Tech Brief

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STRINGLESS PAVING

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INTRODUCTION

String lines have traditionally been used to control paving machine elevation and steering on the grade. Stringless paving (sometimes referred to as "3-D paving") is the process of constructing a pavement using non-contact, electronic guidance systems to guide the paver along the grade without the aid of string lines. Stringless paving allows contractors to eliminate hubs, pins, sensors or wands, clamps, and string lines (wires, cables, rope, etc.). This can produce significant savings of time and labor for establishing and maintaining the string line system, the elimination of stringline-related tripping hazards, and reductions in the required width of operating space for the paver. Additionally, stringless paving offers the potential for more accurate, smoother paving, especially in tight horizontal and vertical curves where stringlines can only simulate a smooth curve using straight line segments.

The technology used in stringless paving was originally developed for earthwork applications in the 1990s and used a combination of global positioning sensors and lasers. These applications were an ideal proving ground for the technology because earthwork tolerances are generally not as tight as in paving. The first successful stringless slip-formed curb-and-gutter project was reported in 1999, followed within a few months by the first roadway in early 2000. Several airport contractors applied the technology to airfield projects in 2001 and the first highway project was paved in Belgium in 2003. Manufacturers have continued to refine the technology with contractor input and more project experience. Stringless paving is now a time-tested technology that has been used successfully for more than a decade. Stringless machine control is still used today in many earthwork applications such as excavation, grading, compaction, trimming, and other subgrade preparation operations.

There are three basic steps involved in using stringless paving: 1) development of the pavement surface model(s), 2) transfer of the model to the paver's on-board computer for use in paving, and 3) establishment of survey control points for paver operation.

The process for developing the pavement surface model(s) depends on the type of project. For construction along a new alignment or for design-bid-build pavement reconstruction, the owner-agency typically provides the contractor electronic plans with a proposed final surface model (and an existing surface model for reconstruction projects). The contractor applies typical digital cross-sections to the surface models to produce the digital paving model (and earthwork, subgrade and subbase surface models, if applicable).

For concrete overlays and design-build pavement reconstruction projects, the contractor must collect and process "x-y-z" (three-dimensional) survey data of the area of interest. Automated data collection, using the global positioning system (GPS) or light detection and ranging (LIDAR), are typically used. These data are used to create a three-dimensional digital computer model of the existing surface. The pavement is then designed, and three-dimensional digital computer models of the proposed pavement profile and cross sections are created using commonly available computer-aided design (CAD) technology.

In either case, the paving model is typically simplified and processed to only include information or inputs that are essential for paving machine control. The simplified model is then transferred to the paving machine's on-board computer.

Finally, a series of survey control points must be established along the project to serve as references for the instruments that communicate with the paving machine. The control points must be tied into permanent benchmarks. Paving is then performed using these control points and a series of total stations and/or GPS controls and lasers to help guide the machine's position.

COMPARING STRING LINE AND STRINGLESS PAVING PROCESSES AND RESULTS

The relative benefits and costs of stringless paving systems become apparent when comparing the paving processes and results obtained with those of string-controlled systems.

Establishing the Control Network

Both string line and stringless systems require establishing a network of control points that are tied into fixed benchmarks. For string line systems, the key control points are paving hubs (or pins) placed at spacings of up to 50 ft (15 m) in areas where the pavement profile and alignment have little or no curve and at more frequent intervals where vertical and horizontal curves will be constructed. A survey crew must transfer the Engineer's design profile and cross section to the hubs or pins. With stringless paving, fewer control points are needed—they may be as far as 2 mi (3.1 km) apart with the distance between points depending on the system used, the surrounding terrain, and the required accuracy of input for paver control. Therefore, stringless paving reduces field survey time and the opportunity for survey errors that can translate into paving errors and roughness.

Differences in Paving Operations

Operating Space

A string-controlled paving operation requires clearance on each side of the machine for machine tracks, worker access, hubs and string line stakes, and safety devices (see figure 1). By eliminating the need for hubs and string line stakes, stringless paving systems typically reduce side clearance requirements to 2-3 ft (0.7 – 1m) and sometimes to as little as 1 ft (0.3 m) when used with special paver and safety device setups. This adds flexibility for concrete paving in tight areas in urban areas and other places where space is limited. In addition, stringless operations facilitate easy and safe access to slip-form sites for crews and trucks by eliminating the string line "barrier."

Figure 1. Operating space requirements for conventional paving (ACPA 2013).

Maintenance of System Control

String lines are a key control for pavement quality and smoothness in string-controlled systems, but they are constantly exposed to potential damage and disturbance during all phases of construction (especially when they are moved for different operations or are temporarily taken down to allow equipment onto the grade). The accuracy of control that they provide is also affected by expansion and contraction of the "strings" (often metal cables or similar devices) with changes in temperature. String lines must, therefore, be maintained (inspected and corrected for alignment and tension/sag) frequently prior to and during construction.

Stringless paving eliminates all of these concerns by requiring the maintenance of far fewer control points (which are generally located away from the construction site and are subject to less potential for disturbance, as is discussed later). This reduces construction costs while offering the potential for improved paving quality.

Differences in Machine Control

One of the most significant benefits offered by stringless paving is the potential for improved machine control because the process places the engineer's design directly into the machines, thereby avoiding string line errors that must be corrected on the grade. In addition, stringless technology also helps control paving height, cross-slope and crown while steering the machines *on a continual basis* rather than through the segmented chords that are necessary in string line-controlled paving. Thus, the machine follows the true lines and curves (both vertical and horizontal) of the designed model in all three dimensions.

There are several potential machine control problems that are inherent with string-controlled technology, such as string line sag due to hot weather line expansion, paving bumps caused by improperly tensioned string line sensors and sensors catching on string line knots or splices, and paving deviations caused by crew adjustments to sensor controls. Stringless paving eliminates these potential problems and helps contractors to place a more precisely-controlled, smoother pavement (often with reduced yield loss).

Job Site Access and Safety

Stringless construction technology can also enhance safety on the grade by reducing or eliminating trip hazards associated with people coming in contact with hubs, stakes, and the string itself. It also improves or eases access to the grade in front of the paving machine, reducing choke points and some of the dangers associated with batch delivery vehicles backing up to the paving site.

Contractor Costs and Savings with Implementing Stringless Construction Systems

Establishing and maintaining a traditional string line guidance system is costly and time-consuming. Up to three separate survey circuits (beyond the original survey) must be performed: 1) setting paving pins or hubs at precise locations; 2) obtaining elevation shots on each hub for comparison with the design elevation; and 3) writing the cut or fill to final grade on the stake so that string height can be properly set. Accomplishing these tasks can require 1 – 4 working days per mile (Cable and Walters 2009, after Angelo 1999 and Means 2005). The total cost of establishing a string line has been estimated at $0.35 to $1.00 per foot (Angelo, 1999). In addition, the time required to establish a string line system can be several weeks for a paving project of moderate length (i.e., 3 – 6 miles) (Cable and Walters, 2009). The use of stringless paving systems can eliminate these costs, but there are offsetting stringless system implementation costs to consider as well.

Contractors must invest capital in new paving systems that feature stringless technology or must retrofit stringless technology on existing paving equipment. They must also invest in special instruments for control points (as discussed later). Contractor training is also essential so that all key personnel develop a complete understanding of the systems they will be working with, including an understanding of survey requirements, development of 3D digital surface and design models, line of sight requirements for the field instruments, and an understanding of weather and environmental considerations for total stations, lasers and GPS. There is also a learning curve in implementing the technology.

Most of these costs (including for training) can be considered "one-time" capital investments that will be recovered with repeated operational cost savings (and possibly paving quality incentive payments) in the long view, but they can still be daunting.

Owner/Agency Implementation of Stringless Construction Systems

Owners/agencies who accept stringless construction technology may need to modify current planning, design, and letting procedures (along with project specifications) to allow contractors to use this option. For example, it may be advantageous for the owner/agency to providing CAD files with the project plans for the contractor's use in creating digital 3D surface models.

Project engineers and inspectors must also be educated in the use of stringless construction technology. Because stringless technology does not provide an on-site visual reference for the pavement surface (as does the use of string lines), owners/agencies and their staff need to be capable of checking the 3D surface models and independently verifying the control points and finished surface (x-y-z coordinates). This requires additional training and equipment.

Owner/Agency Benefits from Stringless Paving

When properly implemented, stringless paving provides concrete pavements with better ride quality and more accurate profile and cross slopes, resulting in safer highways and roadways. More consistent pavement layer thicknesses also mean more consistent long-term pavement performance. Finally, the use of stringless systems should result in lower overall agency paving costs because of the reduced need for surveyors prior to and during paving operations.

FUNDAMENTALS OF MACHINE CONTROL

The Machine Component

Machine control concerns the overall positioning and movement of the paving machine in all three dimensions (i.e., x, y, and z), as well as control of the machine's "attitude" on the grade.

The three basic machine movements are: 1) movement along the grade in the direction of the pavement centerline, 2) movement laterally (perpendicular) with respect to the pavement centerline, and 3) vertical movements that change the elevation of the paving machine relative to the grade. Machine attitude is described in terms of three factors: heading, cross-fall, and main-fall, which all relate to the angles of the machine relative to the grade and/or desired profile of the pavement (see figure 2):

- Heading (also called "yaw") is the degree of rotation of the paving machine about a vertical axis and between the longitudinal axis of the machine and the steering reference line.
- Cross-fall (also called "roll") is the cross-slope control. Changes in cross-fall are monitored by a machine-mounted sensor.
- Main-fall (also called "pitch") is forward or backward slope of the paver relative to the grade. Changes in main-fall are also monitored by a machine-mounted sensor.

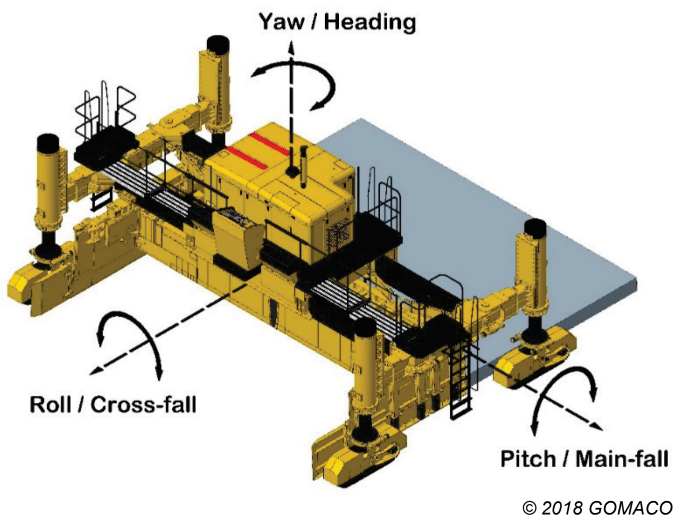

Figure 2. Schematic showing three components of paving machine attitude.

In conventional, string line-guided paving or paving "locked to grade," these movements are controlled by a machine operator. In stringless paving, these movements are controlled automatically in response to paving conditions and changes in the design surface model that is imported into the paving machine's on-board computer (although there may be a tendency for some operators to make minor adjustments while paving).

To better understand machine control and its impact on paving, it is important to know and understand the functions of the following basic slip-form paving machine components (see figure 3):

- The auger or plow, which distributes the concrete in front of the machine.
- The strike off plate, which controls the quantity of concrete being fed through the machine.
- The vibrators that "fluidize" and consolidate the concrete.
- The tamper, which meters the concrete ahead of the profile pan.
- The profile pan and side forms (also known as the slip-form mold), which extrude the concrete pavement.

Machine controls affect the positions of these critical paving machine components, especially the profile pan, which alters the shape and position of the extruded concrete pavement. For instance, machine pitch (forward or backward slope relative to the grade) influences the pressure exerted on the concrete as it goes through the profile pan and side forms. Quality construction requires accurate positioning and attitude control of the paving machine.

The Human Component

Slip-form paving system position and attitude adjustments are typically hydraulically driven. In a string line-controlled operation, the hydraulics react to changes in the position of sensing wands that contact the string line. In a stringless operation, the hydraulics are adjusted by commands from the on-board system computer, which is monitoring indications of the paver x, y, and z position (obtained from the control point instruments) relative to where the paver should be in accordance with the digital pavement model. In either case, the paver operator controls the forward speed of the machine (including machine stops and starts).

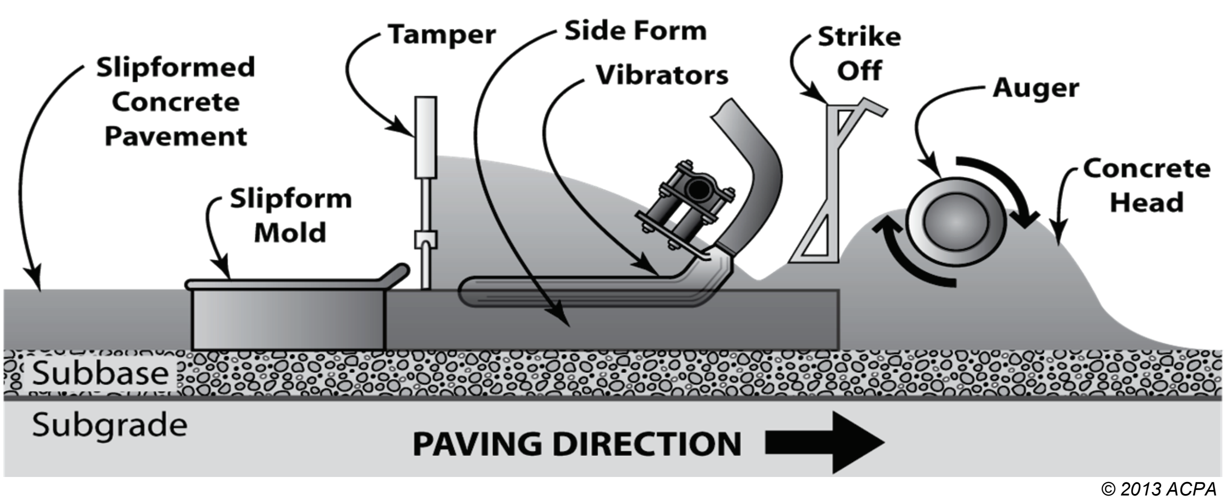

Figure 3. Slip-form paving machine component schematic (ACPA 2013).

Stringless systems are not a substitute for good paving practices. The fundamentals of good paving practice apply to both stringless and conventional string line-controlled paving, including (but not limited to):

- The use of good quality concrete with well-graded aggregates and consistency in all aspects of the concrete production and delivery operations are essential quality pavement construction components.
- A consistent and appropriate head of concrete must be maintained in front of the machine. Too much concrete may create a pressure surge under the paving machine that can overcomes the ability of the machine to adjust appropriately to programming inputs, creating an uncorrectable surface bump. On the other hand, if there is not enough material placed in front of the paver, the concrete head may run out, creating voids or pockets in the pavement surface that finishers will have to address behind the machine. Using a placer/spreader machine (which can also be controlled with a stringless system) or carefully depositing concrete from haul trucks are the best means of avoiding placement or head variance.
- The machine's internal vibrators must be set at appropriate levels for the vibrator spacing, concrete mixture stiffness, and forward speed of the paving machine.
- The paver operator must maintain a uniform forward speed and avoid stops, which can produce surface bumps that cannot be mitigated by the stringless system.

WORKING WITH DESIGN DATA

Design data for stringless paving must be derived from project plans, including the detailed engineering drawings that contain the project's profile, geometrics and terrain model. The contractor must take several steps to create the machine input data that controls the paving machine.

Converting CAD Data to X-Y-Z Data

The first step is to determine x, y, and z coordinates for the edges of the finished pavement. The pavement geometric design data, which is usually in CAD files, is converted into equations for lines and curves that represent the true line and profile of the designed pavement surface and can be used to guide the paver.

Many different CAD design software packages and applications are available and can be used to provide data for stringless paving. Each CAD software package will output at least one type of file (e.g., Land XML, DXF, ASCII, etc.) and some applications have embedded macros to allow different outputs and file types. Land XML is becoming the standard output protocol.

CAD application outputs are then used to transform the series of CAD points or coordinates into equations for lines and curves that represent the true designed pavement profile and will help the machine process data efficiently. 3D machine control system providers typically provide a file converter for use. Some CAD providers also include a direct output that does not require transformation, such as Land XML String, which is expected to become the standard for 3D conversion. The final data file will include only the information necessary to adequately model the pavement edges in three dimensions; excess data are excluded to reduce the amount of information that the on-board system computer must process and interpret.

Error Checking

One of the most important steps in data transformation is checking the data from the CAD files for errors. This should be done ***before*** creating the digital 3D model.

Error checking is intended to ensure that the CAD file data exactly matches the engineer's final design drawings, which typically remain the "plan of record." Even when the CAD files are provided by the agency's engineer, it is typically done with no guarantee of accuracy or adequacy for 3-D paving. Error checking is also critical to finding misalignments and other issues that are not reflected in the CAD files. Thus, it is essential that the contractor perform a QC check on the CAD files and any surface models provided. Any discrepancies identified should be communicated to the design engineer so that they can be correctly resolved prior to construction.

Developing X-Y-Z Paving Data Without CAD Data

There are options for developing suitable inputs for stringless paving machines even if CAD data are not available for developing pavement edge equations. Stringless paving system manufacturers provide software that can be used to simulate string lines and create a 3D grid that can be entered in a spreadsheet and edited as necessary (see figure 4).

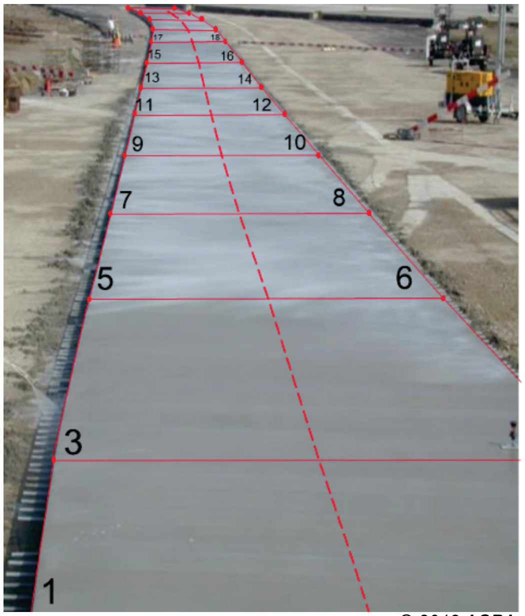

Figure 4. Example grid system generated when CAD data are not available (ACPA 2013).

Such grid models still offer the potential for a much higher resolution depiction of the pavement than could be practically developed using physical string lines at typical staking intervals and will provide a smoother edge line and ride. A tighter grid can (and should) be used to produce smoother cross-slope transitions in curves and other areas with super-elevation or other profile changes. Conversely, less detail is necessary in straight or tangent sections and the grid can be loosened accordingly. Optimizing the grid model will provide a more efficient data file.

Final Considerations

Additional considerations in creating 3D or grid models include:

- Divide the files into paving segments to keep file sizes manageable and avoid slowing the paver's on-board computer with data that are not required for a given day or segment of work.
- Use a stationing-based naming system for paving segment files.
- Include a "run-in" and "run-out" section (or start and end overlap) in the 3D model for each paving segment. Run-ins and run-outs should be several machine-lengths long to make the job easier for the machine operator to get "on-line" and aligned before the beginning of the actual segment.

EQUIPMENT AND PERIPHERALS

The two most common and reliable stringless systems in use on paving equipment today are total station control and GPS-plus-laser control. The technology is advancing rapidly, however, and other systems or combinations of these systems may be preferred in the future. Each system has unique benefits and trade-offs. Contractors are encouraged to consult manufacturers for the right combination of systems for different work and environmental conditions.

A stringless paving "package" typically includes many different components, including those used on the machine and those used for control points away from the machine. Typical machine-mounted components include an on-board computer, software, and dual-axis slope sensors. If total stations will be used for machine control, the machine will also need mast-mounted 360-degree prisms and radios to communicate with the total stations. If GPS will be used to control machine positioning, then the paver will need to be equipped with a GPS receiver; if the GPS is augmented by laser control, then a laser prism will also be needed on the machine. The components that are placed in the field (away from the paving operations) are instruments that reference the control points—total stations, lasers, GPS Base Stations. Each type of system component is discussed in more detail in the following sections.

Robotic (Automatic) Total Stations

A robotic total station—also known as an automatic total station—is an electronically-controlled, high-precision optical instrument used in modern surveying for measuring angles in horizontal and vertical planes, as well as slope distances from the instrument to a particular point (see figure 5). In stringless paving applications, robotic total stations are one option for telling the paving machine control system where it is located in space (three dimensions) to within 0.125 inches (3 mm). To function properly within the system, there must be a clear line of sight between the total station and the paver-mounted equipment that is referencing it for grade control. It must also (generally) be within 250 ft (76 m) of the paver-mounted equipment, and it must be able to accurately determine its own position information by referencing at least three control points along the project (which, in turn, must be referenced to known benchmarks).

Figure 5. Robotic total station in use on a project site (ACPA 2013).

Mast-Mounted Prisms

For total station control, two prisms are typically mounted on masts on the paver. The prisms are typically mounted on the back of the paving machine, although some older systems may feature one prism on the front of the machine and one on the back. These prisms reflect laser signals back to the total stations (or to rotating lasers, as described below), sending precise data about the x, y, and z positions of the prisms (and, therefore, the paving machine). This information is processed by the stringless paving system control computer, which relays the information to the machine's computer or process controller to adjust the paving machine's legs (elevation adjustments) or steering as necessary to best achieve the design surface profile by controlling the positioning of the profile pan.

GPS Receivers

GPS receivers are an alternative to the use of robotic total stations but are typically used only for controlling position (steering) of paving machines because their positioning accuracy is typically ±0.8 inches (±20 mm) compared to

0.125 inches (3 mm) for total stations. The GPS receiver is mounted on a mast above the paver and is connected directly to the stringless paving computer system for direct data transfer.

GPS receivers require the use of a GPS base station (described below) and a clear line of sight to it for best results. They can be vulnerable to signal loss in some paving environments.

Because GPS systems generally have a vertical tolerance of more than 0.75 inches (19 mm), they are typically used in combination with rotating laser systems (described below) to improve the accuracy of paver ***elevation*** control when paving under smoothness or ride specifications.

GPS-based systems offer an advantage over total station-based systems in confined work spaces (e.g., some curb and gutter paving situations) where the lasers between the total stations and the prisms might cross, causing signal and control problems. In these (and other) situations that limit the use of total stations, GPS may be a good option when used together with a base station and laser receiver. GPS-based systems also may be used for economic reasons because they are typically less expensive than total stations. Regardless of the reason for their use, GPS-based systems are typically limited to machine steering functions.

GPS Base Station

A GPS base station is a receiver at an accurately-known fixed or stationary location that augments GPS data obtained from satellite signals. The GPS base station transmits corrections to the paver-mounted GPS receiver that improve the position accuracy information provided to the on-board computer. Steering control accuracy can be improved to ±0.5 inch (±13 mm) when using a GPS base station.

Rotating Lasers

Lasers are an alternative to robotic total stations for controlling the elevation of the paving machine (see figure 6). They are used in conjunction with GPS because GPS accuracy is not adequate for total control of the slip-form paving machine. In these systems, GPS is used to control the position of the paving machine relative to design centerline, while the laser guidance provides elevation control with an accuracy of ±0.2 inch (±5 mm).

As with robotic total stations, lasers must be used in clear sight of the machine using them for grade control. Lasers can be set at a maximum spacing of 500 to 600 ft (152 to 183 m). The lasers communicate with laser receivers (prisms) mounted on masts above the paver.

Figure 6. Rotating Laser for controlling elevation (ACPA 2013).

Radios

Radios are mounted on the paving machine and the total stations to send and receive data about the position of the machine relative to the control points. The machine-mounted radio communicates with the stringless system onboard computer, which then communicates with the paver process controller or other systems that make appropriate adjustments to machine to achieve the correct pavement thickness and cross-slope.

Dual-Axis Slope Sensors

Paver-mounted dual-axis slope sensors are used to sense the cross-fall (cross-slope) and main-fall (forward and backward slope) of the paving machine. These aspects of paver attitude help control pavement thickness and smoothness of the extruded pavement.

On-Board Computer

The on-board computer is the command center of the stringless paving operation. It is typically mounted near the paver operator control panel but may be mounted lower on the paver for ground crew control. This computer processes radio signals from total stations or lasers to determine its exact position, compares that position to the 3D model, and sends signals to the paving machine's process controller or computer so that it can make adjustments to keep the paving machine at the correct alignment and elevation. The on-board computer typically reports positional data through screens available to the operator.

Stringless System Communications

Stringless paving system components "talk" to one another using CANBus, which can be described as "the Internet for machines" because it provides a common network for all of the components. Each device in the system has a unique ID tag, and those tags are also attached to each message sent over the system so that each device can read signals or messages tied to its own ID tag while ignoring other data being transmitted.

Rover Pole

A "rover pole" is used for as-built checking behind each operation (see figure 7). A rover pole is typically outfitted with a prism, and a robotic total station is used for checking the "as-built" elevation and position of the subgrade, the subbase and/or the paving. This is a one-person operation.

Complete System

Figure 8 shows the components described above integrated in a single robotic total station stringless machine control system.

Figure 7. Rover pole for as-built checking (ACPA 2013).

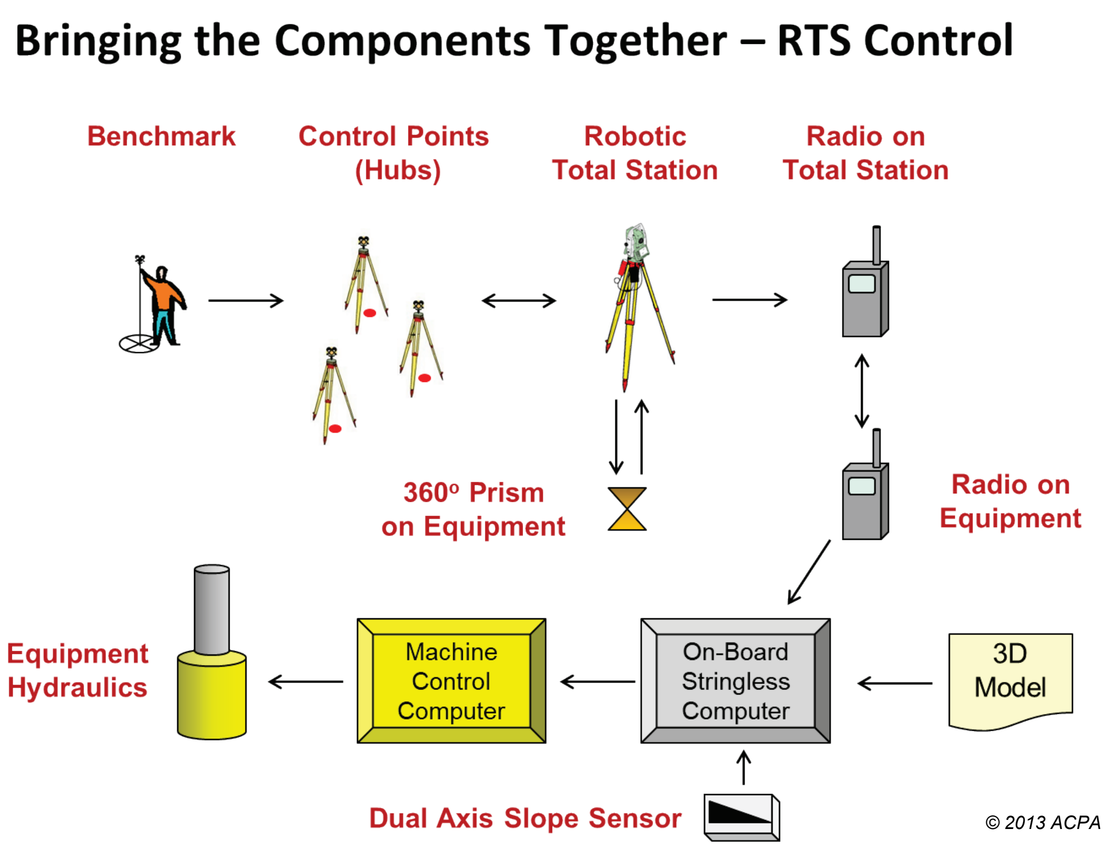

Figure 8. Robotic total station (RTS) stringless machine control system schematic (ACPA 2013).

BEST PRACTICES FOR STRINGLESS PAVING

The following is a summary of best practices for personnel, equipment configurations, data collection and processing before paving, establishing survey and control points, equipment setup, special considerations, and checking the as-built pavement.

Personnel

- Contractor personnel must be properly trained in stringless paving technology.
- Management of stringless paving operations (especially for working with data to create 3D models and perform error checking) may be best handled by staff with a civil engineering degree.
- Paver operators and project superintendents must be familiar with the function and interactions of all system components.

Equipment Configuration

- While new pavers can be purchased with stringless control systems, it is often possible to retrofit stringless systems to existing machines. Some older equipment, particularly older earthwork equipment, may not be compatible with stringless control systems. The manufacturer of any existing paving machine should be consulted to confirm compatibility with stringless control systems before committing to a retrofit.
- A stringless paving control configuration (i.e., total stations, GPS + total station, or GPS + laser) should be selected that is appropriate for the intended location, considering the required accuracy of paving, the number of instruments required and the placement of those instruments.
    - One total station can be used for most curb and gutter, grading, barrier wall, and ancillary paving, but a minimum of two total stations is required for mainline highway, airport, street, or road paving. Three or more total stations are required for “leap-frogging,” as discussed later.
    - When possible, place instruments on both sides of the planned construction.
- ACPA (2013) presents several examples of equipment configurations for various applications, ranging from subgrade trimming to curb-and-gutter paving, to placer-spreader control, and to mainline paving. Figure 9 illustrates the mainline paving case.

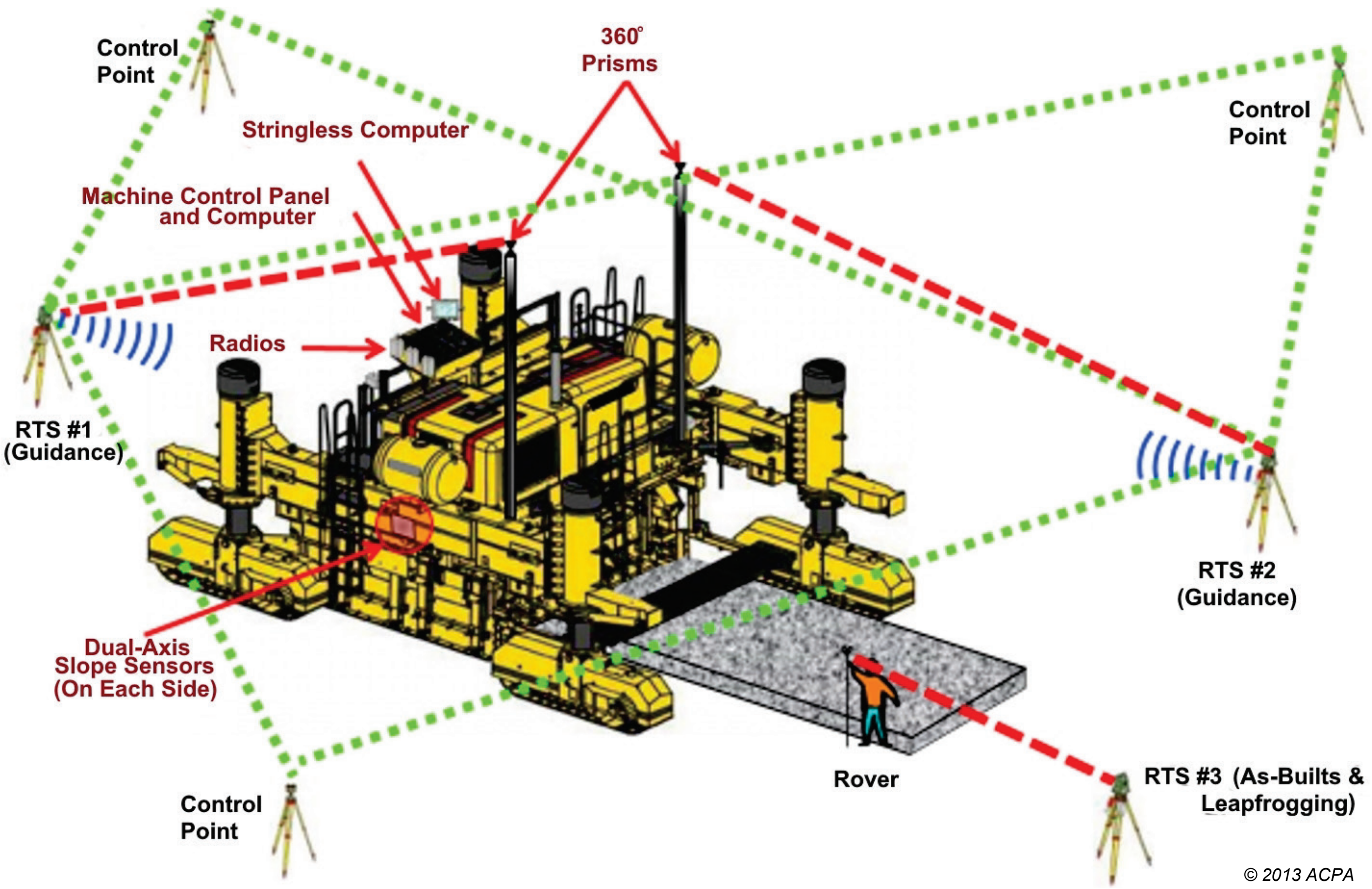

Figure 9. Stringless paving configuration example for mainline paving (modified from ACPA 2013).

Data Collection and Processing Before Paving

- A survey control network must be established that encompasses the project limits and provides access to the reference points required for the total stations. The total station locations must be selected so that clear lines of sight to the paving machines are provided as they travel through the project site.
- For overlays and design-build work where digital profiles are not provided by the agency, consider the use of an all-terrain vehicle equipped with GPS to gather horizontal (X and Y) data and a laser profiler or total station to gather elevation (Z) data for automated mapping of the existing surface. When doing the mapping work, be sure to profile enough paths to sufficiently characterize the existing surface. If profiling where there is an existing pavement, include lane edges, wheel paths, lane quarters and centerline. The data should be recorded at intervals of 25 ft (7.6 m) or less.
- The contractor should become familiar with the 3D digital surface model and error-check the data to avoid roughness issues and thin pavement or yield loss problems.

Establishing Survey and Control Points

- The survey control network must be tied to known, permanent benchmarks.
- It is recommended that control points be spaced approximately 250 ft (76 m) apart and, if possible, staggered on opposite sides of the paving site. The control points must accessible and not out of range of the sensors throughout the project's length.
- The location of total stations and other instruments should be planned such that they are in sight of the machine or machines, in sight of at least 3 control points, and within the recommended instrument range.
- Total stations typically need to be within a range of about 250 ft (76 m) of the machine they are controlling. The specific spacing recommendations of the manufacturer of the total stations or the stringless "package" should be followed.
- At least two total stations are required for most stringless paving applications, but three or more are recommended. In a typical mainline paving configuration, at least one total station will be placed ahead of the paver, one will be positioned behind the paver, and a third will be used for collecting as-built data. Additional units can be used for "leap-frogging" or repositioning total stations forward in the direction of paving, ensuring that at least two stations are communicating with the paver at all times.
- Good practice for "leap-frogging" includes maintaining one unit ahead of the paver and one unit behind the paver and within about 250 ft at all times. As the paver approaches the "ahead-of-paver" unit, a third unit is advanced ahead of the paver to become the new "ahead-of-paver" unit and the previous one becomes the "behind-paver" unit after the paver passes. The previous "behind-paver" unit will be "leap-frogged" to the front when the paver advances further. It is essential that adequate separation is maintained between the total stations to ensure sufficient accuracy in paving. ACPA (2013) provides a detailed discussion of "leap-frogging" techniques.

Equipment Setup (Pre-Paving)

- Always check the paving pan positioning and mast elevations when setting up a machine for a new project and if:
  - The paver is moved to a new location on site.
  - The paver pan width is changed.
  - The mast heights are changed.
  - The prism or other on-board instruments are swapped.
- Always check the radios mounted to total stations and paving machines. Equipment movement and vibration commonly cause radio problems, which can mean that the on-board computer isn't getting all the important paver positioning data necessary for effective stringless paving.
- Always check power and cables for damage and proper connections prior to and during operation. Power greater than or less than 12 volts can seriously affect radio performance and life.
- Check that radios have the correct "pair settings" and COM-port settings for proper linkage and communication.
- Be sure all antennas are set in vertical positions and away from metal that may interfere with the signal. Consult the paving machine manufacturer for the optimal location and setup of the radio antennas for best signal strength. Separate antennas by at least 1.5 ft (0.5 m) or as recommended by the manufacturer for best operation.
- Be sure all equipment batteries are fully charged and have spare batteries on hand.
- Have back-up components on hand for substitution as needed (rather than hold up the paving operation while a replacement is purchased and shipped to the site).
- Ensure total station and rotating laser tripods are in good condition and stable when in use. Use sandbags or other means to anchor tripods, especially in windy conditions.
- Always have a rover unit on hand (to check the elevation and location of extruded pavement behind the operation).

Special Considerations

- Dew and dust can affect the signal reflection off prisms. Clean prisms regularly, particularly for early morning start-ups.
- Low sun angle can affect prisms. Be aware of this phenomenon in the spring and fall and when paving in morning and evening conditions when sun angles are low.
- GPS systems may be vulnerable to interference or loss of signal in the event the paver passes under a bridge, tree canopy, or other obstructions. GPS may also be less reliable in hilly or mountainous regions than in flat terrain. Weather also can affect GPS signal reception.
- One advantage of stringless machine control is that it may allow tighter paving turns than are possible with string line-controlled paving. However, it is important not to exceed the practical limitations of the paving equipment. The limiting factor is usually "how tight can the machine legs turn?" but the turn also can't be so tight as to tear the concrete. Experience will help determine these limiting factors for given paving mixtures.
- Stringless paving can be used when paving a new lane along an existing section by combining stringless control with a "locked-to-grade" control on the side of the pavement that needs to match the elevation of an existing section.

Checking the As-Built Pavement

The as-built surface should be checked as frequently as practical using a rover. In addition, systematic errors, such as errors in elevation, slab thickness and location offset from centerline, should also be reviewed. Errors (and adjustments) will be shown and stored on the total station and should be communicated to the equipment operator/foreman or ground crew responsible for compensating manual adjustments to the on-board computer.

CLOSURE

Stringless paving has evolved into reliable technology and will soon become the standard for concrete pavement construction. Possible future developments include the application of building information modeling (BIM), "cloud" technologies to manage jobsite information flow, and smart phone and table apps or other tools that assist in managing stringless paving operations. There is little doubt that more contractors and specifiers will embrace this technology in the years ahead.

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