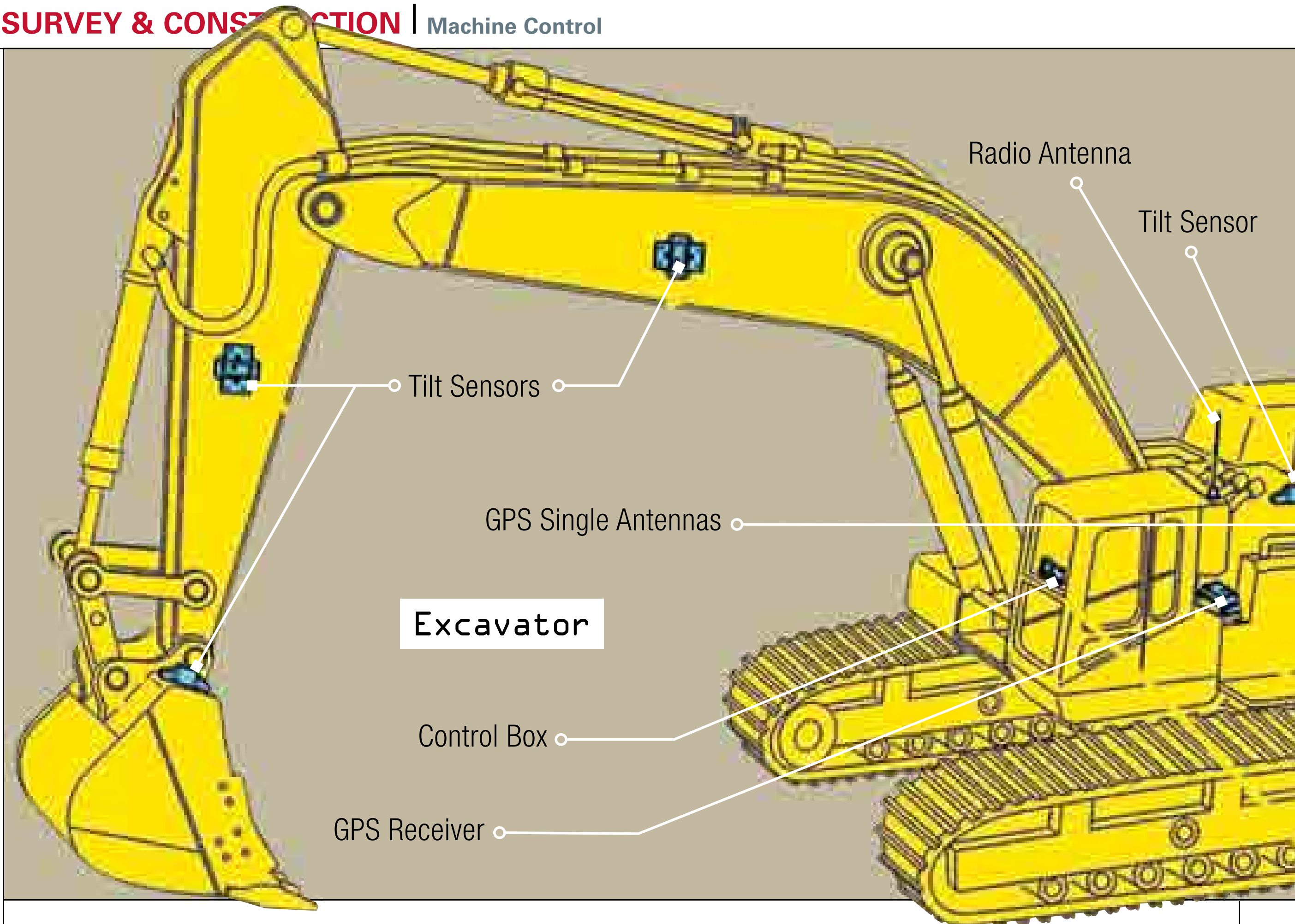

Network Corrections for Machine Control

Network-based real-time kinematic (NRTK) positioning reduces or eliminates the communication, integrity, and affordability problems associated with semi-automated guidance of bulldozers, excavators, and other equipment at centimeter-level accuracy. This new method addresses adequate height control, a crucial factor for machine-control users.

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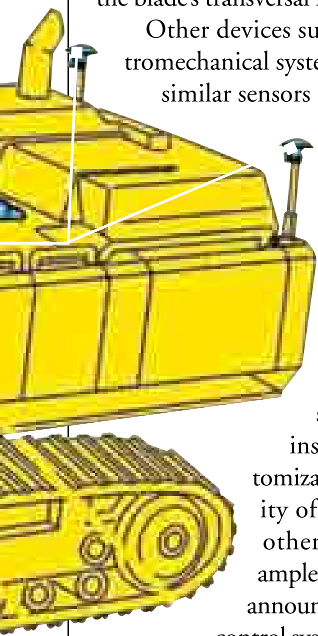
Accuracy improvements and cost reductions in the surveying field have both accelerated rapidly in recent years, driven by changes in work procedures that combine different instruments and techniques. Sensor integration for positioning and precise navigation is the principal innovation responsible for these advances.

This evolution also affects construction, specifically earth-moving machines assisted by GNSS receivers integrated with attitude/tilt sensors. These recently introduced systems continue to undergo new developments, one such described here, as well as study and testing to improve their affordability and performance within the complexity and special circumstances of construction projects.

Currently most companies producing positioning instruments also distribute machine-control systems tailored to the custom requirements and accuracies to be obtained. Such systems are based on satellite positioning and include one or more dual-frequency GNSS receivers. Many of these systems can receive GLONASS as well as GPS signals. Nearing completion as of May 2009, the GLONASS constellation's availability improves the positioning success rate in sites with natural or artificial obstructions.

In bulldozer-type machines, the GNSS antenna is installed on the frontal blade, protected by vibration-damping systems set up in different ways by the manufacturers. These systems must also withstand the high temperatures that can occur during work. A second GNSS antenna measures the blade's transversal inclination.



Other devices such as micro-electromechanical systems (MEMS) and similar sensors also contribute to machine control. Such instruments have many interesting characteristics: large numbers of units produced at low cost, toughness, small size, easy installation and customization, and possibility of integration with other sensors. For example, one company has announced that their next control system for dozers will carry a three-axes MEMS capable of a position and attitude estimation at rates up to 100 Hz. Such a powerful sensor system will further improve productivity of the system and augment the GNSS receiver during poor satellite visibility.

Machines turning around a vertical axis, such as excavators, also carry a second GNSS antenna, as well as two- or three-axes tilt sensors to estimate the inclination of the booms and the position and attitude of the bucket.

Problems and Innovations

The current state of machine control (see **CURRENT BASELINE** sidebar), while representing great advances over traditional building practices, still presents some drawbacks and limitations:

- costs for a base station on each building site (purchase, installation, precise positioning, surveillance);
- necessity of preliminary survey operations for the estimation of a datum transformation between the local datum of the computer-assisted design (CAD) and WGS84, incorporating an adequate number of ground-control points;
- communication problems between base station and the rovers, due to the low radio-modem power permitted by the law in some countries (for example, 1 watt in Italy, limiting the operating range to a few kilometers);
- sites spanning long distances, as in the case of road construction, that require placing and geo-referencing more base stations, or installing radio-repeater devices; and

- affordability and integrity problems for the correction data coming from a single station that require frequent control measures on known points.

To help solve some of these problems, the Department of Civil and Environmental Engineering (DICA) at the University of Perugia conducts research on possible improvements to machine-control systems.

The main avenue we have explored involves permanent networks for the GNSS corrections, which would eliminate the need for one or more base stations in or near the building site. The transmission from the network to the rovers can be effected in two different modes: *direct*, through a GPRS or UMTS modem installed on each rover; or *indirect*, with an intermediate pass on a radio repeater redistributing the corrections all over the building site. This second approach has a consistent advantage over the first one: only one GPRS/UMTS modem is required for any number of machines operating on the site, and it can be placed where the GSM coverage is better.

FIGURE 1 shows the impact of a GNSS permanent network on the organization of the machine-control system. Under the current system architecture, each building site operates with a connection to its own local base station. Figure 1 shows the future set-up utilizing a permanent network, in this case the GNSS network in Umbria, Italy: an unlimited number of

▲ **FIGURE 1** Future proposed organization: all building sites get RTCM corrections from the network Ntrip caster

Current Baseline

The use of real-time kinematic (RTK) and network RTK (NRTK) techniques enable such systems to reach accuracies less than 5 centimeters, but some applications, for example road paving, require even better performances, on the order of a few millimeters. In such cases, laser or ultrasonic levels are installed at the building site, to furnish height determinations with a sub-centimetric accuracy for distances up to hundreds of meters, for an unlimited number of receivers.

The main element of any machine-control system consists of one or more GNSS receivers installed on the machine. A fixed GNSS station installed in or near the building site sends RTK corrections via radio modem to all GNSS rovers operating inside the transmission range. The rovers are installed on machines or carried by operators for tracking and control purposes. A differential technique with code and phase corrections estimates the rover position, reaching accuracies equal or better than 5 centimeters.

The system estimates in real time the plano-altimetric position of the rover. Other sensors, if present, can improve the height accuracy and enable determination of other components of movement, position, and attitude of the excavating blade or bucket, after a brief one-time calibration procedure.

An onboard computer, previously loaded with a digital terrain model (DTM) of the site, processes all data acquired by the sensors. Thus, the machine operator can visualize at any moment the difference between the actual ground surface and the intended design.

In most cases, the system is also connected to the machine's hydraulic control system, so that software automatically commands the movement of the booms or blade. The driver only has to control the excavation result and follow the design plot, assisted by the displayed information: machine position, excavation or filling height, ground slope, cross section, and so on.

Introduction of such machine control has considerably improved the accuracy of earth movement, reducing times and costs. Advantages include:

- complete elimination of costs for preliminary survey phase and for the tracking during excavation (more office work required for design and DTM elaboration and loading, but this is offset by a more accurate data provision);
- direct transition from the design to execution phase, eliminating intermediate passes, with a consistent reduction of time, cost, and potential errors;
- better involvement and efficiency of the machine operators, who control project execution in real time on their display;
- consistent improvement in project accuracy, reducing waste of material, energy, and time;
- on-site technicians controlling the work in a very fast and affordable way by means of the same RTK corrections;
- most machine-control systems, even the newest releases, fully or nearly turn-key, easy to learn and understand by the operators after a quick calibration phase;
- damages to underground cables and pipes avoided if the design drawings includes their position and depth.

▲ **FIGURE 2** GPSUMBRIA network

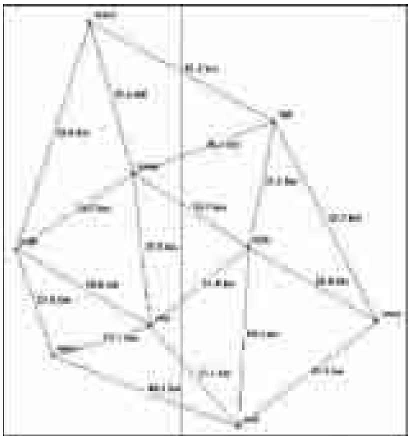
▲ **FIGURE 3** LABTOPO network

operating machines in different building sites work simultaneously and independently, all connected to the permanent network without local base stations.

Networks. The DICA operates two permanent networks:

- GPSUMBRIA, the official GNSS network of the Umbria Region, central Italy, offers both post-processing and real-time positioning services. It comprises 10 stations (two more are scheduled in the next few months), covering the region (**FIGURE 2**). More information about the network and its data (freely available at the moment) is at *www.gpsumbria.it.*
- LABTOPO, a regional network set up for research purposes, is putting together a bundle of GNSS permanent stations of different operators (universities, schools, public administrations, and private companies). It includes 21 stations over a wide area in central Italy from Rimini to Rome (**FIGURE 3**), and offers only post-processing services. See *http://labtopo.ing.unipg.it/labtopo/index.php.*

The monumentation of the stations of both networks is very stable: all GPSUMBRIA stations match the IAG Reference Frame Sub-Commission for Europe (EUREF) and International GNSS Service prescriptions, and most LABTOPO stations are set up with equivalent characteristics. Two GPSUMBRIA stations (UNPG Perugia and UNTR Terni) form



▲ **FIGURE 4** GPSUMBRIA real-time network

part of the European Permanent Network and the EUREF-IP real-time project.

All stations are equipped with GPS-GLONASS geodetic receivers. Most have choke-ring antennas; all GPSUMBRIA antennas are individually calibrated.

All data of both networks are submitted to an automatic quality-control procedure and then distributed to the scientific and technical community through the websites mentioned, in the form of daily or hourly RINEX files at sampling rates of 30, 5, and 1 seconds, to be used for post-processing applications, enabling users to achieve position accuracies down to a few millimeters.

Post-processing data are currently provided free in order to promote their use, but such distribution policy might change in the future, for example requiring a fee for the 1-second files.

The GPSUMBRIA network also supplies real-time positioning services (network code corrections or NDGPS, and network phase corrections or NRTK) to registered users. Registration is currently free because the real-time services are still in a promotional phase; such policy will likely change to a fully operational phase in the future. **FIGURE 4** shows the real-time network.

Phase corrections are transmitted to the users in virtual reference station (VRS) or Flächen Korrektur Parameters (FKP) modes, using the RTCM 2.3 format (correction types 18, 19 or 20, 21). Code corrections are given in RTCM 2.0 format. Users can receive the corrections through a direct connection to a stack of GSM modems set up at the network control center or through our recommended approach, the network Ntrip caster.

The real-time software performs a continuous computation of the network, which besides its primary function (ambiguities and biases computation) constitutes a powerful instrument for network analysis and control.

Network Corrections Tests

Trovati S.n.c., a building and earth-moving company of Perugia, recently acquired two machine-control systems, installed on a dozer and an excavator. The dozer carries a system including a dual-frequency GPS-GLONASS receiver, with antenna mounted on a vibration-damping rod located at the center of the excavating blade. A mono-axial tilt sensor estimates the transversal attitude of the blade. The equipment also includes a control box, an onboard computer with LCD screen, and a radio modem receiving the RTCM correction from the base station (see **FIGURE 5**).

▲ **FIGURE 5** Dozer installation

The excavator has been fitted with a system composed of two GNSS antennas and five two-axes gravitational sensors mounted on the three booms of the excavating machine, plus one on the bucket and one on the machine body. The system includes an onboard computer with touch-screen control panel and a control box including the GNSS receiver, connected to a radio modem.

Both machines carry an oleo-dynamic group actuating the blade movement and

▲ **FIGURE 6** Test with NRTK corrections: left, the design plot; right, a planimetric representation of the differences in meters measured between the designed and the initial survey

an electronic control system connected to the control box.

Standard operating procedure requires in a preliminary phase the selection of a ground point to place the GNSS base station. Its WGS84 position can be obtained by means of a rapid-static or RTK GNSS survey, using the post-processing or real-time data of a permanent network, or connecting the station to some known points, such as vertexes of the Italian Geodetic Network IGM95.

To make the procedure easier for operators lacking knowledge on the reference systems, the base station is often georeferenced in an approximate way (for example, by a simple point-positioning through pseudorange) with the condition that the monumentation and the assigned coordinates (we can call them "pseudo-WGS84") do not change from one day to another.

Using the phase corrections from the base stations, the pseudo-WGS84 coordinates of a series of ground control points are determined by means of an RTK local survey. This way, the control points have a double set of coordinates: the pseudo-WGS84 and the local ones extracted from the design CAD drawings.

The system manufacturer's software estimates a set of transformation parameters between pseudo-WGS84 and the local system. From then on, the operator works in the local system, following the design digital terrain model (DTM) and drawings loaded on the PC and visible on the screen. The machine position, computed in RTK mode in the pseudo-WGS84 datum, is automatically converted by the software into the local system.

With this operating mode, there is an error due to the roughly approximate position of the base station. However, such error has no influence on the work if the base station position does not change in time. If the base has to be moved for any reason, the initialization procedure must be repeated, including a new parameter estimation.

We selected a test area and surveyed it with the GNSS NRTK technique, using VRS corrections from the GPSUMBRIA permanent network and producing an accurate local DTM. We set up a sample design of a road track (**FIGURE 6**) for testing purposes, including a straight part and a 15-meter-radius curve, for a total length of about 100 meters. We exaggerated the transversal slope of the test road (10 percent, more than the values

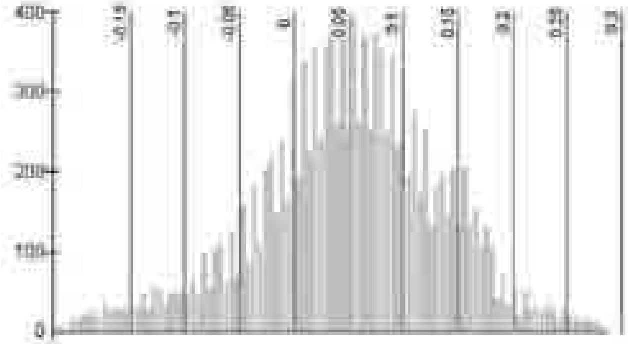
▲ **FIGURE 7** Supplementary equipment for the test

normally allowed) for a better testing of the dozer blade-control system.

To apply the innovative use of the GNSS permanent network, it was necessary to partially modify the machine-control system, which is a closed system, a limit due to its turnkey philosophy. Following the *indirect* method described earlier, we supplemented the system with a small hardware component capable of receiving NRTK corrections through an internal GPRS modem, and redistributing them over the building site by means of a radio modem. The adopted device also includes a basic GPS receiver (code-only, 20 channels) that computes an approximate position by means of the pseudoranges and sends a NMEA message to the permanent network control center (necessary when operating in the VRS mode). The supplementary device configuration is easily done by sending it an SMS code (**FIGURE 7**).

We encountered some practical problems during the tests: a poor GSM coverage over the test area, and some interference on radio transmission. Both were easily solved, the first by changing the supplementary device's location and the GSM operator, the second by changing the frequency on the radio modem.

A further problem concerned the data stream (VRS or FKP corrections in RTCM 2.3. format) transmitted by the GPSUMBRIA network caster. The bit-rate normally given by the technical literature for VRS corrections is about 600 bits per second (bps) for each satellite. During the test, the number of available satellite increased to 14 (GPS + GLONASS), with a total bit rate of 8400 bps. Adding some other data exchanged between the caster and the rover, the bandwidth available on the radio modem (9600 bps) was fully occupied.



▲ **FIGURE 8** Distribution of the height differences between design DTM and execution (meters)

A further increase in the number of satellites available once GLONASS reaches its full operational phase would make things even more difficult in the future. A possible solution is the adoption of the Compact Measurement Record (CMR) format, a standard protocol for reducing the bit rate, usable with any brand of receiver. A CMR bit rate can be estimated as follows:

$$Bytes/s = 6 + N \cdot [8 + (Freq - 1) \cdot 7]$$

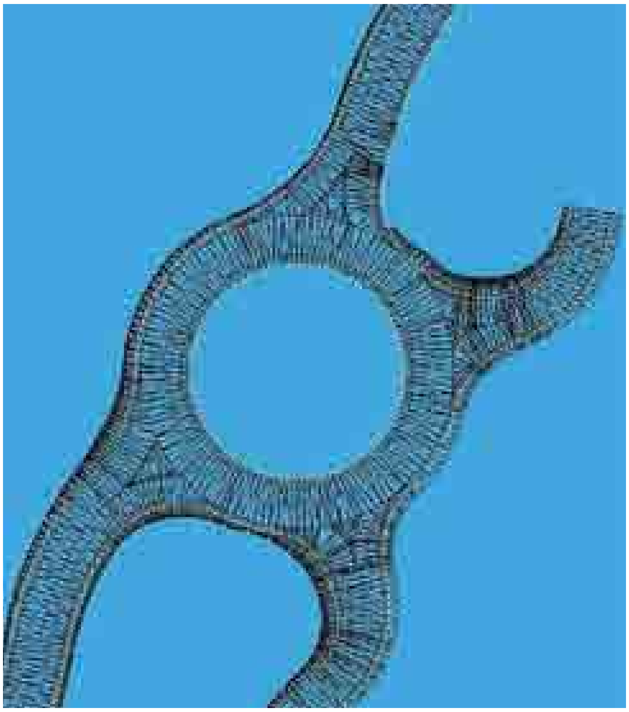
where N is the number of available satellites (GPS + GLONASS) and *Freq* the frequencies (1 for single, 2 for double). In the case of our test (14 satellites), the result is 216 bytes per second, thus 1728 bps. Even adding other message parts necessary to transfer supplementary information about the reference station and its coordinates (about 500 bps every 10 seconds), the 9600 bps limit seems sufficient.

A further possibility is given by the definition of a data stream in the RTCM 3.0 format. A data stream of about 200 bps is estimated for each satellite in the type 1004 message, while the 1003 is about 50 bps smaller. The 1004 or 1003 types only contain GPS observations, but similar evaluations can be made for the 1012 or 1011 types used for GLONASS. Referring once more to the test situation (14 satellites), a stream data of about 2800 bps can be estimated, which is about one third of the RTCM 2.3 value. The manufacturer's support documentation, where a baud rate of 2742 bps is evaluated with 12 satellites for a RTCM 3.0 VRS correction, confirms this.

We carried out the first test using the classic RTCM 2.3 format transmitting VRS and FKP corrections. The limited bandwidth provoked a periodic bottleneck effect in radio data transmission, thus the dozer partially operated without differential corrections.

After the dozer had completed its earth-moving job, a new GNSS survey (NRTK VRS) checked the correspondence between the execution and the design DTM. The mean value of the differences between the two DTMs (shown in **FIGURE 8**) is about 5 centimeters, with standard deviation of 8 centimeters.

Note that a survey performed after the "skinning" phase of the ground is subject to a few centimeters uncertainty, because



▲ **FIGURE 9** Design DTM for the second test

▲ **CONTROL SURVEY** for the second test

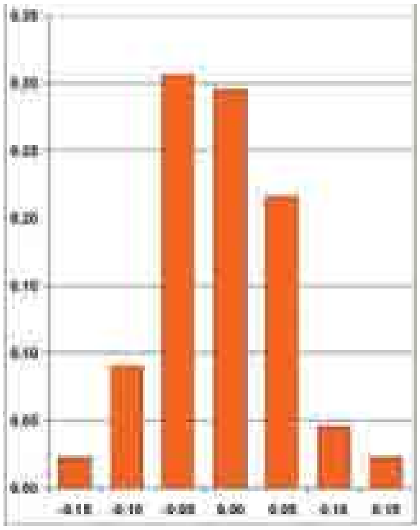
the surface is irregular and the survey shaft tends to sink into the ground. Adding to this the uncertainties of the NRTK survey (about 5 centimeters), and considering the aforementioned difficulties given by the radio bandwidth in relation to the data stream, the test result can be considered successful.

Improvements. To fix the main problem concerning the radio modem bandwidth encountered during the test, the GPSUMBRIA real-time positioning service was improved by introduction of a new data stream in CMR format, accessible through Ntrip. We subsequently performed a second test on a real building site, relative to the realization of a new road track near Perugia, including a traffic roundabout (**FIGURE 9**).

Besides a dozer (the same as the first test), an excavator and a grader were also used. The equipment installed on the grader is the same as that of the dozer: it can be easily transferred from one machine to another by appropriately setting the pre-calculated calibration parameters.

The second test, performed with CMR corrections received from GPSUMBRIA through the supplementary device, shows a regular and continuous operation of the system in NRTK mode. The GSM coverage over the building site, in a suburban area, is very good. In any event, the adoption of the CMR format completely fixed the problem related to the limited bandwidth of the radio modem, even with a great number of available satellites (from 13 to 15 during the test).

To verify the accuracy of the GNSS-controlled machine work (besides the earth movements, the creation of a lime-stabilized ground), a control survey was performed with an handheld rover on a sample of about 100 ground surface points, plus some markers set up for control purposes. A comparison between the design DTM and the surveyed heights is summarized by **FIGURE 10** and **TABLE 1**. The results can be considered acceptable given the rough surface of the ground at the present intermediate phase of the work, before laying down the paving layers. A final check will be performed on the finished asphalt paving. Referring to our earlier research on network phase corrections, an accuracy of about 5



▲ **FIGURE 10** Frequency distribution of the height differences (meters) between design DTM and control survey

Mean	-0.006
Median	-0.012
Max	-0.140
Min	-0.142
RMS	-0.059

▲ **TABLE 1** Statistical data summary referring to the histogram of Figure 10. Values in meters.

centimeters is to be expected as a routine result.

During the roundabout test, we performed a further test, shown in **FIGURE 11**: we determined the 3D position of some control points with the central tooth of the excavator bucket, to test the affordability of the "cinematic chain" going from the two GPS antennas to the bucket through the five tilt meters mounted respectively on the machine body, the three booms, and the bucket itself. The control-point coordinates match at a few centimeters level, confirming once more the good calibration of the system — a rough but effective test.

The Trovati company is completing the roundabout building with the NRTK technique and has adopted the technique as a routine method for their future work.

Future Developments

The tests described here evaluate the potential of using real-time positioning services supplied by a GNSS permanent network for machine-control applications. Use of the supplementary device distributing the corrections over the building area has shown some points of weakness connected with the radio transmission: interferences, limited range, limited bandwidth. Most problems can be fixed, as we have shown, and the experimented technique also has demonstrated obvious benefits:

- elimination of the local base station (one for each building site), with a sensible cost reduction;
- possibility of using a theoretically unlimited number of GNSS-controlled machines in any building area covered by the permanent network;
- reduction of the costs connected with preliminary survey operations;
- improvement of the accuracy and affordability of the machine positioning, in other words of the integrity of the process, thanks to the better performances of NRTK versus RTK;
- use of a global reference system, controlled and monitored by the network, rather than a "pseudo WGS84" system;
- availability of quality control procedures more effective and simple than those currently in use, with possibilities of quality certification.

At present, the use of the supplementary device appears to be a convenient solution to send corrections to the machines operating in a building site. The alternative (installation of a GPRS or UMTS modem on each machine and/or surveying rover) is expensive due to the cost of the GSM services, and can also represent a source of problems if the GSM coverage is not very good over the whole building area. An advantage of the device-based solution is the possibility of moving it to wherever the GSM signal is best. Further tests are still necessary to pass from the prototype to the standard application of the method, in order to satisfy the turnkey operability request.

Precision farming practices can benefit from the same advantages of the GNSS

▲ **FIGURE 11** Excavator bucket test

control supported by a permanent network listed earlier. This is particularly true for the most accuracy-dependent agricultural applications, currently using the base-rover approach with a fixed station, which could be eliminated.

Other farming applications require a lower accuracy and are based on code-differential corrections transmitted by geostationary satellites. An alternative could be obtained receiving the code RTCM by a permanent network, which would permit the use of low-cost receivers. Other testing that we have conducted shows that submetric accuracies are possible to reach with relatively low investments.

Acknowledgments

We thank the Trovati and Geotop companies for collaboration on this research.

Manufacturers

All GPSUMBRIA and LABTOPO stations are equipped with **Topcon** GPS-GLONASS geodetic receivers (*www.topcon.com*). Real-time functionality of GPSUMBRIA is achieved through *GNSMART* software by **Geo++** *(www.geopp.de)*. The dozer (CAT D6M) carries a Topcon 3DMC system, and the excavator (CAT 320CS) a Topcon 3DXi system. The system was supplemented with the *SmallTRIP* produced by **Smalltouch Aps** (*www.smalltouch.com*). The CMR protocol was introduced by **Trimble** (*www.trimble.com*).