite-Based Augmentation Systems (SBAS) or over Internet (Raman & Garin 2005; Lacarra et al. 2013). Some commercial products (Viewpoint RTX) are able to provide corrections with worldwide service coverage for compatible receivers over satellite or Internet.

Public SBAS provide regional coverage to comply with civil aviation standards in North America (WAAS), Europe (EGNOS), India (GAGAN), Japan (MSAS), and Russia (SDCM), while additional systems in China, Africa, Latin America and South Korea are being studied. In Australia, the case for SBAS has been proposed (Australian Government 2011) but no implementation is planned.

2.1.4 PPP

Precise Point Positioning (PPP) was proposed (Zumberge et al. 1997; Kouba & Héroux 2001) as a positioning technique based on the state vector model that corrects the satellite and receiver specific errors and models atmospheric and geophysical effects to derive a float solution with decimetre accuracy after a period of convergence of up to 30 minutes which limits its real-time use. Commercial services however, have provided real-time PPP for remote, open-sky environments where convergence and re-initialisation times (after loss of lock) are not a limitation, such as marine and agriculture applications. The solutions provided by PPP are delivered in a global reference frame (ITRF) and transformations need to be made for local applications.

The combination of PPP with AR (Ambiguity Resolution) and further with RTK (Wübbena et al. 2005) has been proposed to deliver real-time centimetre accuracy and some commercial services have implemented an PPP-RTK approach over large areas (Leandro et al. 2011). A review of real-time PPP services and their AR approaches was done by Grinter & Roberts 2013. In Australia, research is being carried out on the integration of PPP and RTK to take advantage of both wide area coverage and rapid ambiguity resolution (Teunissen & Khodabandeh 2014) to deliver through a National Positioning Infrastructure (Hausler 2014).

Machine guidance in the agriculture, mining and marine sectors are core users of PPP products but its use in civil construction has not been adopted in part due to limitations of centimetre-level accuracy, convergence times, and interoperability.

2.2 Delivery channels for augmentation

GNSS augmentation can be classified in different ways and one of the most common ones has been by the method of data link delivery: Ground-Based Augmentation System (GBAS) vs. Satellite-Based Augmentation System (SBAS) but as new delivery channels emerge and with the availability of mobile internet, which can be delivered by a combination of carrier technologies, this distinction may vanish (Lachapelle et al. 2010). The example of this is current commercial services offering their wide-area/PPP augmentation solution via a mix of satellite L-Band or Internet, proving that all the user needs to receive accurate positioning is a communication link. By including Internet as a separate method of delivery channel for augmentation, the following classification is available.

2.2.1 Ground-based data links

Networks of radio beacon towers delivering GNSS augmentation in the LF/MF & VHF frequency bands are traditionally used as datalinks for DGPS navigation in maritime and aviation applications. The Australian Maritime Safety Authority operates a GBAS in the country's coasts and ports in the LF/MF band (285 -325 kHz) (Australian Maritime Safety Authority 2013). In aviation, a GBAS or Local Area Augmentation System (LAAS) for CAT I approaches operates in Sydney Airport since 2014 and is considered for extension to other airports (Airservices Australia 2015). This type of DGPS augmentation provides increased accuracy, integrity monitoring and reliability using industry standard RTCM & NMEA data formats. The range of the radio link and thus the coverage of the augmentation datalink stretches to around 300km for LF.

For higher accuracy applications using RTK augmentation, the current standard for ad-hoc GNSS base & rover operations and most adopted channel for delivery is the licenced UHF band in the 450 – 470 MHz range (unlicensed Spread Spectrum in the 915 – 928 MHz and 2400 – 2483.5 MHz are also available with limited range and compatibility). As of February 2016, the ACMA Register of Radiocommunication Licences shows over 26300 UHF (450 – 470) frequency licences in Australia (ACMA 2016) and managing the frequency assignment and interference becomes an issue in densely populated areas. The transmission range of UHF is generally limited to 10km in optimal conditions but in practice a range of a few km can be expected around rough terrain and vegetation cover although radio repeaters can be used to extend the range of the data link. Standard message formats have been well established for RTK with additional proprietary options from commercial equipment manufacturers.

2.2.2 Satellite-based data links

The Wide Area Augmentation System (WAAS) in the US and other public access, aviation-style SBAS with regional coverage utilise the same L1 frequency used by GNSS so standalone receivers can decode its correction signal within the GEO satellite's footprint. Currently, there is no regional augmentation system with coverage for Australia.

Satellite L-band communication has been widely available for the maritime and offshore industry using Inmarsat satellites and several augmentation systems have stemmed from these applications to diverse commercial products. Initially offering code based augmentation, now capable of providing PPP and PPP-RTK like performance. The range of applications of commercial satellite-based augmentation has expanded from maritime to aviation, agriculture, mapping, survey and engineering as performance improvements reach below the decimetre-level accuracy threshold and convergence times are reduced from around 30 minutes to several minutes (Leandro et al. 2011; Banville et al. 2014). Due to the limitations of satellite communication, the bandwidth is efficiently used with proprietary compression algorithms and data formats transmitted to capable receivers and antennas on the user end.

A proposed approach to satellite delivered augmentation relies on the existing E6 frequency band in some GNSS satellites (QZSS, Galileo) to provide a cross between Regional Augmentation and PPP commercial services, reduing the hardware requirements on the user side and enabling commercial products offered directly by the system providers (Choy et al. 2014; Fernández-Hernández et al. 2014).

2.2.3 Internet Protocol data links

As mobile internet expands its coverage, it became practical to use Internet delivered GNSS augmentation to users in diverse applications and without the coverage/bandwidth limitations of traditional ground-based data links. Currently Australia has mobile internet coverage on most built-up areas with vast remote areas out of Internet delivered coverage, a characteristic of this country's size and population distribution and in contrast with denser populated areas such as Japan and Germany. An additional benefit of having two way data link has enabled the creation of Network RTK methods using CORS networks and offer code, RTK and PPP augmentation from research, government, public and commercial service providers.

Australia has several CORS Networks managed by government Data Service Providers that distribute DGPS, RTK and NRTK augmentation services through a Value Added Reseller (VAR) network described by Hausler (2014). Commercial PPP providers deliver several augmentation services over Internet (Trimble RTX) and public access PPP solutions exist for research purposes (International GNSS Service 2016).

With increased coverage and availability of mobile internet and as delivery channels expand into different frequency bands including satellite delivered internet (Feng et al. 2009), the classification of data link as ground and space is blurred and Internet may become a means of providing a communication link for multiple integrated services of which GNSS augmentation is a part of, like telemetry and Internet of Things.

3. THE PNT MARKETPLACE

Positioning services that augment GNSS use one or a combination of the signal processing methods referenced previously and they are transmitted to the user through one of the delivery channels also discussed. Following this classification, Table 1 presents a summary of currently available GNSS augmentation providers and services in Australia and their characteristics. While this list is not extensive, it cover most providers as far as can be determined by the author. Some of the PPP providers have been omitted as they focus on the marine and offshore markets, and the objective of this list is to provide solutions to machine control applications on land.

The type of provider describes the sector as private, government, research, VAR, and user-owned. The coverage area is divided into global (for PPP solution coverage) and regional, coastal, and local (for DGPS, RTK, and NRTK). Delivery method is described as satellite L-Band (assuming that the user owns compatible equipment with the service provider), Internet, Beacon, and Radio UHF & SS. Finally, the GNSS constellations supported and the solution type.

Accuracies, specified at 95% confidence level unless otherwise noted, have been gathered from service provider's specifications and previous studies demonstrating experimental results while DGPS and RTK accuracies do not consider baseline distance effects (Trimble Navigation Limited 2016; Terrastar 2016; NavCom Technology 2016; Jokinen et al. 2014; Samper et al. 2014; Laurichesse 2011; Hausler 2014; Hemisphere GNSS 2016).

Table 1. Summary of Positioning Services

Provider	Service	Type[1]	Area[2]	Delivery[3]	GNSS[4]	Solution	Accuracy (95%)	
							Horizontal	Vertical
OminSTAR	VBS	Priv.	Global	L-Band	G	WADGPS	<1m	
	XP			L-Band	G	PPP	<10cm	
	G2			L-Band	G+R	PPP-AR	<10cm	
	HP			L-Band	G	PPP-AR	<10cm	
Trimble	Viewpoint RTX	Priv.	Global	L-Band, I	G+R+B+J	WADGPS	<1m	
	Rangepoint RTX			L-Band, I	G+R+B+J	PPP	<50cm	
	Centerpoint RTX			L-Band, I	G+R+J	PPP RTK	<4cm	
NavCom	StarFire	Priv.	Global	L-Band, I	G+R	PPP	<5cm(68%)	<10cm(68%)
Novatel	CORRECT SBAS	Priv.	Global	L-Band	G	WADGPS	<60cm(68%)	
	CORRECT PPP			L-Band	G+R	PPP-AR	<4cm(68%)	<6.5cm(68%)
TerraStar	TerraStar-M	Priv.	Global	L-Band	G	WADGPS	<1m	
	TerraStar-D			L-Band	G+R	PPP	<10cm	<20cm
Hemisphere	Atlas H100	Priv.	Global	L-Band, I	G+R	WADGPS	<1m	
	Atlas H30			L-Band, I	G+R	PPP	<30cm	
	Atlas H10			L-Band, I	G+R	PPP-AR	<8cm	
IGS	IGS-RTS	Res.	Global	I	G+R	PPP	<10cm	<15cm
GMV	magicPPP	Res.	Global	I	G+R	PPP-AR	<10cm	<15cm
CNES	PPP Wizard	Res.	Global	I	G+R	PPP-AR	<10cm	<15cm
AMSA	AMSA DGPS	Gov.	Coastal	Beacon	G	DGNSS	<10m	
NT Lands		Gov.	Reg.	I	G+R	DGNSS NRTK	<1m <3cm	<3m <5cm
Landgate		Gov.	Reg.	I	G+R	DGNSS NRTK	<1m <3cm	<3m <5cm

SunPOZ		Gov.	Reg.	I	G+R	DGNSS NRTK	<1m <3cm	<3m <5cm
GPSNet		Gov.	Reg.	I	G+R	DGNSS NRTK	<1m <3cm	<3m <5cm
CORSNet NSW		Gov.	Reg.	I	G+R	DGNSS NRTK	<1m <3cm	<3m <5cm
Trimble	VRS Now	VAR	Reg.	I	G+R	DGNSS NRTK	<1m <2.5cm(68%)	
RTKnetwest		VAR	Reg.	I	G+R	DGNSS NRTK	<1m <3cm	<3m <5cm
Smartnet		VAR	Reg.	I	G+R	DGNSS NRTK	<1m <3cm	<3m <5cm
SST GPS		VAR	Reg.	I	G+R	DGNSS NRTK	<1m <3cm	<3m <5cm
AllDayRTK		VAR	Reg.	I	G+R	DGNSS NRTK	<1m <3cm	<3m <5cm
User Owned	RTK	User	Local	UHF, SS, I	G+R+B	RTK	<3cm	<5cm

[1] Type of Provider: Private (Priv.), Research (Res.), Government (Gov.), Value Added Reseller (VAR), User
[2] Area Coverage: Global, Coastal, Regional (Reg), Local
[3] Delivery Method: L-Band, Internet (I), UHF Radio (UHF), Spread Spectrum Radio (SS)
[4] GNSS Constellations: GPS (G), GLONASS (R), Galileo (E), BeiDou (B), QZSS (J)

4. AUTOMATED MACHINE GUIDANCE APPLICATIONS

Providing a position and navigation solution for machines in construction, agriculture and mining is an ongoing research and development area and has been a growing commercial application for GNSS in recent years. Initial applications in the late 1990s provided machine operators with the localization and navigation parameters to perform a given guidance task, additional examples such as tele-remote operated and fully autonomous robots are discussed in Billingsley et al. 2008; Corke et al. 2008. Automation in the construction industry particularly is focused on automating processes and equipment by applying principles of industrial automation to the construction sector with the aims of improving productivity, safety, quality and reducing costs (Saidi et al. 2008).

One of the most interesting areas of applied research in automation and robotics has been the development of Automated Machine Guidance & Control which has benefited from two enabling technologies; high accuracy GNSS navigation using RTK and the use of CAD and Digital Terrain Models (DTM) in the design, engineering and construction phases. In the field of robotics, the terms guidance and control apply to the localization and motion control of machines to a specified path and more specifically for heavy machinery used in construction and agriculture, the term Automated Machine Guidance (AMG) implies an operator is given localization and navigation parameters to perform a given task while manually controlling the machine or implement. Conversely, the term Automated Machine Control (AMC) applies to the full control of the machine or implements without operator input by integrating the guidance and machine's control systems. Some tasks only require the blade or implement to be controlled while the operator is in charge of steering and driving.

The benefits of AMC have been studied in Australia by (ACIL Allen Consulting 2013) demonstrating that machine control in the construction sector can deliver up to a 20% reduction of projects costs with potential for improvement. The elementary processes of construction where

AMC has a main presence are excavation, trenching, bulk earthmoving, grading, trimming, compacting, and paving. These tasks have varying requirements for accuracy but there is a general emphasis on vertical accuracy and control (<5cm).

Machine controlled equipment use monitors inside the cab that allow the operators to visualise the 3D design and change parameter for controlling the machine in software designed for each machine application. Excavators can use 2D laser guidance systems (to indicate elevation and slope) which give operators the elevation information to manually excavate, grade slopes and trench to a simple design level. Full 3D systems use GNSS to show operators the location of the bucket in relation to a 3D design model and perform excavation tasks with more complex designs.

Bulk earthmoving and grading using scrapers, dozers and graders use a combination of sensors with 2D or 3D guidance systems where laser receivers or GNSS antennas are pole-mounted on the blade or implement. The position of the machine and blade is shown to the operator in reference to the 3D design who manually controls the blade (for guidance only systems) or has the control system move the blade to design level automatically (for automatic control systems).

Figure 1. (a) Control screen of an excavator machine control system. (b) Excavator with 3D-GPS system. (c) Dozer with 3D-GPS system. (Position Partners 2015)

The last three construction applications previously mentioned, trimming/fine grading and paving, have higher positioning accuracy requirements (<2cm) that cannot be performed by machine control with GNSS alone and they require complementary sensing methods (Robotic Total Station, laser, INS, tilt sensors, ultrasonic) to provide an accurate solution.


Figure 2. (a) Motor-grader using automatic blade control with Robotic Total Station for fine grading. (b) Tracked Paver controlled by GNSS and Millimeter GPS laser system. (Position Partners 2015)

While not all construction machines need to be accurately controlled, there is an increasing focus on real-time asset tracking of equipment/personnel and collision detection systems to prevent accidents and improve safety. Construction sites are busy, dynamic environments with heavy equipment, trucks and workers with varying levels of engagement (project owners, equipment sub-contractors, delivery drivers) sharing the same space and asset tracking uses autonomous and differential GNSS along with RFID tags to warn drivers of potential collisions with other equipment/personnel.

Future trends in research for machine automation and robotics look to implement semi-automatic construction machines (Vähä et al. 2013) and fully-automated machines for agriculture tasks (Edan et al. 2009) while integrating them with real-time telematics, and information workflows in *smart construction sites* (Kuenzel et al. 2015) and precision agriculture systems (Whelan 2007). In the commercial environment, heavy equipment manufacturers (Komatsu, CAT, John Deere) are moving from retro-fitted after-market systems from machine control providers (Topcon, Trimble, Leica) towards factory integration of machine control systems for semi-automated machines with the integration of various sensing technologies (Bennink 2015).

5. USER REQUIREMENTS

A broad requirements framework for navigation purposes from several user perspectives has been specified in the US Federal Radionavigation Plan while different industries define requirements of navigation systems to establish interoperability and safety of life standards. Examples of this are in the aviation sector in the International Civil Aviation Organization's (ICAO) Required Navigation Performance (RNP) Manual and similarly for Intelligent Transport Systems where RNP standards are currently being proposed.

A study on delivering positioning services in regional Queensland was proposed by the CRCSI and user requirement parameters for positioning and navigation were defined as: accuracy, initialisation, repeatability, availability, integrity, timeliness, continuity and reliability (Feng et al. 2009). These navigation parameters should be included as requirements for civil construction applications using machine guidance.

The civil construction industry has no standardised requirements for machine control in Australia and it is difficult to implement standards for positioning applications given the dynamic nature of large scale civil project environments, but as machine control becomes increasingly common, road authorities, project owners and construction contractors have started to implement specifications for the use of this technology in construction projects. Some Department of Transport (DOTs) in the US have studied the application of AMG to improve automation in the construction workflow and proposed requirements for construction. The Iowa DOT published a set of best practice rules in an implementation manual for 3D modelling and AMC and (Hammad et al. 2012) reviewed the state of practice of AMG in this and various other DOTs in the US.

In Australia, each state publishes its own specifications manual for road construction projects and local councils have their own requirements for civil works. In the case of the state of Queensland, the Department of Transport and Main Roads specifies the construction tolerances (State of Queensland 2014) for road projects in Table 2.

Table 2. Summary of Construction Tolerances

Application	Minimum Tolerance (95%)	
	Horizontal	Vertical
Clearing and Grubbing (MRTS04)	100cm	
Excavation (MRTS04)	5cm	2.5cm
Bulk Earthworks (MRTS04)	5cm	2.5cm
Fine Grading of Unbound Pavement surfaces (MRTS05)	5cm	1.5cm
Fine Grading of Insitu Stabilised subgrades using Quicklime or Hydrated Lime (MRTS07A)	5cm	1.5cm
Fine Grading of Insitu Stabilised pavement using Foamed Bitumen (MRTS07C)	5cm	-0.5 to 1.0cm

It is important to note that as the civil construction industry requires AMG as mandatory for equipment working in projects, there is a need to define standards in the performance of positioning services for AMG to ensure construction tolerances are met. In the example of MRTS04 specifications, the bulk earthworks 95% vertical tolerance of 2.5cm is achievable with RTK machine control under ideal conditions, but presents a problem in obstructed environments and at longer baseline distances. Equipment sub-contractors, surveyors and engineers should be aware of this limitation and make decisions to implement additional positioning technologies when higher accuracy is required.

CONCLUSIONS AND FUTURE WORK

PPP can deliver a precise solution through satellite link in remote areas without relying on base station which is why its application is well established in marine positioning and precision agriculture, however in the civil construction industry, the preferred positioning technique for machine automation is RTK. One of the main factors for RTK's growth in construction is the cm-level solution it offers but as new services become available extending the performance of PPP with the addition of multi-frequency, multi-constellation, INS integration, ambiguity resolution and fast convergence times, it is feasible to apply these techniques to certain tasks in the civil construction sector including automated machine guidance and control.

In recent years, several commercial services have expanded offerings of high accuracy PPP solutions through satellite L-Band and Internet and users now have a wide range of positioning services to choose from, adding to existing conventional RTK and NRTK services. In an effort to standardize GNSS positioning services and end-user requirements for automated machine guidance applications, this work presented a summary of available services in Australia and studied the current state of machine guidance requirements in the civil construction industry.

Automated machine guidance and control is a growing application of GNSS, nevertheless, there are applications with <2cm vertical accuracy tolerances (fine grading, paving) where GNSS cannot deliver consistent real-time performance that rely on complementary positioning technologies (laser, robotic total station, INS, ultrasonic) that replace or enhance GNSS.

The realization of a new dynamic datum (Geodetic Datum of Australia 2020) is currently being proposed by the Intergovernmental Committee on Surveying and Mapping (ICSM) as part of Australia's Datum modernisation to, among other factors, enable better integration of geospatial data needed once high accuracy positioning products are established in diverse industry sectors. The use of PPP facilitates the integration into a single dynamic geodetic reference frame in the International Terrestrial Reference Frame (ITRF) and would benefit further geospatial integration in Civil Integrated Management Systems for road construction and Intelligent Transport Systems for road management.

Further work will focus on user-centred studies to capture and standardise requirements in civil construction and evaluate performance of available services for machine automated tasks using RNP parameters proposed for positioning systems in previous research.

ACKNOWLEDGMENTS

This review is part of a Master's by Research project partially supported by the Cooperative Research Centre for Spatial Information (CRCSI), RMIT University and Position Partners.

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BIOGRAPHICAL NOTES

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