Synchro Application Guide

Synchro Fundamentals

As a circuit element, the synchro is essentially a variable-coupling transformer; the magnitude of the magnetic coupling between the primary and secondary, and hence the magnitude of the output voltage, varies according to the position of the rotatable element. In function, the synchro is an electromechanical transducer. A mechanical input such as a shaft rotation is converted to a unique set of output voltages, or a set of input voltages is used to turn a synchro rotor to a desired position.

Synchros can be classified in two overlapping groups: torque synchros and control synchros.

Torque synchros include transmitters (CG), differentials (CD) and receivers (CR).

Control synchros include transmitters (CG), differentials (CD) control transformers (CT), resolvers (CS), linear transformers (LT), and the two hybrid units – transolvers (CSD), and differential resolvers (CDS).

Synchro Types

TRANSMITTER

The synchro transmitter (CG) consists of a single-phase, salient-pole (dumbbell-shaped) rotor and a three-phase, Y-connected stator.* The primary or input winding is usually the rotor; the stator is usually the secondary or output element. The rotor is excited through a pair of slip rings with an AC voltage. The field produced by the input voltage induces a voltage into each of the stator phases. The magnitude of the induced phase-voltage depends on the angle between the rotor field and the resultant axis of the coils forming that stator phase. Since the axes of the three stator phases are 120° apart, the magnitudes of the stator output voltages can be written as:

$$V_{s1-3} = k\ V_{r2-1}\ \sin\theta$$
$$V_{s3-2} = k\ V_{r2-1}\ \sin\ (\theta+120)$$
$$V_{s2-1} = k\ V_{r2-1}\ \sin\ (\theta+240)$$

- Where k is the maximum coupling transformation ratio (TR)
- Which is further defined as TR=$\frac{\text{Vout (max.)}}{\text{Vin}}$ and is a scalar quantity.
- θ is the rotor position angle.
- V_{s1-3} is the voltage from the S1 terminal to the S3 terminal, and all other voltages are similarly defined here and throughout this discussion.

These stator voltages are either approximately in time-phase or approximately 180° out-of-time-phase with the applied voltage. The amount by which the output voltages differ from the exact 0° or 180° time-phase relationship with the input voltage is known as the synchro (time) phase shift. For a synchro operated at 400 Hz working into an open circuit, the output voltage will always lead the input voltage by a few degrees (8° to 20° for small sizes; 2° to 8° for larger sizes).

From the above transmitter equations it can readily be seen that nowhere over the entire 360° rotation of the rotor will the same

*In this guide, the use of the word "phase" will always indicate a space-phase relationship, unless a time-phase relationship is specifically referenced.

set of stator voltages appear. The transmitter thus supplies information about the rotor position angle as a set of three output voltages. To make use of this information, however, it is necessary to find an instrument which will measure the magnitude of these voltages, examine their time-phase relationships and return them to their original form – a shaft position. Such an instrument is the synchro receiver (CR). These two units – the transmitter and the receiver – form the most basic synchro system.

RECEIVER

In construction, the receiver is electrically identical to the transmitter. The output voltages vary with rotor position in the identical manner as that given for the transmitter. In use, the receiver is connected back-to-back with a transmitter; i.e., like-numbered terminals are connected together (See Figure 1) and the rotors are excited in parallel. At the instant the system is energized, if the rotors of each unit are not at the exact same angle relative to the stator phases, voltage differences exist across each pair of stator windings causing current to flow in both stators. This stator current produces a torque on each rotor.
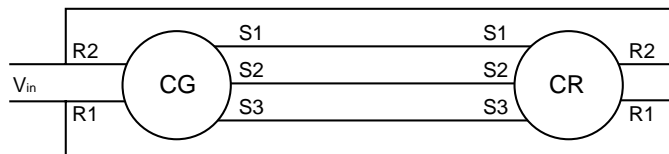

FIGURE 1

Since the CG rotor is constrained from turning, the resultant torque acts on the CR rotor in such a direction as to align itself with the transmitter. When alignment occurs, the voltages at each stator terminal are equal and opposite, and no current flows. Perfect synchronization is never achieved in practice because of the internal friction (due to bearings and brushes) of the receiver. To minimize this error, the receiver is designed to have a maximum starting friction of 2700 mg-mm.

Turning the transmitter rotor from the equilibrium position will again exert a force on the receiver rotor. As soon as this developed force exceeds the internal friction of the receiver, the CR will track the CG to its new position. The torque developed on the receiver shaft is proportional to the angle between the two rotors and is usually expressed in mg-mm/deg. Methods for measuring the torque produced by a transmitter-receiver pair are to be found in Society of Automotive Engineers Specification ARP-461.

Receivers are constructed to minimize oscillations and over-shoot or spinning when the rotor is turning to a new position. The time required for the rotor to reach and stabilize at its new rest position is called the damping or synchronizing time. This time varies with the size of the receiver, the inertia of the load, and the system torque. By special receiver construction, the damping time can be reduced if required by system consider-ations.

The CG-CR system is used to transmit angular information from one point to another without mechanical linkages. The standard transmission accuracy for such a system is 30 arc minutes. The information can be sent to more than one location by paralleling more than one receiver across the transmitter. The more receivers used, however, the less accurate the system, and the larger the power draw from the source.

DIFFERENTIAL
A third type of synchro may be added to our basic torque system – the differential (CD). The differential stator is three-phase, Y-connected and is usually the primary element; the rotor is cylin-drical and is also wound with three Y-connected phases. The output voltages of the CD depend not only on the input voltages but also on the rotor shaft position. As shown in figure 2, the differential stator is normally excited from a transmitter stator, and the differential rotor is connected to the receiver stator. The output voltages of the differential are dependent now on both the transmitter rotor position (θ_{CG}) and its own rotor position (θ_{CD}). The receiver rotor will seek a position (θ_{CR}) which is either the sum or difference of the transmitter and differential rotor angles ($\theta_{CR} = \theta_{CG} \pm \theta_{CD}$), depending on how the CG and CD stators are interconnected.
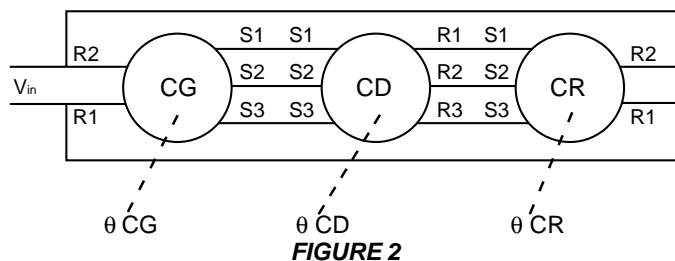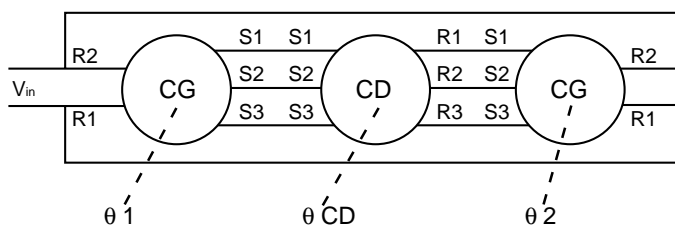

FIGURE 2

FIGURE 3

The differential may also be energized between two transmit-ters as shown in Figure 3. In this system, each transmitter is turned to its desired angle, and the differential rotor is forced to assume a position which is either the sum or the difference of the angles between the transmitter rotors ($\theta_{CD} = \theta_1 \pm \theta_2$). In this application, the differential is sometimes called a differential receiver and is especially constructed with an extremely low starting friction (5000 mg-mm) to minimize system errors. An accuracy of 1° is standard.

All synchro systems are subject to one serious drawback – torque levels typically run around 3000 mg-mm per degree of receiver displacement. This is sufficient to turn a dial or a pointer but nothing larger without increasing system errors. When higher torques are required, synchros are used to con-trol other devices which will provide these torques. An integral part of these control systems is the synchro control transformer. (CT).

CONTROL TRANSFORMER
The CT consists of a three-phase, Y-connected stator and a single-phase drum (cylindrical) rotor. In normal usage, the stator is the primary element, the rotor is the secondary, and the unit is connected as shown in Figure 4. From the sche-matic of Figure 4, it can be seen that the transmitter sets up a voltage field in the CT stator whose direction is exactly that of the transmitter and whose magnitude is directly proportional. As the transmitter rotor turns with the CT rotor stationary, the magnitude of the CT stator field remains constant, and its direction exactly matches that of the transmitter. The field cut-ting across the CT rotor induces a voltage in the rotor. The magnitude of this voltage depends on the sine of the angle between the axis of the rotor winding and the stator flux vector; the time phase of the CT output voltage is either approximately in time-phase or 180° out-of-time-phase with the exciting volt-age on the transmitter rotor. Since the angle of the CT stator flux field depends upon the transmitter rotor angle, the CT output voltage can be used to obtain information about the transmitter rotor angle.
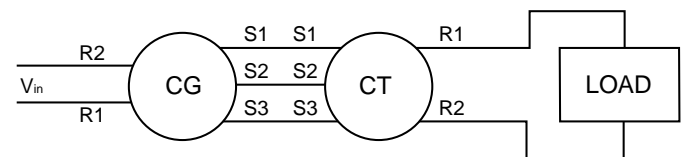

FIGURE 4

The basic CG-CT control system is shown in Figure 5.
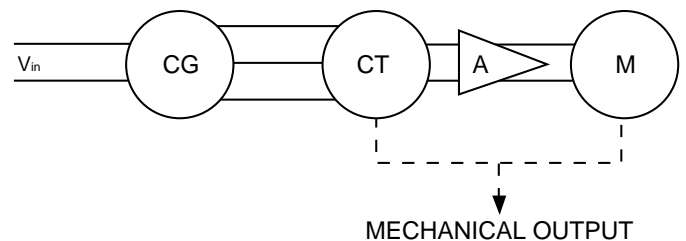

MECHANICAL OUTPUT
FIGURE 5

If the CT rotor angle is not the same as that of the transmitter, a voltage proportional to the sine of the angular difference ap-pears on the CT rotor. This voltage is impressed across the input of a servo amplifier, which, in turn, is connected to the control phase of a servomotor. The motor, which is geared back to the CT rotor shaft, will turn to oppose the voltage caus-ing its motion. It will rotate until the CT rotor is at the same angle as the CG rotor; at this position, the CT output voltage is theoretically zero and motion will cease. With additional gear-ing the synchro motor provides a mechanical output for other useful work. This synchro system, which develops no torque of it own, acts as the control device which moves high torque

loads. The accuracy of the entire system depends on synchro error, amplifier gain, servo response, and gearing errors. Using standard components, the synchro system error is usually specified as 10 arc minutes maximum; by selecting synchros or by trimming, this error can be reduced well below the given figure. If multispeed pancake synchros are used, accuracies measured in seconds of arc are standard.

In some systems, a control transformer is made to act, through switching circuits, as both a transmitter and a CT. This practice is not recommended. Because of its impedance levels and its cylindrical, distributed-winding rotor, the CT can never act as a transmitter without causing degradation in system accuracy and system null voltage. Whenever a synchro must serve as both a CG and a CT, we recommend the use of a transolver (CSD).

TRANSOLVER, DIFFERENTIAL RESOLVER

The transolver is essentially a control transformer with a second rotor winding wound in space quadrature to the main winding. When used as CT, the transolver's second rotor winding is dummy-loaded symmetrically with the main winding to avoid unbalances. When using the transolver as a transmitter, the unused rotor winding is shorted to ground, thus providing electrical saliency and permitting the transolver to operate as a transmitter without introducing additional errors. The differential resolver (CDS) is the inverse of the transolver (i.e., the rotor is the three-phase element, the stator is two-phase). In function, the transolver and differential resolver are identical. The advantage of the differential resolver over the transolver lies in those applications where four-wire outputs are desired; it is more economical to bring out four stator leads than to provide four rotor slip rings and four sets of brushes. Both the transolver and the differential resolver find considerable usage in systems where it is desirable to convert three-wire data into four-wire data. These units form the bridge between the three-phase devices – transmitters, receivers, differentials, and control transformers – and the two-phase units, or resolvers.

RESOLVER

The resolver (CS) consists of a cylindrical rotor with two phases wound in space quadrature and a stator also with two quadrature phases. In standard resolvers (CS), the ends of the rotor phases are internally connected and brought out with a common lead. A resolver with all four rotor leads brought out separately is designated by CZ. The classic function of a resolver, as the name implies, is to resolve a vector into its components. Energizing one phase of the input element – either rotor or stator – with a voltage V induces a voltage into one output winding whose magnitude varies according to the sine of the rotor position angle θ. The other output winding, being in space quadrature to the first, must then have an induced voltage whose magnitude varies as sin (90-θ) or cosθ. The two outputs are thus V sinθ and V cosθ (assuming a unity transformation ratio), which are the components of the input vector V.

A resolver which is specifically meant to separate a vector into its components is the vector resolver (CV or CW). This unit type differs from the standard resolver because the rotor is wound with only one phase.

The vector resolution is reversible because if two voltages, (X and Y), representing vector components are applied to the inputs of the resolver, the corresponding polar coordinates, (R, θ), can be obtained. Since the two inputs are in quadrature, applying voltages X and Y to these inputs will set up a resultant field whose magnitude is $\sqrt{(X^2 + Y^2)}$ or R. If one output phase is connected through an amplifier to a servomotor which is geared back to the resolver shaft, the voltage on the other output will be proportional to R, and the rotor position angle will indicate θ ($\tan^{-1} Y/X$).

Exciting one input of a resolver with voltage A produces outputs of A sinθ and A cosθ. Exciting the other input with voltage B produces outputs of B sin (θ + 90) or B cosθ and B cos (θ - 90) or –B sinθ. Energizing both windings at once then gives two outputs Y and X whose magnitudes are of the form:

$$Y = A \sin\theta + B \cos\theta$$
$$X = A \cos\theta - B \sin\theta$$

From analytic geometry, these two equations represent a transformation of axes by rotating without translation; Y and X are the new components obtained by rotating A and B through the angle θ. Resolvers then find usage wherever transformation of coordinates from one system to another is desired. Spacecraft and aircraft often require the craft's pitch, roll and yaw to be transformed back to earth references. One resolver is needed to provide two-axis transformation; three resolvers, to provide three-axis transformation.
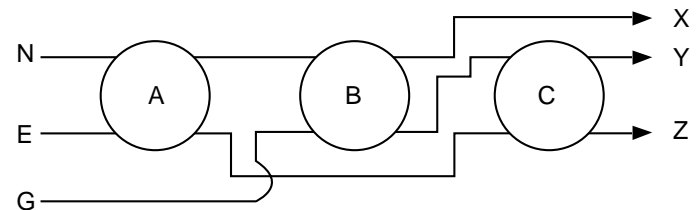

FIGURE 6

Figure 6 schematically represents the interconnections of three resolvers necessary to transform from inertial platform coordinates (N,E,G) to an airborne vehicle's coordinates (X,Y,Z). This resolver chain essentially solves the matrix equation:

$$
\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} =
\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos C & \sin C \\ 0 & -\sin C & \cos C \end{bmatrix}
\begin{bmatrix} \cos B & 0 & \sin B \\ 0 & 1 & 0 \\ -\sin B & 0 & \cos B \end{bmatrix}
\begin{bmatrix} \cos A & \sin A & 0 \\ -\sin A & \cos A & 0 \\ 0 & 0 & 1 \end{bmatrix}
\begin{bmatrix} N \\ E \\ G \end{bmatrix}
$$

Resolver chains are commonly used to solve trigonometric problems of varying degrees of complexity. The resolvers in this application are specially designed to work with a buffer, booster, or feedback amplifier and they are known as feedback or compensated resolvers (CQ or CY). The rotor of a compensated resolver is identical to that of a standard resolver; however, the stator has two additional sets of coils called the compensator or feedback winding. The compensator winding is laid in the same slots as the stator winding. Practically all the flux generated by the stator exciting current links all the turns of the compensator, so that the compensator output is essentially equal to the input voltage, and is naturally constant with rotor position. The time phase shift of the rotor output voltage of the compensator voltage is identical with the time phase shift of the rotor output voltage,

since both voltages were induced by the stator flux field. Because of the resolver's construction, any change in the stator flux due to temperature or voltage immediately produces a change in the compensator voltage. The negative feedback through the amplifier restores the stator field to its original conditions. A resolver-amplifier pair is thus basically error-free, with respect to resolver chain performance, over a wide range of environmental conditions.
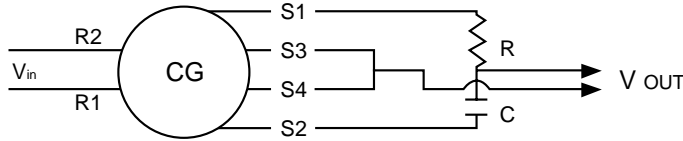
FIGURE 7

Resolvers also are used in time-phase-shifting applications. A typical connection for a resolver phase shifter is shown in Figure 7. The resistance R is chosen to match the reactance of the capacitor C at the operating frequency, and both R and X_C are substantially higher than the resolver output short circuit impedance. Under proper operating conditions, the phase shifter output is:

$$Vout = k\ Vin\ \angle\theta$$

Note that the output voltage is constant with rotor position, but the time phase shift in electrical degrees between the output and the input is equal to the rotor position angle in mechanical degrees. Using a balanced R-C network and a stable frequency source, standard resolvers can be used as phase shifters with an accuracy of ±¼° or better.

Resolvers are also used in control systems exactly like those described for three-phase units. In such applications, the units are sometimes referred to as resolver transmitters, resolver differentials, and resolver control transformers. Their construction is identical to standard resolvers with the exception of the resolver differential, which should have four-wire input and four-wire output. Data transmission by resolvers is usually preferred over three-phase transmission, as resolvers are generally more accurate than their three-phase counterparts.

LINEAR TRANSFORMER

In many resolver circuits involving vector resolution, the input voltage to the resolver is taken from the output of a linear transformer (LT). The linear transformer consists of a one-phase, salient-pole rotor and a single-phase stator. Unlike all other synchros where the output voltage is proportional to the sine of the rotor position angle, the LT is constructed so that the output voltage is directly proportional to the angle itself. In equation form:

$$Vout = k\ \theta \quad (-50°<\theta<50°)$$

The angular band over which the output equation remains valid is known as the excursion range. Beyond the excursion range, the plot of output voltage against rotor position tends toward a sinusoid. The LT acts as a circuit replacement for a potentiometer with the chief advantages of low starting friction and infinite resolution over the excursion range. Because of construction similarities, the LT also matches the performance of resolvers over environmental service conditions.

Synchro Parameters

ACCURACY

Of all synchro parameters, accuracy is probably the most important. The synchro is meant to give unique information about the rotor position angle as a set of output voltages. Synchro error is thus defined as the electrical angle, as indicated by the output voltages, minus the rotor position angle. Calibration is the process of determining the error at specified angular intervals for the full 360° rotor travel. The calibration starts at a reference point called electrical zero (EZ) and defined as a rotor position angle of 0°. The electrical zero point is defined differently for each synchro type, but it always is a rotor position where a specified output winding has minimum voltage induced in it with a specified input winding energized with rated voltage and frequency. During calibration, the units are held and precisely positioned in an Index Stand. The Index Stand provides a mechanical position that is accurate within ten (10) arc seconds. The calibration itself is in accordance with the proportional voltage methods of military specifications MIL-S-20708E and MIL-R-23417B.

Synchro accuracy is of necessity a function of the electrical balance of the windings comprising the input and output phases.

Total turns, pitch factors, distribution factors, insertion patterns, winding integrity must all be in accordance with design requirements if the synchro is to be calibrated within specification limits. Surpassing the electrical problems, however, are the mechanical ones. Accuracy is to a great extent dependent on mechanical perfection. To obtain proper accuracy, it is extremely important to control eccentricities of the air gap surfaces with respect to the mounting surfaces, roundness of the air gap surfaces, mechanical parallelism and perpendicularity, and the radial and axial position of the rotor inside the stator. Our long experience in recognizing and combating these problems insures you of accurate, repeatable synchros.

Component accuracy itself, however, is only one part of system accuracy. When units are cascaded in a synchro chain, unbalances in time phase shift, transformation ratio, and impedance may far outweigh inherent unit accuracy in determining system error. A resolver with a five minutes maximum error cannot exhibit that accuracy when working into unbalanced loads. Severe impedance mismatches may cause sufficient distortion of the voltage waveforms with subsequent loss of accuracy. Our Engineering Department stands ready to help you with recommendations for proper synchro usage in your applications.

NULL VOLTAGE

Theoretically, when a coil is exactly parallel to the direction of a flux field – such as at electrical zero – no flux lines link the turns of this coil and the voltage induced in it is exactly zero. At any minimum-coupling position, however, there is always some residual voltage. This voltage is called the null voltage.

The null is composed of a fundamental component, which is in time quadrature with the exciting voltage (the in-time phase component is always forced to zero), and odd harmonics. The

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fundamental component is due mainly to winding imperfections and magnetic circuit distortions; the harmonics, to non-sinusoidal distribution of the air gap flux.

Nulls are measured in accordance with the phase-sensitive voltmeter method of MIL-S-20708E at each synchro minimum-coupling point. Because of symmetry, each output winding has two null points which are 180° apart, for each input winding. A transmitter has six null points; a resolver, eight; and a differential, eighteen.

Low synchro nulls are essential to proper system performance. Currently, we specify that the maximum null voltage shall not exceed 0.1% of the applied voltage.

OTHER ELECTRICAL PARAMETERS

The remaining electrical tests – transformation ratio, phase shift, DC resistance, input current and power, impedance – are performed in accordance with applicable industry and military specifications.

MECHANICAL PARAMETERS

In addition to checking mounting dimensions, our Final Test checks each synchro for conformance to our shaft end play, shaft radial play, and starting friction requirements. Shaft end play is the total axial motion of the shaft when an eight-ounce reversing load is applied along the shaft axis. Shaft radial play is the total side-to-side motion of the shaft measured as close to the bearing as possible, when a four-ounce reversing load is applied radially to the shaft within ¼ inch of the bearing. Starting friction is the torque necessary to overcome the internal friction of the bearings and brushes and to commence shaft rotation.

Because of the important relationship between accuracy and shaft end and radial play, these parameters are controlled as rigidly as possible. If end and radial play are too loose, higher errors and non-repeatability of the calibration pattern result; if they are too tight, performance over environmental service conditions may suffer. Friction, except in receivers, is relatively unimportant. We currently specify four gram-centimeter maximum friction which has been found to be an optimum level for operation in both normal and extreme temperature ambients. On units where lower friction limits are a system requirement, however, we will work with our customers to establish these limits consistent with the end requirement and with good design practices.

Brushless Synchros

For synchro applications where conventional commutation such as slip rings and brushes is either undesirable or unwanted, we has developed several varieties of brushless synchros, for both full rotation and limited rotation.

ELECTROMAGNETIC TYPE

In the electromagnetic brushless synchro, energy is transferred from the rotor by means of a circular transformer mounted at the rear of the unit. There are no physical connections to the rotor so the life of the unit is limited solely by the life of the bearings. Tens of thousands of hours of operational life at high rotational speeds are easily achievable with this type of unit. The major disadvantage of the electromagnetic brushless synchro is that the dual magnetic structures (synchro and transformer) do not allow the duplication in this design of standard synchro parameters. In general, when compared with a standard unit, the brushless synchro will have higher power consumption, lower impedance angle, higher phase shift and lower unit torque gradient. This can be a problem if the intent is to replace a synchro in an existing system. In new applications, the variations in unit performance can be accommodated. Closer conformance to existing synchros can be achieved with additional unit length. In any case, multi-phase rotors require additional length.

HAIRSPRING TYPE

Limited rotation units are made with spirally wound conductors used to pick off information from the rotor. These hairspring conductors allow a rotation of as much as ±165° from the electrical zero position. The units are normally supplied with a mechanical stop to prevent damage to the hairsprings due to excessive shaft rotation. The addition of the stop normally engenders extra length.

The advantage of a hairspring synchro over an electromagnetic brushless synchro is that any standard synchro can be manufactured in a hairspring design with no change in electrical parameters. If the application permits limited rotation, a hairspring unit can replace the conventional unit already in the system with no effect on system performance except for the benefits attendant on the elimination of sliding contacts. Properly designed hairsprings, such as ours, will perform millions of operations without failure.

FLEX LEAD TYPE

A flex lead brushless synchro is designed with thin flexible lead wires to transfer energy from/to the rotor. These units have all the advantages of the hairspring type and are used in applications where short unit length and low friction are required. Rotation is usually limited to ±90°.

To discuss the possibility of the use of a type of brushless unit in your application, contact our Engineering Department.

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Division Headquarters
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Core business description:
Design and manufacture slip ring assemblies, fractional horsepower DC motors, integrated motion technology systems, resolvers and fiber optic components.

Murphy Operation
Clifton Precision
Location: Murphy, NC
Core business description:
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Litton Poly-Scientific

Blacksburg Operation
1213 North Main St.
Blacksburg, VA
USA
24060-3100

540-552-3011
800-336-2112
FAX 540-953-1841

Murphy Operation
1995 NC HWY 141
Murphy, NC
USA
28906-0160

828-837-5115
800-577-8685
FAX 828-837-0846

Springfield Operation
750 West Sproul Rd.
Springfield, PA
USA
19064-4084

610-328-4000
FAX 610-328-4016

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