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Introduction to Automated Machine Guidance

Introduction

Automated Machine Guidance (AMG) is also known as Machine Control (MC). It is a process that uses continually updating measurements from:

- Laser Systems.
- Sonic Systems.
- Real Time Kinematic (RTK) Global Positioning System (GPS), or
- Robotic Total Stations (RTS).

These guidance systems are used to report the position of a piece of construction equipment. When the position of the equipment is known in relation to a design, the equipment can be guided to a desired location on a project.

There are several advantages to using MC that include:

- Increased Efficiency.
- Reduced Labor.
- Increased Accuracy in placement of material compared to conventional stakeout.

There are several types of MC such as:

- Laser systems which are used in 2D MC systems which include:
    - Flat Plane Lasers which emit a laser beam on a level line.
    - Adjustable Slope Lasers which can be set to indicate the line of a grade.
    - Adjustable Dual-Slope Lasers which emit beams to indicate the line on 2 grades.
    - Fan Lasers which emit a cone of coverage.

    - Single Slope, Dual Slope and Fan Lasers - The difference in traditional lasers and fan lasers is that the traditional lasers emit one or two beams of light. The working area for traditional lasers is limited to exactly the grade that the laser beam is transmitting.

      Fan lasers on the other hand, have a working area that includes an upper limit, a lower limit and any of the area in between the two. Fan lasers are a newer technology.

    - The uses for 2D MC Lasers include site grading, foundation work and utility construction. Flat Plane Lasers have been in use for well over 30 years. This is often used with a worker holding a rod to determine if the desired grade is higher or lower at that point. This is typical of a foundation or grading application. These systems can also be mounted on construction equipment and used with a screen in the cab for the operator to view. This is called an ‘Indicate System’.

    - 2D MC Lasers Indicate Systems. Common installations are on:
        - Excavators or back hoes and includes sensors placed on the boom, stick and counter weight.
        - Bull Dozers where the sensors are located on the blade, and
        - Motor Graders where the sensors are located on the blade.

      In one mode the operator can place the bucket or blade on a known bench mark and through the use of a cab mounted screen, operate the bucket or blade up and down in reference to the bench mark elevation. The system can also be used with a laser. In this case the operator moves the bucket or blade until a laser sensor (laser catcher) acquires a reading from the onsite laser. The operator then uses the cab mounted screen to operate the bucket or blade.

  - 2D MC Lasers Automatic Systems. Automatic mode involves a series of hydraulic valves which are controlled by a cab mounted computer that receives the output from the laser. The advantage is significant in that the operator simply concentrates on keeping the machine in the work area. There is no need to operate the machine and read the output at the same time.

- 2D MC Sonic Systems are used to control the depth on cutting blades. The sonic unit can be installed on one side of the blade or on both sides of the blade to control the pitch of the blade.

  - 2D MC Sonics is also used to control the mold offset on asphalt pavers.

- 3D Machine Control which is used on grading machines such as bull dozers, graders and excavators. This type of Machine Control uses either RTK GPS or Robotic Total Stations (RTS) to determine the location of the machine. In 3D Machine Control we also have the addition of a 3 dimensional model named a Digital Terrain Model (DTM).

  - The DTM is computer generated file that is made up of elements named nodes. A node is defined by a northing, easting and elevation. A DTM is only used to define the elevation at a given location. To support a MC mission, a DTM is best used with additional elements named polylines and stakeout points.
  - 3D Machine Control also comes in an Indicate configuration and an Automatic configuration. The operation is similar to 2D Indicate and Automatic systems.

- 3D Stringless Machine Control for finished grade machines such as milling machines, trimmers, asphalt pavers, concrete pavers and curb and gutter machines. This is an advanced form of 3D MC and is currently only offered by a manufacturer named Leica GeoSystems.

  - Stringless MC is the top of the line and completely replaces stringlines. There are no strings of any kind that are needed for Stringless MC, but the accuracy is as good or better than the stringline controlled systems.
  - Stringless MC gives us the ability to very precisely control our machine by the use of a machine mounted computer that is giving us a continuous readout. The readout includes:
    - The heading or direction.
    - The relative elevation at each track on some machines or front and rear on others.
  - With this information, we can make adjustments as small as 0.01’ vertically while we are laying material.

2D and 3D Machine Control Compared

- 3D MC can follow curves and alignments where lasers are limited to a grade.
- 3D MC performs all the functions of lasers and in most cases can replace your laser.
- 3D MC offers the greatest amount of labor cost savings that is available.
- 3D MC gives the user the greatest amount of schedule control that is possible.
- Leica’s 3d Stringless Technology provides almost limitless access to the jobsite during your concrete pours, paving, milling, trimming and curb and gutter work.

Guidance Systems

The following will discuss Guidance Systems and their precisions as well as some advantages and disadvantages.

- Lasers emit a nearly invisible light and are mounted in a housing that can be precisely leveled by the use of compensators.

    - The precision of Lasers are measured in arc seconds, like a traditional stakeout instrument. The caveat to lasers is that we have a working range or distance. As we get to the outer limits of the working area the accuracy decreases.

    - The following chart defines the accuracy we can achieve given the precision of the laser:

Precision	Distance	Accuracy 100’	Accuracy 500’	Accuracy 1000’
1 arc second		0.0005’	0.0024’	0.0048’
5 arc seconds		0.0024’	0.0120’	0.0240’
10 are seconds		0.0048’	0.0240’	0.0480’

- Sonic Systems are short range systems that are positioned to look straight down to control the vertical position of the equipment. The precision of Sonic Systems is in the 0.02’ range.

- RTK GPS is probably the least understood technology that we deal with. As a rule of thumb the horizontal precision of RTK is 0.05’+/- and the vertical precision is 0.10’+/-. This is very easily verified by reviewing the manufacturer’s specifications. By example:

    - Horizontal precision which is stated as 10mm + 1ppm. In feet is equal to 0.033’ + 1ppm per unit.

      This means, that for any measurement we make, the precision is 0.033’ (for the base) and 0.033’ (for the rover) which adds up to 0.066’ horizontally. The manufacturer will not guarantee any measurement is more precise than the stated precision.

    - Vertical precision which is stated as 15mm + 1ppm. In feet is equal to 0.050’ + 1ppm per unit.

      This means, that for any measurement we make, the precision is 0.050’ (for the base) and 0.050’ (for the rover) which adds up to 0.100’ vertically. The manufacturer will not guarantee any measurement is more precise than the stated precision.

    - PPM is part per million based on the distance from the base to the rover. PPM precision is insignificant for most distances used in construction. The ppm error for 1 mile equals 0.0053’+/-. This would be added to the horizontal or vertical precision.

  RTK GPS computes it’s position based on radio signals received from satellites in orbit around the earth in relation to a correction signal transmitted from a known position on the earth. This is why we have a base unit set on a known station and a rover unit installed on the machine.

RTK GPS also requires that we have a direct radio communication link between the base and the rover. Often times this is an internal radio, but can be external as well.

There is another kind of RTK which generically can be called Virtual Reference Station (VRS) GPS. VRS is not widely used in construction at the present, but is being tested. At first glance VRS appears that a single GPS unit is being used, but in reality, there is a base located off site that is transmitting the correction via an internet link. The most important thing is that all GPS, no matter what kind of process we are using requires a base unit and a rover unit.

Some advantages for RTK GPS are:

- Has a very long working distance. Over a mile from a base in some cases.
- Is not subject to line of sight issues like RTS.
- One Base can control several rover units.
- The learning curve is less than for RTS.

Some disadvantages for RTK GPS are:

- Subject to periods where the satellite constellation is not suitable for RTK. This results in down time, even when the other conditions for RTK are good.
- More operating limitations than RTS. RTK GPS doesn’t work under trees or in structures. Operating close to buildings or fences can return a false answer.
- The precision and accuracy of RTK GPS is not as good as RTS.

- A note on Laser Augmented RTK GPS. These are fan lasers that are sold based on their ability to increase the vertical precision of RTK GPS.

  - Laser augmented RTK GPS is subject to the same advantages and disadvantages as RTK GPS.
  - Laser augmented RTK GPS is also limited to the working distance of the laser both vertically and horizontally.

- Robotic Total Station or RTS is a traditional Total Station that has servos installed that move the instrument based on commands issued by the operator. When in motion, RTS uses lasers to track a prism. When in tracking mode, there is no need for an operator to stand behind the instrument to run it. RTS measures both angles and distances simultaneously.

  Typically, the commands that run the instrument come from a controller that is mounted in the cab of the machine. There is radio communication equipment installed in the instrument and at the controller as well. These radios are generally external radios. The RTS can be controlled by your stakeout personnel too. These radios are often internal. Internal and external radios can be used in combination.

  The precision in RTS cannot be matched by any other technology. As in RTK GPS there are specifications that define the accuracy that we can achieve.

  - Horizontal and Vertical angles are stated in arc seconds. RTS for MC would typically be 1 arc second for both horizontal and vertical angles.

An instrument with a precision of 1 arc second can theoretically obtain an accuracy of 0.01’ at a distance of 2,000.

In addition to the angular specification, there is an Electronic Distance Measurement (EDM) specification. A typical tracking EDM specification is 3mm +/-. In feet this equals 0.01’+/-.

- The working specification that I generally recommend for tracking (moving) RTS MC is 0.02’ both vertically and horizontally at a distance of no more than 500’.
- Although the specifications of RTS are so good, on a real construction site application we have other factors that affect the precision. Some of these factors are weather and other atmospheric conditions (heat waves, fog, etc.) and general site conditions (the amount of dust in the air, etc.). In addition to these factors, we must remember that the RTS is tracking a moving object.
- In addition to the MC applications, the RTS can be used by your stakeout personnel for stakeout and grade checking. This is a different type of measurement to a stationary point that is called a static measurement. In a static measurement on a construction site it is possible to achieve an accuracy of 0.01’.
- RTS can be used to establish horizontal and vertical construction control. This is another example of static measurement. Control can be set to 0.01’ horizontally and vertically.

Some advantages for RTS are:

- RTS is the most precise method of MC and stakeout that is available to us.
- RTS is not limited by overhead obstructions as is RTK.
- RTS can be used for levels and eliminates the need for additional instruments to set bench marks or check grade.

Some disadvantages for RTS are:

- RTS is subject to line of sight issues.
- RTS can only control one prism or machine at a time.
- The learning curve for RTS is greater than for RTK.

General Notes on Guidance Systems

- RTK GPS should be limited to applications where material placement of 0.1’ +/- will suffice.
- RTK GPS should not be used to establish control where material placement needs to be better than 0.1’+/-.
- RTS can be used to replace most RTK applications, but RTK can’t be used to replace high precision RTS applications.
- RTS should be used where material placement needs to be better than 0.1’+/-.
- RTS should be used for any control work.
- When used properly, RTS can establish vertical control as good as conventional levels.
- There is no need for RTS to be set on established control points. RTS instrument locations are very easily established if 3 (preferably 4) existing control points are visible.
- RTS is the only system that can be used in stringless applications.
- The time to think ahead is before the purchase any MC system. The purchases we make should address the needs that we have now. More importantly we should think about any

needs that we will have in the future. Purchasing the proper equipment today will give us the ability to build on that purchase in the future.

3D Models, Polylines and Stakeout Points

3D Model is the term we generally use for a Digital Terrain Model (DTM) or 3D Faces. The DTM is used to define the elevation at a location on your model.

A DTM is a single entity, but it can have thousands of sub elements. It is created with the data provided by your designer. This data can be typical sections and profiles or in the case of concrete paving it is usually design elevations on the joints. In the case of joint elevations you might have thousands of points. There will be DTM nodes for all of your surface elements (asphalt, concrete, curb and gutter, etc.). These nodes are defined with just the position and elevation. When you look at a printed list of the DTM nodes, the list doesn't indicate that the node is for a curb line or a spot elevation. The DTM node simply defines the elevation at that point.

- A DTM can take different forms:
    - One is called a Triangulated Irregular Network or TIN.
    - Another is called a Grid.
    - The common element to both of these is called a 3D Face

- A 3D Face is a triangle formed by 3 positions defined by the northing, easting and elevation.
- 3D Faces exist as separate entities in a computer file.
- Combining the 3D Faces into a single entity creates a DTM.

In addition to the 3D Model, there are other elements that are necessary for a MC project:

- 3D Polylines are elevated lines created in the Computer Automated Drafting & Design (CADD) software. 3D Polylines represent things like profile lines, curb lines, and edges of pavement. In the 3D environment, a 3D Polyline can be thought of as a series of nodes that are closely spaced and connected by a line for a continuous slope or profile.

  3D Polylines are very important and will be used to help guide your operator. They are used like the stakes on a traditional project. Instead of looking out of the cab to see where the line is, the operator will use the polyline on the screen to see where the line is.

Accuracy of the 3D Model, knowing which MC file format needs to be delivered and thorough understanding of the CADD software that you will use is paramount to a successful MC project. The 3D MC project that you build cannot be more accurate than the 3D Model that you use.

If there is one concept that needs to stressed, it is that the 3D Model loaded into your machine's controller is exactly what your machines will produce in the field. If the DTM is wrong, your job will be built wrong.

The steps to create a 3D Model include:

Analysis of the Data

- The designer issues the design. This may be a CADD file and a paper plan set, or just a paper plan set.
- If we have just the paper plans we need to create the model from the design elements such as the Typical Sections and Profile.
- If we have the CADD file, we first need to check the CADD against the paper plans to verify that the CADD data is usable.

- The next step in the CADD file is to review the data to determine if the CADD file is 3D or 2D.
- If the CADD file is 2D, we need to elevate the data to use it in the Model.
- If the CADD file is 3D, we can create the Model from this.

Creating and Formatting the DTM

- Before we create the DTM, we need to know the MC file format in which the data is used.
- Each MC field control unit requires a specific format. The most common type of format is a TIN. The advanced systems require a Grid.
- Just as there are different MC field controller requirements, there are different CADD softwares.
- The combination of files types and CADD softwares are too numerous to document in this discussion, but the 3D CADD elements that are commonly used to create a DTM include:
    - Points
    - Polylines or Chains
    - Profiles
    - Centerlines or Baselines
    - Typical Sections
    - Cross Sections
    - Other DTMs

QA/QC

Quality Assurance and Quality Control is a necessary part of every element of a Machine Control project from the preliminary design survey to the as-built.

One of the most important steps in the QA/QC process for the DTM took place in the analysis of the data prior to building the Model. The next QA/QC function will be the comparison of the model to the design. There are numerous things that can go wrong in the modeling process such as input error or anomalous data in the design. Our role is to find them and get them rectified before the model is used in the field.

Some obvious examples of what we need to do are:

- If we used centerlines, profiles and typical sections to build the model, we need to compare that to the cross sections.
- On the other hand, if we used cross sections to build the model, we need to use the centerline, profile and typical sections and do periodic checks against the model.
- If we extracted digital data from the design that has plan dimensions, such as concrete joints, we need to check the digital dimensions to the plan dimensions.
- Check the cross slopes (etc.).

The final QA/QC of the DTM should be accomplished by using the CADD software. This is where the skill set of the modeler will pay dividends. In general the process might include:

- Viewing the rendered DTM with an exaggerated vertical scale.
- Driving or doing a Fly Over of the rendered DTM.
- Doing cut/fill computations comparing the design points and polylines to the DTM.
- Assuming you were provided with a surface by your designer, doing surface to surface cut/fill contours or doing surface to surface volume computations.

If the model is delivered to the field and flaws are discovered during construction, no matter what the cause, the modeler did not do their job….period.

Stakeout Points

3D Models and Stakeout Points share a common element with RTK GPS in that the relationship between the two is one of the least understood concepts in a MC project.

The misunderstanding is that a DTM is made up of things that appear to be points, but in fact, they are actually nodes. Nodes have no intelligence and Stakeout Points have intelligence. The stakeout data controller can't recognize a node to do Coordinate Geometry or COGO.

- A DTM Node is made up of a Northing, Easting and Elevation.
- A Stakeout Point is made up of a Point Number, Northing, Easting, Elevation and Description.
- Stakeout Points are also referred to as COGO Points.

NOTE - One thing I have seen that causes confusion is that CADD software can create points from DTM nodes. But since the DTM node did not have any intelligence associated with it, the points extracted from nodes are of little value.

Examples of Data Contained in the Point Database (COGO) File.

```
- <CgPoints>
  <CgPoint name="1" desc="OLDSYS">5062.963 4848.697 82.480</CgPoint>
  <CgPoint name="4" desc="MISC/TBM">5027.430 4977.536 86.001</CgPoint>
  <CgPoint name="5" desc="EOG1 jpn333">5208.416 4985.334 84.297</CgPoint>
```

Examples of Data Contained in the TIN Node File

```
- <Surfaces>
- <Surface name="06028_2">
- <Definition surfType="TIN">
- <Pnts>
  <P id="1">5005.062 5076.276 82.300</P>
  <P id="2">5005.108 5081.845 82.300</P>
  <P id="3">5001.098 5081.724 82.300</P>
  </Pnts>
```

Examples of Data Contained in the TIN 3D Face File

```
- <Faces>
  <F>325 320 342</F>
  <F>277 270 333</F>
  <F>136 148 88</F>
```

The three examples above come from a LandXML output file. I have used the LandXML format because it is more descriptive of the data types. The common elements of the Point Database (COGO) file and the TIN Node file are:

- Northing
- Easting
- Elevation

The differences are:

- The points in the Point Database are defined by Cogo Point Numbers (CgPoint name) that are usable by mapping, plan production and field data controller softwares.
- The TIN Node file is defined by line number which is not usable by the aforementioned softwares.
- The points in the Point Database have a descriptor which describes what the point represents and the TIN Node file does not.

Uses of the data:

- The points in the Point Database can be used to create linework and other objects in CADD software. They can also be used for stakeout in field data controllers.
- The points in the TIN Node file are used for creating DTMs and contouring.
- TIN data can be created from the points in the Point Database.
- Stakeout data cannot be created from the points in the TIN Node file.
- There is a significant relationship between the COGO points and the DTM on a project, but that relationship is limited to the elevation.
- It is likely that a COGO point and a TIN Node exist in the same location. This does not change the significance of the TIN Node. In other words, a TIN Node that exists in the same place as a COGO point still cannot be used for COGO.

We can’t expect our stakeout personnel to do stakeout with TIN Nodes and have any success. It is possible that your less experienced personnel might attempt to do so, but they will not be able to perform to your expectations. This will be especially so on roadways with multiple alignment objects like curbs, roads and medians.

We are not in business to attempt to build anything, we are in business to build things and meet specifications. To do this we need to take full advantage of the tools that we have.

Conclusion

As a construction contractor whose ultimate responsibility is to provide a project that is built to the specifications, you should question anyone who attempts to tell you that the modeling and stakeout process is simple.

- There is nothing simple about:
    - Creating a 3 dimensional model of every detail contained in a set of construction plans.
    - Checking each model element against a set of construction plans to make sure they are correct.
    - Creating stakeout data that exactly matches the plans and the model.
    - Staking the necessary points that match the plans and model to build your job.

When someone tells you how simple 3D Modeling and stakeout is, remember whether they have a contractual agreement to support your project by providing those services and the professional liability insurance to back it up.

Putting It All Together

Most firms that purchase Machine Control and use it purchase more within 6 months. Here are the reasons:

- You will take more control of your business.
    - The labor reduction that most contractors realize is in the un-skilled labor area.
    - Fewer employees that need to be managed equals fewer headaches.
    - Once the cost savings of the equipment is factored in, the additional profit can be used to compensate your employees, buy more equipment, or simply just take the profit.
    - You will find that the equipment will pay for itself very quickly when you take maximum advantage of it.

- You will take more control of your projects.
    - Get training on the technology with qualified providers.
    - Decide whether you want to do it all in-house or outsource parts of the work.
    - Put a team together that you can trust to support you.
    - Machine Control will take more of the 'surprises' out of your work.

- Control the Technology, don't let it control you. The object of machine control is to make you more efficient and make you money.
    - You know your business better than anyone; buy the things that will pay for themselves.
    - Learn how to use the equipment and use it. There will be a learning curve, but it won't be as bad as you think.
    - Decide if you want to take the liability to do it all in-house.
    - Outsource the things that you decide not to do in-house.
    - Make a plan and stick to it.

There are several things that haven't been discussed in this paper such as:

- What model to build and the best way to use it.
- Construction Control and how it relates to the design and to Machine Control.
- How to establish your own control to make the project go smoother.
- Calibration of the equipment.
- How to start a day's work and know the work will be right.
- Interaction of the machine work and your stakeout personnel.
- How to check grade and do rough stakeout with your machine.
- Volumes with machine control.
- How to use RTK GPS and RTS on the same job at the same time.
- The additional files you need for your machine operators.

I hope that this write up has answered a few questions for you. If you have any specific questions that I have not addressed, there are several write ups on the Gulf Surveyors website at:

www.gulfsurveyors.com

Feel free to call or to send any question that you have by email.