Drawbridge Control as Total System Design

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SYNOPSIS

Drawbridge control design has remained almost static since the early 1920's; being based on manual torque control of wound-rotor motors and crude relay logic to enforce the interlock sequences. The maturation of solid-state electronic variable speed controls for motors, Programmable Logic Controllers, and electronic sensors offer the control designer many new options. Since this new technology comes from industry, the manufacturers and sales representatives are familiar with the industrial environment where many PLC's and Drives are operating in the same location and afforded tender care by trained control technicians. The drawbridge's operating and maintenance environment is totally different; and, due to the relatively small potential market, an application with which the equipment suppliers are only vaguely familiar. Many of the manufacturer's well meant recommendations are not suitable to our application and special reliability requirements.

This paper is based upon thousands of hours of experience and study of the operational requirements and failure modes of drawbridges, and the maintenance requirements and abilities of typical DOT and other civil engineering based organizations which wish to make use of the new technology but can not provide the support structure afforded by industry. The design guidelines recommended here are specific to drawbridges, not to paper plants or steel mills ... the very significant differences must be recognized by the designer when listening to a manufacturer's rep that has probably never set foot in a bridge control room or had to duck rocks and bricks when the bridge is inoperative.

A relay is a relay, when a design is completed by revising the drawings from the previous 30 years of designs there is little need to supply the control fabricator much freedom in circuit configuration. The new technology requires much greater freedom of circuit design to take advantage of the different characteristics of the various PLC's. New performance oriented specifying and purchasing procedures are required to assure fair bidding and to benefit from the control vendor's expertise. It's a new ball game and we're just evolving the new rules.

IN GENERAL

Don't Rush In Just To Use The Latest Thing - We have seen designs that use PLCs to implement the same logic as previously performed by relays except to include analog speed control for the variable speed drives. This we consider a mistake; the control logic has not gained any significant power while losing its maintainability by electricians, and the drives and all machinery are dependent on the PLC for operation. We urge that if the PLC is not to be used as a computer, to enhance the reliability and maintainability of the bridge above what is possible with relays, then stick with the relays. Nothing is lost in the operation of the bridge and you have equipment with which your electricians are competent and comfortable.

Circuitry such as 4-20mA analog loops are very common in industrial process control and specified without thought. Electricians are not used to such circuits and do not know (nor need to know) how to troubleshoot or repair them. The PLC affords the first "single point failure mode" where the loss of this component can shutdown every bridge operation. Design allowances must be made to permit emergency operation in the remote possibility of a PLC failure and to permit segmenting of the system for initial commissioning and for routine maintenance. We feel strongly that the PLC's function is Captain of the bridge, ordering the various crew members to perform their individual tasks while overseeing and supervising everything. Each crew member (drive) must be capable of operating independently without benefit of the PLC enforcing the interlock sequence, and thus depending on the Operator's eyes and intelligence for safety if the PLC is incapacitated.

It's easy to make a bridge run when everything is working properly. The mark of a good design is to make the bridge keep running when things break; or to restore it to service as soon as possible after an equipment failure.

On Terminology - We use "drive" to mean any item of equipment operated by the control system (Traffic Safety Gate, Brake, Span Drive Motor). The Variable Speed Motor Controller, usually referred to as VS Drive, is part of a span's motion drive.

"Owner" (or "Department") indicates the bridge's owner in the usual contractual sense, and does not indicate ownership of any vendor's proprietary process or materials.

"Vendor" or "system supplier" refers to the system fabricator or assembler that detail designs and builds the control system using both materials he manufactures himself and components he purchases from manufacturers.

"PLC" means Programmable Logic Controller to differentiate from personal computers and from the other forms of programmable controllers that program in languages such as BASIC, etc.

DESIGN & SPECIFICATIONS

Detail Design Responsibility

We don't see how a design consultant can be familiar enough with all available PLCs and ancillary circuit configurations to detail such circuit's as precisely as is done for relay circuits. A vendor who spends full time on PLC applications in the particular civil engineering field should have greater specialized knowledge of the practical circuit and logic configurations for the PLCs that he uses than does a consultant (unless, of course, the consultant spent full time on applying PLCs to drawbridges). The goal of the consultant should be to specify the system form, response, and performance desired; and then review the vendor's proposed implementation to assure compliance with the specifications. Control equipment specifications should be left as loose as possible except as to quality, environment, and performance requirements.

The arrangement of the Control Desk operator controls and the I/O types and count are important to establish a common standard for bidding. Equally important is to specify a minimum size of PLC I/O capacity, memory, and memory type to provide equality in bidding. (If the specs don't establish equipment minimums, the vendor that knows what he's doing is at a real disadvantage compared to the industrial vendor that isn't familiar with the particular needs of a bridge project and isn't going to design to meet them.)

The initial specifications should hold the control system vendor fully responsible for the detail design and implementation of the control system. Requirements that any bidding vendor be qualified as to engineering capability (state certification being an easy to implement requirement) and prior applicable experience and knowledge is almost mandatory to assure a satisfactory system.

Anticipate and plan that a knowledgable vendor may recommend changes in the physical or logical design based upon his expertise that will result in significant improvements to the system for relatively minor contract price changes. No matter what the expertise of the consultant, changes in control and power equipment are so rapid today that any specification design is almost sure to be outdated before the plans are issued for bid.

Use Of Licensed Proprietary Software

The secret to utilizing the power of the PLC, as with all computers, lies in the power and elegance of the software. The basic sequence enforcing (relay replacing) part of the program is quite simple to write and short ... a small 1k memory can handle this task. To produce what we consider a bare minimum program requires 2k-3k of memory and much more sophistication in the program's algorithms. A satisfactory system that provides for the operator guidance, fault tolerance, and maintenance guidance we consider proper given the present state of the art in industrial control configuration requires 5k to 8k of memory and represents many hundreds of man-hours programming effort.

The cost of such a program's development readily explains why such systems are just beginning to appear on civil engineering projects. Industry amortizes such programming over multiple machines or it represents a negligible part of a multi-million dollar process line. In the computer (back to PCs) applications industry, thousands of copies of a word processing software package will be sold for hundreds of dollars each to return (hopefully) a profit to the programmer. In our field, the programming labor would equal or exceed the balance of the total engineering design effort on a bridge. While a bridge contract may be for millions, the control package is typically between $50k and $200k ... the vendor can't invest the programming manpower into such a single contract. So control designers are stuck between knowing what is proven and common practice in industrial applications, and clients who are unfamiliar with the possibilities and benefits to be derived from applying these modern control techniques ... and any slight interest is quickly squelched when you offer to perform these miracles for only a $10k increase in material cost and $250k programming labor cost.

If a Department has enough bridges to justify the development costs, then total system detail design is a possibility with the Department being responsible for all programming support. ......

...... Another answer comes from the exploding PC applications software field ... license the use of a "standard" control program. A vendor develops a specialized drawbridge control program and system at his own expense on the expectation of recovering his expenses and making a profit spread over a number of bridge projects. The basic program provides for all the standard control functions and is modified for a particular bridge only the minimal amount required to adjust the number of TSGs, leafs, and miscel. alarms. Such a system (surprise) is /ese/'s "Span/A\Mation" control system [NOTE: Span/A\Mation and the abbreviation S/A\M are trademarks of /ese/, Inc.; the S/A\M program is the copyrighted property of /ese/].

The cost of a proprietary software license for use on a bridge is approximately the same as the purchase or development cost of minimal system software that offers none of the control advancements we are discussing here. The restriction is that licensed software is for use on a single bridge and is not the Department's property to freely duplicate and use on all their bridges (the vendor must sell many copies in order to return a profit on the sizable programming investment).

A fringe benefit of the use of proprietary software is program warranty and support. As with PC applications software, when improvements and enhancements are made to the program they may be added to the bridge's control system as updates at low cost. Unlike previous control technology where the design is frozen at commissioning, a PLC based system can grow to incorporate new features such as unmanned automatic operation without any significant equipment changes (assuming the initial PLC is specified of sufficient size to allow updating and expansion).

Since, as a program licensee, the Department or bridge Owner is basically at the mercy of the program's owner (the vendor) when it comes to future updates, the license should contain provisions for programming support during the initial shake down period and access to the program's source code listings in the event something happens to the vendor. At /ese/ we offer full program support for a 1 year warranty period; the only restriction on program changes is that they be possible within the limits of the installed hardware. After the warranty period, we charge our standard hourly rates for reprogramming unless the Owner has entered into a maintenance agreement with us.

The program source code is not critical with existing PLC's since the programming terminal will permit reading out the PLC's program in standard ladder diagram format; a much better situation than trying to disassemble a PC's machine specific binary program code. However the annotated listing of the program with explanations of how the program operates and access to the designer's notes would be a great help to another programmer that needs to make changes should the original vendor no longer be available. At /ese/ we assure availability of the program listings by archiving them in secure storage along with Copyright releases to be turned over to our licensees in the event we are no longer around to support the software. You should insist on some such arrangement with any licensed program.

Why such concern about the program, after all a copy comes in the maintenance manual? Wrong! The program is the copyrighted property of the vendor, that's why the Owner is licensing it rather than buying it. In a properly designed system, the program listing is not needed for maintenance (or even helpful, see Program Submittal below). The program in the O & M manual will normally be presented in flowchart form which is useful for maintenance.

Program Provision For Sequence Options

The program should be written with sequence step options controlled by data bits so that the sequence may be easily modified by non-programming maintenance personnel without any program modification required. Examples of such options are: push button seal-in (whether momentary action or sustained hold down required of control switches); automatic or manual program advance (eg TSGs automatic lowering seconds after TSLs are red; leafs automatically opening after locks are drawn) - very important for possible remote control. A properly written program permits the Owner's adjustment of the sequence without need for a programming terminal or a trained programmer's skills.

Design Submittal Documentation

Program Documentation With Flowcharts - Electrical designers and electricians associated with bridges are used to ladder diagrams for relay logic. These diagrams are vital to troubleshooting and repair of such circuits since cause and effect can only be determined by following the diagram. For simple PLC control programs such diagrams serve the same purpose; for more complex programs such as being discussed here, such a diagram is almost impossible to follow by any except the author or a skilled programmer with lots of time to study and chart out the program. In relay logic the relationships between inputs and outputs are direct and simple; in PLC programs an input may be processed thru many steps including mathematical manipulation and sequencers before controlling an output ... it is much more practical to use the PLC itself to inform the operator or electrician in plain english via an alphanumeric display why things have stopped.

The purpose of program review is to assure that the system being supplied will RESPOND to commands and events in the desired manner, the logical or mathematical manipulation required to produce these responses is not a subject of normal specification compliance review. How the system will react is documented much clearer by sequence or logic flow charts than by program listings; the programmer will sketch such flowcharts for many operations before trying to write the actual program (he can't follow the ladder diagram listing very well himself; it's the PLC's language, not man's).

Flow charts can be drawn to several levels of detail. The level required for review will depend on the reviewer's faith in the ability of the programmer and his own skill in programming. We call a "Level 1" flowchart one which shows the entire operating sequence for a normal automatic opening plus the alarm and miscel. annunciations. Such a chart will normally fit on a single sheet and is usually the only program submittal required.

"Level 2" expands the chart to show the responses and messages generated by equipment failure and the bypass operation required of the Tender. Such a detailed chart would be included in the operating instructions and could be the required design approval submittal.

"Level 3" charts show the system's response to every possible event or combination of events including any control operated at any time including all possible conditions of manual operation, and the operating details of each control algorithm. It would be a ......

...... many paged monster that should be reserved for request only when it is apparent that the vendor or programmer really doesn't know what he's doing, and the reviewer does. Such a flow chart is so segmented, and has so many connecting links, that it's almost as hard to read at the ladder diagram listing. Unless specified in the purchasing documents, such a listing would never be supplied as part of a control system. Such a listing would probably not be available for a licensed program since it could disclose proprietary material.

PLC I/O Diagram - The PLC's interconnections with the external control sensors (inputs) and drives (outputs) must be reviewed for compliance with the overall design including the various limit switches and interconnection wiring requirements. At the same time, the CD's intraconnections between the PLC and the control switches and displays falls into the area of detail circuit design which may involve data buses, input and display multiplexers, and other specific circuit details that are not normally part of design review but fall into the area of shop drawings.

The I/O drawing as shown in Figure 1 has evolved to depict the relationship between system components without getting mired down in circuit detail. The control switches and indicators are represented as shown in Figure 1A for correlation with the CD's panel layout; while data busses are represented at shown in Figure 1B leaving the exact TTL signal input details up to the designer.

PLC Specification

The processor should be specified as an industrial grade Programmable Logic Controller constructed to NEMA and UL standards and interfaced with standard plug-in interface modules which are surge and transient rated to NEMA standards. It is not only possible, but practical, easy, and extremely cost effective, to implement control functions with a "monocard microcomputer" also know as a "computer-on-a-card" interfaced with optocouplers and solid-state relays. Such a custom computer would be very difficult to service; the user would be virtually tied to the builder for any maintenance support. Without the testing and known reputation of the major PLC manufacturers working to NEMA and industry (primarily automotive) specifications the durability and maintainability of such a system would be very suspect, and the reviewer would have to be an industrial computer and electronics expert to even begin to judge such a system.

Our experience indicates a minimum 8k PLC with advanced sequencer and math instructions is necessary to run a full program with the features described in this paper. I/O rack capacity is hard to pin down since multiplexers and double density modules make the rack's basic size rating meaningless. Our experience indicates a minimum 256 I/O addressing capacity is advisable.

We are strong opponents of RAM program memory with battery backup. It's fine until the battery goes dead and isn't replaced; then the memory is erased on the first power failure. Our first choice for program (or backup) memory is EPROM with a second choice of magnetic core or bubble. Many of the larger processors only offer core which simplifies the choice. We would not accept any PLC that didn't use nonvolatile, not battery dependent, storage for program backup memory. Such memory is also required for the messages and any other stored system information.

OPERATOR INTERFACE / HUMAN ENGINEERING

The Obvious Control Arrangement

Our years of experience struggling with the application of human engineering to the design of control panels for broadcast stations, military communications systems, and industrial control units didn't prepare us for our first exposures to drawbridge control desks. Even though the control sequence of a bridge is fairly simple, and we thought our technical knowledge adequate, study of the control arrangement and legends didn't give more than the vaguest hint what each control accomplished or how to run the darn thing. These were not antiques, although they closely resembled a control system we replaced that was manufactured in the early 1920's. There was no hint of consideration by the designer of the operator oriented control layout concepts that were developed by the military during WWII under the term "human engineering" and have now been stuck with the strange buzz word "ergonomics" to indicate work-economics.

Industry does not expend funds or effort to incorporate ergonomics because it makes control panels look "neat". Designing to the operator (since we can design the panels; no matter what our desires, we can't redesign the operators): reduces training required, it's easier to learn the obvious; reduces the possibility of operating error, especially under stress; and reduces machinery stress and wear by anticipating operator limitations (such as in producing a consistently smooth span seating) and compensating for them.

Most conventional designed CDs we've seen have been decorated by additions such as mail box numbers glued onto the panel to indicate the sequence of operations. The layouts seem to have been determined by a draftsman who had never visited, less more operated, a bridge ... the controls and indicators are arranged in geometric patterns that please the eye on a drawing. When we started out to develop S/A\M we began with a blank sheet of paper, we designed the software, hardware (sensors and drive interfaces), and control panel as a integrated unit; then modified the designs to conform to the expected norms.

A typical CD panel is shown in Figure 2. The panel is divided into four areas by function: Automatic Operation - those controls used for normal operation and maintenance. Manual Operation & Maintenance - indicators that directly indicate the various sensors' (limit switches, etc) status; and control switches that in normal operation may be used to manually step the equipment thru all or part of a sequence, and in the maintenance mode (enabled with a key switch) perform the "force" testing function to control any drive independent of the sequence control logic. Utility Controls - the general utility and housekeeping controls such as main power volt/amp meters, house light switches, generator controls, and miscellaneous alarms such as pier flooding ... we feel these controls should be in a separate panel away from the control desk, but with the exception of one LA design we saw, haven't gotten anyone to agree with us. Communications System - paging channel selectors, handset and speaker, telephone interface circuits, and marine radiotelephone.

Typical moving span control panels are shown in Figures 3 & 4. Distinctive is the arrangement of controls on a outline drawing of the bridge so that control locations "mimic" the actual locations on the structure. This graphic control arrangement has been standard in industry for many years and aids the Tender's grasp of the use of the various controls and the interrelationship between the Automatic Panel and the status indicators on the Manual Panel.

Automatic Control Panel

The Automatic Control Panel is shown in Figure 3 for a 2-leaf bridge. The design rule is that each drive operation that is potentially hazardous to the public (TSG lowering, leaf rasing) must be initiated by the Tender who acts as the system's eyes to determine when things are clear ... thus a pushbutton for each such drive. When the opening sequence is initiated by pressing the (OPEN) button, the sequence (OPENING) indicator lights, the automatic control sequences the TSLs to red, pauses the required time, then instructs the Tender to "Lower TSGs" on the a/n display. The TSG buttons' (UP) indicator slowly flashes to guide the Tender in operation, when the buttons are pressed the corresponding TSG lowers and the button flashes rapidly to indicate machinery operation (whether maintained holding down of the button is required is a selectable program option as is the gate's automatic lowering after a suitable delay without Tender intervention).

After the gates are fully down, the controls automatically release the brakes in sequence (and also draw the locks on bridges so equipped). The Tender has the option of selecting single leaf operation by momentarily pressing either of the (SELECT) buttons ... all leafs, sequenced as required, is the default selection. When the machinery is ready for an opening the a/n display instructs the Tender to "Raise Spans" (it has been informing him of the various steps as they were taken) and the (OPEN) button slowly flashes to invite operation. Pressing the (OPEN) button momentarily starts the leaf(s) raising which will continue to full open unless terminated by the Tender pressing the (STOP) button which produces a deceleration controlled soft stop of the leaf at any intermediate position.

While any machinery is operating on the bridge, the (STOP) button flashes and will stop whatever machinery (TSGs, locks, leafs, etc) is operating; a separate (EMERGENCY STOP) mushroom button removes all power from the control systems outputs, over riding the computer and causing an instant hard stop of any machinery operating. Span position is indicated as a 0-100% rising red bar on the solid state bargraph meters, and motor speed is indicated on the optional tachometer meters.

Once the leaf(s) has been lifted and is stopped, the (CLOSE) button flashes; if the leaf isn't full up, the (OPEN) button will also flash to invite the Tender to resume leaf motion in the appropriate direction. When closing, the automatic sequence assures a soft but full seating by controlling both speed and torque. When the leaf contacts the live load shoes the drive stalls out at the reduced torque limit, firmly placing the shoes in contact. The PLC then reduces the drive's speed to zero which permits any mechanical windup to release slowly, the service brakes are set, and the drive shutdown.

After the spans are fully seated, the automatic sequence sets the machinery brakes and drives the locks. The Tender is then invited to "Raise TSGs" and the (UP) indicators of the gates' buttons ......

...... flash to direct the Tender to the proper switches. Momentary operation of the buttons causes the gates to fully open and the (STOP) button will stop gate movement once started. When the gates are fully open, the TSLs return to green and the sequence is reset to the wait condition.

The heart of the Tender-Control interface is the alphanumeric display which produces 20 character messages, 1-line in a minimum system and 2-lines in the full S/A\M system. During normal operation the messages displayed are almost trivial and the Tender could operate without them; but when things go wrong, the a/n display takes over to inform the operator what is wrong and what corrective action to take (reset or use bypass controls) to operate the bridge. The a/n display replaces 250 different pilot lights and presents clear human messages instead of the cryptic legends possible on pilot lamps. In addition, the display incorporates variable numeric data into messages to show the opening count, time & date, and to display the PLC's program constants in the maintenance mode.

Manual Control Panel

A typical Manual Panel is illustrated by Figure 4. The basic panel configuration is determined by the maintenance mode's need for a indicator light for each limit switch or operation sensor, and a control switch for each drive control element (motor starter, etc) for force testing. The maintenance requirement is then blended with the operating mode requirements for manual control of each step of the bridge operating sequence. Examples of the compromises to meet the needs of both modes of operation of this panel are: The brake starters need only a single switch for force testing, but start (Release) and stop (Set) switches for manual operation; therefore the (SET) switches aren't used in the maintenance mode. Conversely, the leaf drive controls require some form of speed control in the maintenance mode, but in the manual mode the speed is automatically controlled by the PLC; here the TSL switches are used to control speed in the maintenance mode.

In manual mode the interlock sequence is enforced by the PLC and the leaf speed is controlled by the PLC from operator input rather that the leaf position indicator. Speed control is different from the automatic mode in that it depends on the Tender to determine deceleration points by releasing the individual span buttons and provides back-up control in the event of a position sensor failure. No operations are automatic, the Tender must turn the TSLs thru Yellow to Red, then lower the each gate, release each brake, and draw each lock before the PLC will permit leaf operation. Manual is equivalent to operation of a tradition relay based control system except there are separate controls for each drive whereas on a tradition system a single switch might operate all brakes and another all locks.

Emergency (Bypass) Operation

Whenever the Tender attempts to operate a drive out of the permitted operating interlock sequence, whether because of drive failure (a TSG won't move and traffic is being controlled by a flagman), sensor failure (the gate is down but the limit switch didn't operate), or special needs (lower a single gate to block one lane for a repair crew ......

...... while other lanes are open) the a/n display indicates the problem and suggests the correction with a message such as "NrOn TSG Not Down - ByPass?". There is a separate bypass pushbutton for each drive group (Lights, Gates, Brakes, Locks, Spans), and the appropriate button slowly flashes to invite operation. Operation of a bypass switch is only possible at the step in the operating sequence where the bypass is required and only affects the one drive sensor; if all four TSGs require lower bypass, the (GATE) ByPass button will have to be pressed four times in response to the messages. As a further safety precaution, each bypass is effective for only one opening sequence; at the end of the sequence all bypasses are cleared and must be manually reentered during the next sequence. The button flashes rapidly during the sequence in which the bypass is effective, then remains lighted steadily until reused or reset by the Supervisor's keyswitch.

The bypass operation was carefully designed in response to several mishaps that have occurred. First the telltale lock-in of the bypass switch's light until reset by a supervisor prevents the situation where a Tender's defense is that he couldn't have jumped the sequence because he didn't use a bypass, but there is no way to prove the switches weren't used; or a Tender coming on duty isn't told that bypasses have been used and their use wasn't recorded on the operating log. Any Tender faced with a red telltale light will make sure it's noted in the log so they won't be responsible for it.

There is significant chance of accident where traditional bypass switches bypass an entire group of interlock switches (such as all TSG interlock limit switches) and a second equipment failure goes unnoticed; this is prevented by bypassing limit switches individually. This is an excellent example of a circuit feature that can be implemented with a PLC and not feasibly with relay logic (unless you want 30 bypass switches, and can figure out how to tell which one needs operating).

We know of an accident where a Tender used a bypass and didn't tell the replacement. The new Tender didn't notice the bypass was on and failed to lower the gates before opening. Resetting all bypasses each opening prevents either forgetting or failing to notice a bypass is active.

Logging

An automatic system should include a log printer or other form of log recorder to keep a record of all bridge operations. For normal operations the log provides statistical data about each opening including: the time from sounding the horn acknowledgment to the opening ("they kept me waiting 40 minutes"), the time traffic was stopped ("25 minutes is outrageous"), and the opening times. Such information is important to defend against unwarranted complaints as well as scheduling and identifying trouble spots where corrective action may be indicated.

Whenever a bypass control is used the log records the date & time, opening number, and specific switch bypassed. This information can be quite valuable to the maintenance electrician trying to identify which limit switch is intermittent, as well as invaluable as legal evidence in the event of an accident

When drives are fully connected to the PLC to report all internal alarms, the log records the specific equipment alarm(s) produced on a fault. ......

...... This feature alone justifies the inclusion of a log by greatly increasing the repairability of the system. Concrete and steel may not suffer form intermittent faults, but electrical systems sure do ... and such faults can take months, or years, to find. It is the nature of an intermittent that the service man's mere presence on the bridge will cure it ... until after he leaves. A record of exactly what was wrong permits finding and repairing most faults. Also, we won't say that Tenders ever give confusing or inaccurate reports of equipment failures ... but logs don't!

DESIGN IN RELIABILITY

Industry has proven that reliability can be designed into a system. It is much easier to design a system that will run than it is to design one that will keep running. Some things are obvious such as proper transient protection for we lightning prone Floridians, or low temperature equipment ratings or protection for the Yankees. Some areas that have attracted our specific attention for bridge controls are:

Redundant Limit Switches & Wiring - Fault Tolerant Sensing

Limit switches seem to be the most failure prone electrical control elements on a bridge. Figure 5 illustrates a TSG interlock circuit (copied from one of the newer bridges that we have serviced) that not only is susceptible to failure because it uses multiple switches to accomplish the necessary operations (and 3 switches fail three times as often as one switch), but is also very difficult to repair. The series connected 230V interlock circuit is very difficult to troubleshoot since both sides of an open measure 115V to ground or common and standard electrician's testers can't differentiate which hot leg is being measured.

The PLC's logical processing ability and redundant limit switches come to the rescue in the configuration shown in Figure 6. One NO and one NC limit switch is used to monitor each position of each critical drive. The opposing switch operations permit the convenient H-O-A emergency operation switch arrangement shown in Figure 8. By feeding each of a pair of switches with separate wires and using separate mechanical operators, the switches are made as independent as practical. The PLC program monitors switch transitions rather than absolute condition so that it will sense a "stuck" switch and uses majority voting logic to determine drive position when a switch fails. Yes, two switches will fail twice as often as one; but the chances against both failing at the exact same time is astronomical, and the ability to make the repairs on a schedule basis rather than an emergency basis far outweighs the additional repairs required by using four limit switches rather than two ... four is still fewer limit switches than used in a relay TSG control circuit. The PLC generates an alarm message on single switch failure but continues operating normally (no bypass required) so maintenance can repair the switch fault without interruption of bridge operation.

Isolated Ungrounded Power Supplies

In marine design, ungrounded (actually high impedance grounded) power distribution is the norm for three reasons: Vessel Safety - many critical circuits such as steering gear and propulsion control must keep operating even with a short to ground on a power leg. Personnel Safety - in a tossing sea it's easy to get thrown against a hot conductor while standing in salt water on a steel deck. Hull protection - routing ground currents thru a metal hull can dissolve the darn thing and ruin your whole day. The increased reliability of isolated power is very applicable to bridges, especially when transformers are already desirable such as for line regulation and transient protection of the control circuit, or for voltage stepup and noise filtering of electronic drives.

Figure 7 illustrates an isolated ground supply with ground fault detector. A foreign ground fault, even a motor winding shorting to case (a common fault mode for electric motors), doesn't halt operation. The fault current is limited by the grounding impedance and trips the current sensing relay to produce an alarm so that maintenance can correct the fault without interruption of operation. Additional benefits of ungrounded power circuits are the great reduction of damage caused by accidental grounds (especially in wiring and motors); and greater protection from power line transients which are a major source of "unknown cause" motor and electronics failures.

Emergency (H-O-A) Controls

It is common to see Hand-Off-Auto (H-O-A) switches on industrial motor controls for service and emergency operation. We've never seen such controls on any bridge ... guess industry considers it more important to keep its machines running that governments consider it important to keep bridges running. A relay based control system will normally only lose one or two circuits on an equipment failure, and they can be either worked around with the use of bypass switches or a reasonably skilled electrician can do some fast haywiring. As reliable as they may be when properly installed; in a PLC based system when the control dies, everything is dead.

Individual H-O-A switches on each motor controller are relatively cheap operating assurance. It may take two or three people to operate the bridge (one looking for safety & issuing go-ahead clearances); but the bridge will be operating. Plus the H-O-A's are very useful for individual drive exercising and testing during maintenance such as adjusting and testing each brake. The use of dual limit switches as discussed above permits a H-O-A circuit such as shown in Figure 8 to have limit switch controlled motion and indicator lights that are totally independent of the CD and PLC.

Speed Control Integral To VS Drive

There is a strong temptation to use the power of the PLC to continually control the VS drive's speed either thru an analog (4-20mA) or digital channel; we have designed and built such a system. Our experience has shown that there is no need for continuously variable speed control, three speeds (approx 5%, 15%, and 100%) adequately handle even the precision meshing of mechanically locked leafs. ......

...... Use of analog control signals introduces a failure prone circuit that is extremely difficult for an electrician to adjust or troubleshoot and does not improve the operation of the leaf drive. Continuously variable speed commands also introduce some significant programming hazards that are best avoided.

The VS drive itself supplies the needed continuously variable speed thru its internal acceleration and deceleration ramp controls. By leaving the speed control in the drive and relegating the PLC to only command the discrete preset speeds, the drive is much more independent of the PLC for H-O-A manual operation in an emergency. Custom control circuitry and programming cannot normally compete with the VS drive's fully developed and mass produced internal speed control circuits.

Select Components Suitable For Environment

This is the age of "new and better", especially in the field of electronics. Unfortunately just because something is new and much more technically sophisticated doesn't always mean it's better for a specific application. Transient susceptibility (bridges are extremely susceptible to lightning induced transients for reasons too technical to go into here), and maintainability with existing personnel, are two reasons for carefully considering the ramifications of any component change.

Limit Switches - Electronic proximity limit switches are one component we are very hesitant to recommend or use. Their extreme susceptibility to transient damage, especially with mounting locations spread all over the structure, make their reliability doubtful. A standard industrial rotary arm limit switch is a very dependable device when properly mechanically arranged. The major failures we see are caused by improper alignment of the actuator, improper design selection of the operator arm, and failure to use sealed corrosion resistant units (when it's eaten away, it doesn't matter if it was mechanical or electronic). When non-contact sensing is desired, such as to permit misalignment, the vibration tolerant and corrosion resistant electromechanical magnetic sensing proximity switches such as "GO" switches appear to be a good alternative.

Position Transmitters - There seems to be an almost lemming-like desire to specify any alternative position sensor except a synchro transmitter; yet the synchro resolver has proven qualities that seem to make it the best choice. It is common to see synchro position indicators that aren't working; but this is almost always a mechanical fault of the complex gearing of the fancy two pointer bridge picture indicators than of the synchro equipment itself. We have yet to see a failed synchro (although there surely are some). The electric motor construction is extremely resistant to transient induced damage (as opposed to any of the suggested electronic replacements); the associated wiring and signals are normal voltages that electricians are comfortable with (as contrasted with TTL level signals and many paralleled conductors of optical encoders); the resolution, with only 5 wires, is excellent and well exceeds the requirements for bridge control; and the construction is rugged and suited for the bridge's machinery deck environment. In addition, the synchro is self calibrating; ......

...... hook two units together and you've got a complete indicator loop without any electronic decoders, dependence on the PLC for emergency operation, or use of logic bus probes and special training for alignment.

Modern synchro to binary converters can feed the PLC with up to 16 bits of resolution if required; although our tests and experience indicate 8 bits is perfectly adequate when the synchro is geared so that full travel of the leaf produces approximately 270 deg rotation of the transmitter (this amount of rotation is important, not only for resolution but also for mathematical reasons within the control program). Manual or standby synchro indicators should be the direct pointer (non-geared) type where the pointer moves the same distance as the transmitter over a scale that is calibrated in degrees or percent rotation of the leaf. Gearing the pointer so it moves the same angle as the leaf requires a very expensive indicator that has proven mechanically unreliable ... as a matter of fact, the main position indicator failure mode we have seen is the pointer has simply fallen off its shaft, the second most common fault is the cover glass has been smashed down against the pointers or broken.

Minimize Single Fault Points

A control system has single fault points that will render a leaf or the bridge inoperatable. Such points are the motor or its controller; few drives, other than some leaf drives, have two motors and will keep moving when a motor dies. Another is the electrical main, no power no go. The PLC and electronic VS drives introduce new single point failure modes which may be (at least partially) design compensated for.

There doesn't seem to be much that can practically be done about the PLC processor and its power supply, fortunately these components are remarkably reliable when properly installed and protected. The PLC I/O modules are less reliable components due to their exposure to the outside world.

In a S/A\M CD the controls and indicators are arranged to minimize single point failure. The Manual Panel and other assorted pushbutton switches are connected to the PLC thru a contact multiplexer (logic level switching) while the Automatic Panel switches are connected thru discrete 120V input channels; thus failure of a single input module or auxiliary power supply will not disable both sets of switches and operation is maintained. Similarly, the Manual Panel and a/n display are controlled thru a multiplexed TTL level bus while the Automatic Panel and alarm indicators are controlled with discrete 120V outputs. As described in the Manual Panel's operation, the circuit and program contains provisions for alternate leaf control in the event of failure of the position sensors or convertors.

There can be no denying that electronic VS motor drives are, if not more subject to failure, much more difficult to repair than regular across-the- line motor starters. Although we are not familiar with any such installations on bridges, it is common practice in water and waste water applications and critical industrial applications to have a spare standby drive installed with switching provisions to permit it to be quickly switched into service as a replacement for any of the regular units that fail. ......

...... The only special requirement is that provisions be made to regularly rotate the units in service since standing idle for a long time will almost guaranteed the death of the standby unit. This option of a standby VS drive should be considered for critical bridges.

Hot Standby (Redundant) PLCs - Some processes are extremely critical to keep operating continuously; such as a steel furnace or glass production line where even a short term non- scheduled shutdown will produce destruction of product or equipment. In these cases cost of control equipment or maintenance requirements is unimportant compared to preventing any interruption of the process. Typical in such an installation is dual (or triple, or more) redundant processors with one processor running on hot standby with its memory always updated and ready to resume control if the operating processor as much as hiccups. The Space Delivery System (aka the Shuttlecraft) uses both three and five computer redundant arrangements.

Note the key word is "continuously" ... bridge controls don't operate continuously; as a matter of fact the percentage of time the PLC is actually working is quite small compared to most industrial applications. And while the continuous control reliability of a redundant processor is much higher that a single processor, the equipment failure rate is many times higher. Not only do N processors fail N times as often as a single processor; but the extremely complex voting and control circuitry required to monitor and select the processors further increases the fault rate. The end result is that if you do a lot of careful maintenance, fixing everything as quickly as the failures occur, you'll probably never miss an operation because of processor failure; but will have done many times the normal amount of maintenance.

The catch is that for a awful lot of extra equipment expense and maintenance work, you really haven't gained any significant reliability increase as far as a bridge is concerned. The processor is one of the most reliable devices in the control system, and a redundant processor still uses the same I/O module arrangement so the statistical improvement in reliability is negligible in a bridge's control system. Needless to say, we do not recommend redundant systems.

Safety & Protection Circuits

MAIN POWER SHUTDONE is required by any designer that has experienced an electrical fire. We've seen the results of such fires, especially with PVC wire insulation, and fully agree with the need for this safety circuit. The most secure circuit uses an undervoltage trip coil in the main entrance circuit breaker so that power is shut off if a wiring fault occurs in the shutdown circuitry; unfortunately such a circuit also requires the operator to reset the main breaker after each power failure, even though the generator and ATS have automatically begun supplying power. We recommend a shunt trip coil in the main breaker operated by a CD panel mounted switch which is periodically (semi-annual) tested.

An EMERGENCY STOP CIRCUIT is mandated by codes and recommended practices for computer based solid state control systems. The E-Stop circuit supplies power to the PLC's control outputs thru an e/m Master Control Relay that is 3-wire controlled ......

...... by the Control Power switch and E-Stop button; this assures control power will also be removed following a power outage and require operator reset before any motion of drives resumes.

SAFETY DISCONNECT SWITCHES should be mounted on the structure adjacent (per NEC) to any drive motors that are a maintenance personnel hazard such as the leaf drive motors. Hazardous manual controls such as hand cranking provisions must be equipped with interlock switches to prevent accidental starting of a drive when a crank or operating leaver is attached.

BRAKE LIMIT SWITCHES should be provided to indicate the fully set and fully released condition of each brake. Many leaf drives can overpower a single brake and move the leaf; this can damage the drive by overloading and cause a fire hazard by extreme heating of the brake. Traditional designs included brake manual release limit switches which are interlocked to prevent rasing the leaf unless minimum safe holding brake power is available.

LEAF DRIVE MOTOR OVER-TEMP SWITCHES are recommended to prevent damaging the motors under protracted slow speed operation. These motors are sized and rated for relatively brief operation at slow speeds where the internal cooling circulation is very inefficient. In normal operation this limitation is not important; but during testing or abnormal emergency operation, the motor may overheat and be seriously damaged if not protected by power being removed by an over temperature interlock.

A DISCONNECT SWITCH INTERLOCK in the form of an auxiliary contact on the motor's safety disconnect switch to disable the VS drive is recommended for drive protection. Some electronic drives may be damaged by attempting to operate into a open circuit; most drives would be damaged by opening the circuit while the motor was operating.

STANDBY GENERATOR INPHASE SWITCHING CONTROL or Time Delay On Neutral (TDON) control is required to condition the ATS switching from emergency power back to normal power. Switching to emergency power normally follows a power failure by some time during which the generator is started and brought up to speed; this gives spinning motor loads on the bridge sufficient time to come to a stop. Return switching from generator back to normal power is a different manner; being almost instantaneous. This is fine for the lighting and normal loads for which these general purpose emergency ATSs are designed; but is very dangerous for spinning motor loads. Unless the ATS either delays on neutral to permit the motors to stop, or has a phase sensor that only permits switching when the generator and mains power are nearly in phase; the inrush currents caused by the motors being out of phase with the mains power can be destructive to the motors, VS drives, and motor control components ... at a minimum, several circuit breakers will have to be reset.

CIRCUIT MONITORS may be indicated for some functions whose failure will not be obvious to the Tender. A glaring example is the traffic signal lights and navigation lights which may be monitored by simple current sensors. TSLs are usually not visible to the Tender; ......

...... and, because of their low and random usage, failure is not notices or reported by regular law enforcement traffic. Control and sensor circuits may be monitored by passing a small current thru the circuit that is well below the operating threshold and monitoring this current for any circuit failure such as an open or loss of power. S/A\M uses a zero offset to monitor the validity of the binary position signal from the synchro converters.

PLAN & PROVIDE FOR MAINTAINABILITY

As with reliability, maintainability should be designed into a circuit rather than depending on chance. Figure 8 is a classic example of a circuit that could not have been deliberately designed to be harder to troubleshoot and repair. There is a wide communications gap between designers and maintenance personnel ... there is little feedback about what circuit elements are actually failing and why, and the designers have little grasp of the troubleshooting skills and techniques of the maintenance personnel.

Specific maintenance areas that are attracting our attention are:

Operator Maintenance (Resets)

Draw Tenders seem about equally split between those that have some knowledge of the equipment and can handle routine resets and adjustments, and those that are strictly button pushers and have no technical idea of what's going on, or why. It's a pity to have a bridge out of service while an electrician has to drive miles to reset a random circuit breaker tripping. It's also a pity to have a bridge put out of service for several days when a operator leans on a seating limit switch bypass and burns out a motor. System design needs to acknowledge there are two levels of maintenance, operating and repair, and provide for non-technical Tenders to supply a first level effort at restoring service. The more safety circuits and monitors are included in the system, the more important Tender maintenance becomes.

DIAGNOSTIC INSTRUCTIONS can easily be provided by the PLC and the a/n display when all overloads and trip circuits report to the PLC. The display can instruct the Tender exactly which reset button to push, and can even be programmed to tell the Tender where the button is located. Connection of trip circuits to the PLC is required for complete data logging and is not a major addition in terms of expense; multiplexing techniques permit the addition of many such circuits with small penality in cost or size.

Trip indicator lights adjacent to the reset buttons on all controllers is a fairly common practice in industry and worthy of consideration. Circuit breaker panelboards should have comprehensible directories, and should be located so tripped breakers are easy to spot ... breaker trip aux switches and indicator lights should be considered for critical circuits.

TRIP RESETS should be plainly marked on the control cabinets. What is obviously a reset button to an electrician may appear to be a decoration to a Tender. Electronic VS drives often have multiple resets; and random trips on these devices are routine as the electronic smarts do their best to protect the equipment against transients ... as a matter of fact we recommend remote reset switches on the CD panel for VS drives.

Repair Maintenance

With relay based control circuits the symptom is usually that when a button is pushed nothing happens. An electrician must then study the elementary schematics and ladder diagrams and figure out which circuit elements affect that button, and then go thru a process of elimination to determine the fault. Diagnostic provisions, if any, consist of no more than neon indicators across fuses and maybe a circuit test meter in an electronic controller. Substituting a PLC for the relays adds a couple of LED indicators on the processor and indicator lights on the I/O modules; the troubleshooter must still study the logic diagram to determine which inputs affect which outputs.

SELF DIAGNOSTIC PROGRAMMING uses the power of the PLC to report on the a/n display what circuit element (limit switch, overload, etc) has brought things to a halt. More sophisticated programming using sequencers and logic comparison functions monitors all circuits and reports when a circuit element is starting to act up before it actually causes trouble such as a limit switch that is becoming intermittent. When the PLC can't pinpoint the precise fault because of a lack of sensors, a troubleshooting flowchart ("tree" chart) may be programmed into the PLC to guide the troubleshooter, step by step by yes or no questions, to the fault ... in other words the PLC becomes the maintenance manual. The system detail designer can put his expert knowledge of the system to work doing all the future troubleshooting by programming that knowledge into the PLC.

DIAGNOSTIC INDICATORS should be provided for all major parts of the CD's electronics including the PLC, power supplies, fuses, etc. A non-electronics trained electrician should be able to quickly identify major failures without resorting to schematics. Military style BITE (Built In Test Equipment) latching indicators, LEDs, and internal test meters are options. Latching indicators for first-out indication following cascade failures are excellent troubleshooting aids. Some VS drives now include battery powered LED first-fault indicators to provide this vital information hours after the drive shuts down.

INTEGRAL DRIVE AND SENSOR TESTING should be provided by the CD. The tradition methods of testing controller output contacts by jumpering with a clip lead can destroy solid state output relays, as can testing with highly inductive "wiggy" type testers. We provide circuitry that is enabled by a keyswitch to force on each control output when the appropriate button is pushed on the Manual Panel (one circuit at a time - this is a test feature, not an operating mode) providing end to end testing of the drive controls including the starters and overloads. Key security is required to restrict access to this feature to persons with the technical knowledge to safely use it and disable actual drive motion by opening feeder breakers when required for safety.

Status of sensor switches is visible on the I/O indicators (when so equipped) and each group of sensors (pair in redundant circuits, or multiple in series circuits) is directly represented at all times by the indicator lights on the Manual Panel. A full system should provide for the PLC and a/n display to be switched to monitor and report any individual sensor selected including a pulse stretching feature to trap intermittents ... the Tender or a helper then watches the display and advises the electrician the status as he traces the circuit on the structure (a perfect justification for a maintenance intercom system).

<u>INTEGRAL CONTROL ADJUSTMENT</u> should be provided by the program and CD controls for easy modification (restricted by keyswitch or other security means) of any control variables (time delays, option bits, etc) without the need for a programming terminal which is expensive, non productive, does not suffer storage gracefully, requires special training to use, and permits infinite mischief either accidentally or intentionally. Some PLC manufacturers offer data entry and monitor units or the monitoring and inputs may be provided using the a/n display in conjunction with a thumbwheel switch or numeric keypad. The exact method of such I/O will largely depend upon the PLC manufacturer's offering and the system vendor's experience and design standards.

<u>REMOTE I/O</u> appeals to us as engineers as an elegant solution to the messy problem of interconnection wiring; both between the CD and the Control Panel (CP, motor control center), and crossing the channel. Using a separate CP on each machinery deck with remote PLC I/O racks in each CP permits all the controls and sensors to be tied together with two twisted pairs or a single small coax cable depending on the PLC's manufacturer. A electrical contractor's dream ... and a maintenance electrician's nightmare.

Remote I/O control is common in industry; it not only greatly simplifies installation, but is well suited to modification as machines are moved and changed on an assembly line. A bridge is static in design, we don't make significant changes in the number of leafs once construction in completed.

Remote I/O arrangements can be extremely difficult to troubleshoot by electricians. Is loss of a output signal at one point caused by a output module failure, a input module failure at another location, programming goof, or communications fault? Standard troubleshooting techniques involve replacing the Remote I/O module with a small PLC and using the test PLC as a diagnostic tool in conjunction with a programming terminal ... not a procedure we care to teach an electrician (we've already tried ... unsuccessfully). The problem is the remote I/O units are dumb communications units and do not have the self diagnostic capability of the controlling PLC. Also the I/O equipment being placed out on the structure is much less rugged and immune to transients than the wire and cable it's replacing.

The jury is still out on the subject of remote I/O. We feel it's practical between the CD and a nearby central CP, both to simplify interconnecting wiring and to provide I/O space (CDs are rather small) - especially when all overloads and fault indicators are monitored. This is not true remote operation since the CP is normally within 20 or 30 feet of the CD; ......

...... it's just placing the PLC in the CD with I/O for the CD controls and indicators, and placing the rest of the motor control and sensor I/O in the CP where its connections terminate. Due to reliability and maintenance considerations, we don't recommend splitting the CP in two and using remote I/O to cross the channel (with the exception that this is a excellent way to construct a temporary or emergency system).

MAINTENANCE DOCUMENTATION for licensed proprietary control systems will tend to be much more thorough that that for a one-of-a-kind system. Since the vendor lives with his product on multiple projects he has an opportunity to develop and refine the maintenance procedures and documentation as well as the software. A project's manuals will be updated as the product's documentation evolves; contrasted with the minimal information provided for a tradition system which normally consists only of the manufacturer's literature for the individual components and no system overall information except for the schematics showing the interconnections.

Outside Maintenance Support

Recognizing that modern electronics based control systems are sometimes beyond the capabilities of maintenance electricians, but the workload doesn't justify the Owner staffing the maintenance department with skilled control technicians, is causing a search for alternative methods of performing maintenance. The first level solution to this problem is to make the equipment itself as self maintaining as possible, as has already been discussed.

REMOTE TELEPHONE ACCESS provides the Owner's maintenance personnel with rapid access to the system's designer or other support organization. The CD and PLC are provided with a telephone modem connected to the bridge's telephone line. When the electrician calls for help, the consultant can remotely access the PLC's memory over the telephone from his computer and troubleshoot the problem. By switching back and forth to voice communication with the electrician, the consultant supervises the troubleshooting process.

We believe that every PLC based control system should include telephone communications ability. The telephone link can also be used for uploading and downloading program files, and can also be used with the Owner's computer for reporting failures or downloading operating logs.

OUTSIDE MAINTENANCE SERVICE either under contract or on a per call basis provides the ultimate backup for repairs. A qualification for any system vendor should be that they offer field maintenance service in a reasonably timely manner (remote telephone access is always faster than traveling). The maintenance contract including preventative maintenance requirements is probably the best alternative. Maintenance Departments usually concentrate on emergency repairs of breakdowns and preventative work doesn't get done; a contracted service supplier performs the preventative tasks carefully since each breakdown call reduces his profits. The Owner's maintenance staff takes care of all routine repairs such as burned out lamps and fuses, both to return the bridge to service as quickly as possible and to minimize the cost of the service contract which is based on supplying skilled control technicians.

The optimum solution to the maintenance problem appears to be remote telephone access and a maintenance contract with the same service consultant. Any service organization that is capable of maintaining the equipment will have the computer expertise to supply remote access support. When emergency repairs can be accomplished using the remote access, the bridge is returned to service quickest. When the consultant must travel to the bridge to perform the repairs himself, at least he's got a good idea of what the problem is and can take the necessary specialized test equipment and parts. This can save a lot of downtime over the traditional method of going and looking, then ordering the parts. Many main frame computer manufacturers, including IBM, use remote telephone access very successfully.

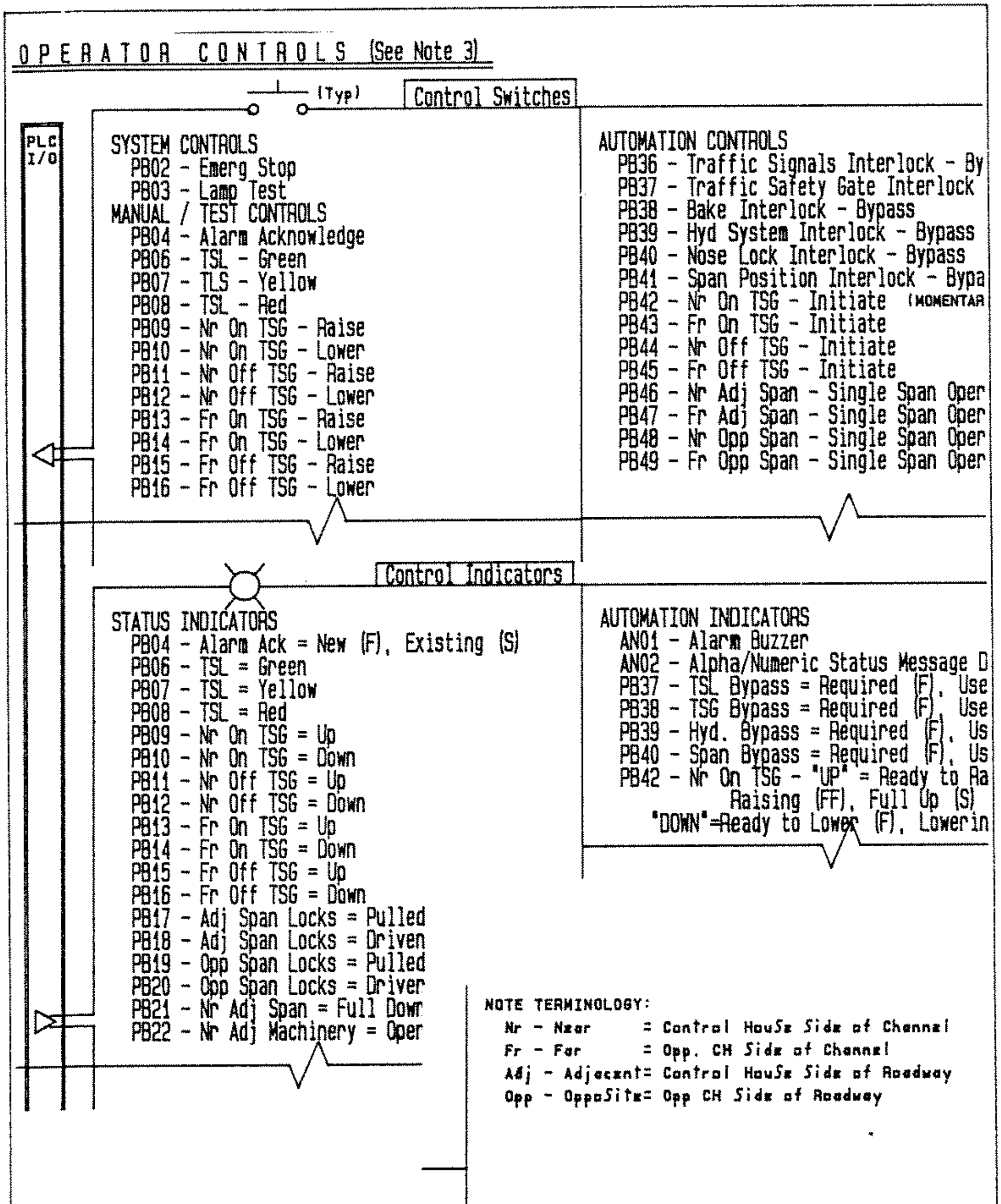

FIGURE 1A

PLC I/O Diagram – Controls & Indicato

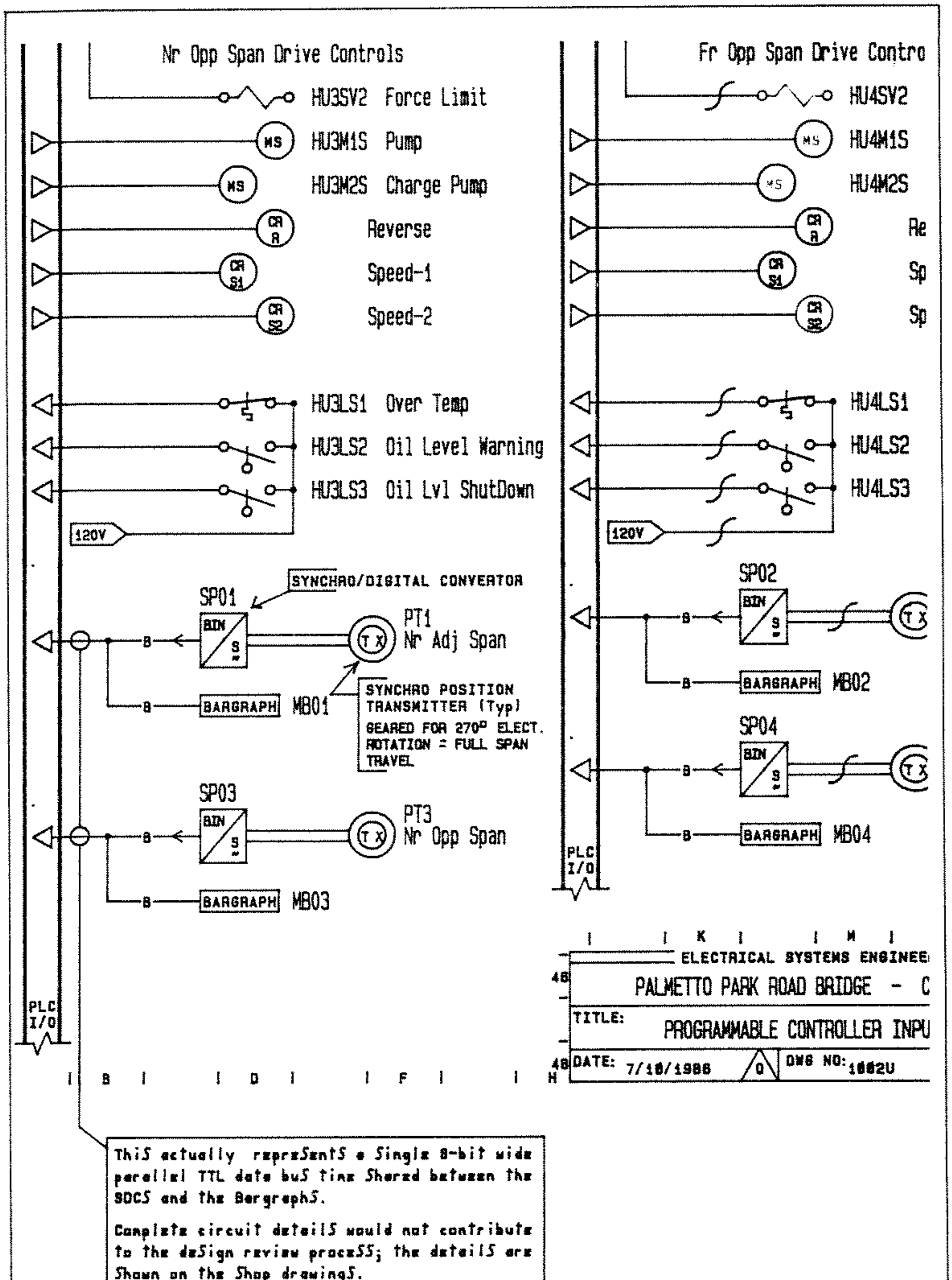

FIGURE 1B

PLC I/O Diagram – Field Device Connections

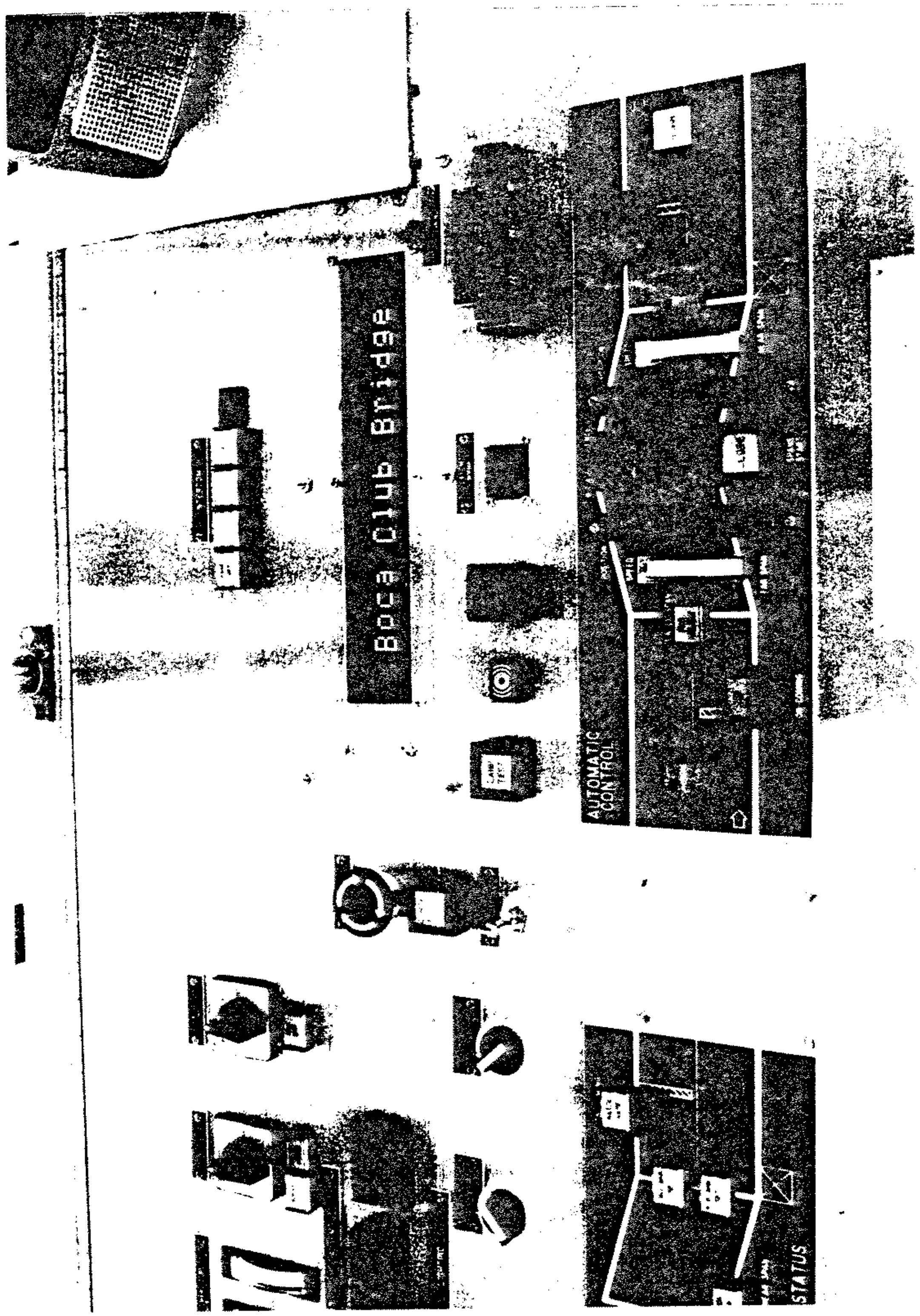

FIGURE 2

Control Desk Arrangement

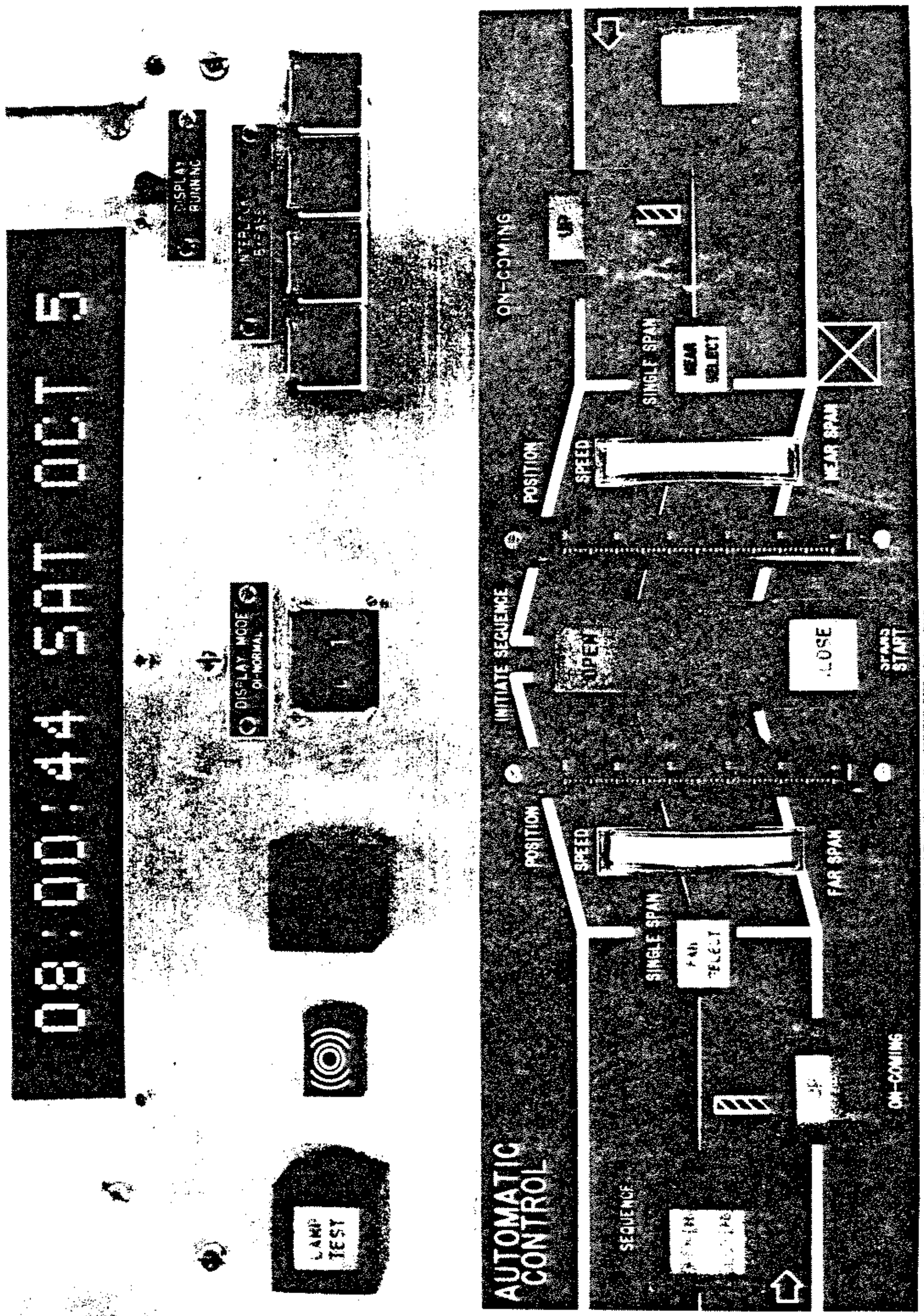

FIGURE 3
Automatic Control Panel

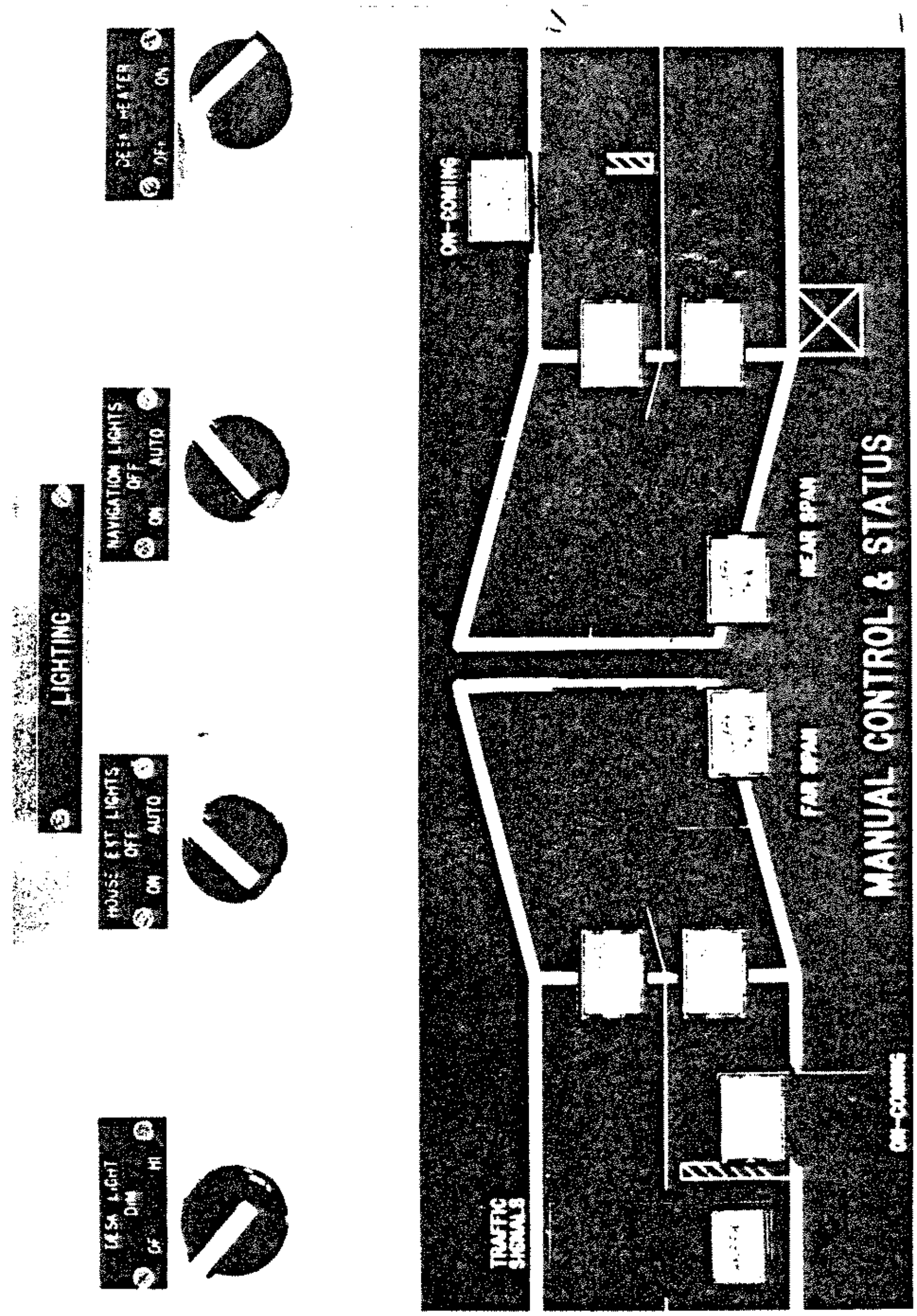

FIGURE 4
Manual / Test Control Panel