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"From Drum Switches to Microprocessors:
A Case History", Richard F. Newcomb,
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I. INTRODUCTION

The University Bridge is a double-leaf bascule bridge which was built in the early 1920s and remodeled in the early 1930s. Prior to this rehabilitation project, all of the motors and drive machinery were original 1920s vintage; the drive motors were series wound split case mill motors operating at 600 VDC. The speed control relays were also part of the original equipment; however, the control desk had been replaced in the 1960s. This paper will address the control system of the University Bridge as it was recently designed and built.

In 1986, the City of Seattle Engineering Department conducted a survey to evaluate the condition of the mechanical and electrical systems of the three city-owned movable bridges over the Lake Washington Ship Canal all of which were completed around 1920. During these inspections, cracks were discovered in several gears on each bridge. Although the program was originally funded for inspection and evaluation only, funding became available for engineering new machinery as well, and was later expanded to include engineering of new drive and control systems.

With the aid of the Bridge Operations and Maintenance Department, the consultants developed design criteria for the bridges, including eliminating the traditional submarine cables; relocating the control desk to the opposite tower; instituting new electrical service and emergency power generation for both sides, as well as new leaf drive motors and controls; and incorporating existing traffic gate and centerlock controls into a new integrated control system.

A standard design was developed for all three bridges, and completed plans and specifications. The construction work had to be prioritized due to limited capital funding from the City of Seattle Engineering Department and, to-date, only the University Bridge has been completed.

II. DESIGN CRITERIA

As new design criteria for the three city-owned bridges evolved, three primary issues in the design became apparent. Controls for all three bridges needed to be standardized, submarine cables had to be eliminated, and the emergency operation system had to be modified.

STANDARDIZED CONTROLS AND SYSTEM OPERATION

Although all three bridges had been built at about the same time, each had a different console and slightly different control logic, due to modifications over the years. The new design criteria provided a standard control desk and operating logic which would give all three bridges the same "look and feel."

Another issue regarding controls for the bridges was that the existing traffic gates and signals had to be integrated into the new design as much as possible. All existing controls were reconnected to the new system, and interlock logic was put in the software. In addition, the new design was also to allow a manual means of operating the signals and gates, should the communications link between the bridge piers be out of service.

ELIMINATION OF SUBMARINE CABLES

The cable inspections in 1986 indicated that the submarine cable insulation for all three bridges was steadily deteriorating. Because of these findings, in addition to a complete cable failure on another bridge in the Seattle area at about the same time, the Bridge Operations and Maintenance Department wished to eliminate the submarine cables altogether. The design used programmable controllers (one on each side of the bridge) to echo inputs from one side to outputs on the other, thereby replicating the function of a cable.

EMERGENCY OPERATING SYSTEM

The existing emergency operation system was a power transmission unit driven by a gasoline engine. The unit had to be manually engaged by wrapping a chain around a sprocket on the primary reduction gear of the main drive system. This process often took more than 30 minutes after someone from the maintenance department arrived. To buy back this valuable time, the new design allowed emergency operation from the control tower without having to rely on a second person.

III. THE DESIGN

BRIDGE CONTROL SYSTEM

The control design philosophy for the bridge provided as much automation as was practical without compromising safety. In addition, the philosophy provided a system which, should the main control system fail, would be operable by some type of designed-in emergency bypass.

Programmable Controller System

A programmable logic controller (PLC) allows us to address several of the design issues. The flexibility of the PLC programming allows us to standardize operation (from the operator's point of view) for all three bridges whether or not the systems were actually of the same configuration or design. The PLC communication system is also ideal for concentrating and transmitting control and interlock signals without using a traditional submarine cable.

The PLC system is configured with two processors in a hot backup mode, with distributed input and output (see Figure 1). The remote input/output (I/O) racks are connected to the processors by means of two independent communications cables. Each I/O rack has a transfer module which will automatically switch from the primary to the backup channel, should a fault occur. For additional redundancy, a third processor, connected to a telephone modem, is provided on the far side. In the event of communication failure, the processor on the near side is designed to switch to an autodial modem and then re-establish communication to the far side via telephone lines.

The remote I/O racks, located in control panels near the equipment, substantially reduces the required number and lengths of interlock and control wiring. The traditional relay panels and the interconnecting wiring are replaced by software. Instead of looping interlocks from one end of the bridge to the other for traffic gates, limit switches are connected to inputs and motor starters are connected to outputs. Virtually all control wiring is designed to originate and terminate within four electrical rooms.

An additional I/O rack is provided in the control desk (see figure 2). All of the operator control and indication wiring now originates and terminates in the control desk; only the communication cables enter and exit the desk.

A personal computer is connected to the main processors for diagnostics and recording events. Graphics interface software is used to allow the operator to view the status of any device in the system. The graphic displays are organized by subsystem so that the operator can, in the event of an emergency, quickly

access pertinent alarm information. Alarm messages and events are both printed on hard copy and stored on hard disk memory as they are received.

Leaf Motor Drive Controls

The new leaf drive motors, two on each leaf, are 100 hp shunt-wound DC motors, each driven by a regenerative 4-quadrant SCR controller. The DC drive system was chosen for its low-speed regenerative braking characteristics.

Each drive is provided with its own PLC-type controller with programming capabilities for operational parameters such as maximum torque, maximum speed, rates of acceleration and deceleration, phase imbalance tolerance, and over-speed tolerance. The advantage of this system is that, since motor control intelligence is kept in the drives, the motor drives will operate with the same characteristics, regardless of the source of the control signals. For example, on the University Bridge, the PLC provides direction and analog speed reference signals to the motor drive controller which, in turn, accelerates and regulates motor speed according to its own programming. For emergency operation, hardwired rotary switches equipped with voltage-drop resistors also provide direction and analog speed reference for each leaf. Likewise, the motor drive controls all acceleration, deceleration and speed.

The drive controller can also be programmed with logic functions such as lead/lag selection and load sharing. On the University Bridge, the motor brake thrusters and main motor cooling blowers are also controlled by the drive controller.

Each pair of motor drives is designed as an integrated system. Either motor and motor drive is capable of operating the bridge by itself, although normally both are online. The design also provides the controllers with selector switches which allows the operator to set a number of parameters, including selecting either or both motor drives, a lead controller, remote or local operation, and normal or emergency operation.

Shaft Encoders

The design replaces the trunnion limit switches with resolver-type shaft encoders. The resolver provides a 4-digit binary coded digit (BCD) input to the PLC. The PLC, in turn, translates the BCD into a digital value. Comparison statements (i.e. greater than, less than, equal to) in the PLC logic serve the same function as limit switches. Adjustments to these limits are as simple as changing a comparison value in the program. The resolver also replaces the selsyns, and an analog output module translates the digital value into a proportional 1-5 vdc signal. A switchboard meter with special markings replaces the selsyn receiver.

Other Motor Controls

The traffic gate, centerlock and machine brake thruster motors are all controlled by the PLC. (Motor brake thrusters are controlled by the main motor drive.)

In the case of the traffic gate and centerlock motor controls, the control circuits from the existing control desk and operator limit switches have been intercepted in the bridge junction boxes and extended to the PLC I/O racks. "Manual-Off-Auto" switches were also installed in boxes next to the existing starters. The PLC programming is designed to replace all of the traditional interlock wiring.

Typically, the motor starters are connected in a 2-wire control scheme with a selector switch for "manual," "off," or "auto" operation (see Figure 3). Although we built redundancy into the PLC, a hardwired means of operation was left, should there ever be a need to disable the device.

To provide status indications, the motor starters are also connected to inputs. Input from the auxiliary contacts provides operational status, and the operator can sense readiness by monitoring the voltage in the "auto" position of the "Manual-Off-Auto" switch circuit.

Traffic Signals

The traffic signals are both controlled and monitored by the PLC. Like the traffic gates, the existing traffic signal circuits were modified to operate via the PLC, but were left with enough of the existing circuits intact to also operate conventionally in a backup situation. In addition, to the sequence control the signal circuit amperage is monitored. If a signal lamp is out the PLC indicates trouble on the control desk and a diagnostic message on the computer screen identifies the location of the failed lamp.

Control Desk

The control desk is designed to optimize the best features of the previously existing control desks, while incorporating modern control hardware. Although the layout of the controls is typical of any other movable bridge, the indicators provide not only status but also prompting and trouble indication (see Figure 2).

Between bridge openings, the control system is turned off and all of the operational status lights are dark. When the bridge is down and the control system is turned on, the green traffic signal status light illuminates; all other indicators remain dark. When the traffic system is activated the traffic signal indications change to yellow, then to red. After the signals turn red there is a ten second delay before the traffic gate control logic is enabled. Upon time out the oncoming gate status

lights illuminate. When each oncoming gate is down, the indicator light for its offgoing counterpart illuminates and so on to the centerlocks and finally to the leaf motor and brakes status. Should any motor starter fail or its control circuit not be ready for automatic operation, the indicator light will flash, indicating some sort of trouble. The operator can consult the computer for a message detailing the trouble.

The design provides two modes of operating the bridge leaves via the PLC. Normally, the bridge operator will operate both leaves by pressing a single open or close button. In normal operation the PLC operates both leaves at full speed. For single leaf operation, the design provides individual rotary switches. When using these rotary switches, the operator may control the speed in 20% increments of full speed.

A single emergency stop button is connected to both motor drive systems and the PLC. In the event of an emergency, all systems shutdown simultaneously. Emergency hardwired rotary switches are located in a covered recess on the desk top. These switches provide signals which are identical to the output signals from the PLC to the motor drive. The selector switches on the motor drives determine which signal the drive will receive.

Other indicators include the position meters (previously mentioned with the shaft encoders), power distribution status, a normal clock and clock indicating elapsed time. The elapsed time is also recorded on the event print-out.

A communications system which incorporates a telephone, intercom, public address system and a VHF radio into a single station was also incorporated into the control desk; however, the telephone and radio were disconnected.

SYSTEM OPERATION

The traffic signals, gates, and centerlock all operate as if they were hardwired. The PLC simply replaces all of the timers and relays. The main motor drive control is more involved, as the PLC and motor drives work in concert with each other.

As previously mentioned, the PLC provides a speed reference signal to the motor drive which, in turn, regulates motor speed according to its own programming. There are two operating scenarios available to the operator: Normally, both leaves are operated by a single control, but as an alternative each leaf may be controlled separately.

The following operational sequences begin with the assumption that the centerlock is pulled.

Normal Operation

Assuming the leaves are both in the fully closed position, operation begins when the operator pushes and holds the "open" button. Immediately, the PLC starts the machine thruster brakes. When the machine brakes are released, the PLC provides a full-speed reference as well as direction signals to the far side motor drive controllers (which, in turn, provide power to the main leaf motors). When the controllers sense 20% full load current the controllers start the motor brake thrusters and the main leaf motors are accelerated.

As the far side leaf rotates, the far side trunnion shaft encoder transmits its position to the PLC. When the far side leaf reaches six degrees, the PLC sends a full-speed reference signal to the near side motor drive controllers which, in turn, operate the brakes and accelerate their respective motors. The PLC maintains the full-speed signal to each leaf until the leaf either reaches its nearly open position--at which time the speed signal is reduced to 10% of scale--or the operator releases the open button.

When a leaf reaches its fully open position the PLC sends a zero speed signal. The motor controllers decelerate and stop the drive motors according to their program. The motor brake thrusters are turned off but the PLC holds the machine brakes on until the leaf is once again seated. If the operator at any time during the operation releases the PLC sends a zero speed signal to the motor drive controllers and the leaves decelerate and stop, per the controller program.

To close the bridge the operator pushes the "close" button. The sequence is the same except in reverse. The near side is started down first. When a leaf reaches the nearly closed position the PLC reduces the speed signal to 10%. When the leaf reaches the fully closed position the PLC sends a zero speed signal but maintains the direction signal. The motor drive maintains a reduced torque on the motors while the motor brakes set. When the close button is released the machine brake thrusters are turned off. If the bridge is operated from any position between full open and full closed the drives are started simultaneously.

Single Leaf Operation

Either leaf may be operated singly or both may be operated simultaneously using the rotary switches. Starting from the fully closed position, the operator turns the rotary switch of the selected leaf to the desired speed. The PLC starts the machine brake thrusters for that leaf only, and when the brakes are released, the PLC sends the speed reference signal for the selected speed to the motor drive controllers. The motor drives operate the motor brakes and accelerate the motors to the selected speed. The PLC maintains the speed signal until the

leaf nearly reaches the fully open position, at which time the signal is reduced to 10%, as before. When the leaf is fully open the PLC sends a zero signal and the motors are stopped.

If the operator changes speeds mid-travel the motors are accelerated or decelerated per the motor controller program.

If the operator should suddenly change directions, the motor controller brings the leaf to a controlled stop, then reverses and accelerates the motors in the opposite direction.

Emergency Operation

The emergency controls are connected directly to the motor drive controllers when switched into service. In order to operate the bridge in this mode the machine brake thrusters must be started manually using the "Manual-Off-Auto" switches on the starter. The operator begins the sequence by turning the emergency rotary switch to the desired speed. Voltage-dropping resistors provide the speed signal variation. The motor controllers energize the main motors and start the motor brake thrusters and operation is the same as when using the individual controls via the PLC. The motors are accelerated and maintain speed until the leaf is nearly open and the corresponding limit switch is operated. This time, the logic programming in the controller automatically reduces the speed. The motor drives reduce speed to 10% capacity, and then stop the motors when the fully open position is reached.

When closing the bridge, the above sequence is reversed. When the leaf reaches the fully closed position, the motor torque is reduced but held for a moment while the motor brake thrusters are stopped and the brakes are set.

Emergency Stop

There is a single emergency stop button located in the middle of the control desk top. It is a 3-pole maintained contact switch which is connected to a PLC input, as well as to each motor drive pair. If the bridge is in motion and the operator pushes the emergency stop button, the PLC logic is immediately disabled and the motor controllers immediately remove all voltage from all motors. The bridge is stopped by the motor and machine thruster brakes which have been adjusted to set one brake at a time over a 4-second period. The motor brakes are activated during the first 2 seconds, followed by the machine brakes. Normally the bridge is stopped by the motor brakes before the machine brakes set.

To restart the bridge system after an emergency stop, the operator must pull the emergency button back out and restart the PLC control with a keyed switch.

ELIMINATION OF SUBMARINE CABLES

The control interlocks and status indications on virtually all bascule-type movable bridges cross the channel by means of a submarine cable. A programmable logic controller (PLC) was chosen to replace all of the interlock and indication conductors. By placing PLCs on each side of the channel, all inputs and outputs can be transmitted to opposite sides via telephone modem, infrared, radio, or microwave. Each method was evaluated and unfortunately, all had some shortcomings.

Infrared was eliminated early, due to the fog conditions that Seattle experiences in the fall and winter. At the time of the evaluation, suppliers had not convinced us that the fog would not be a problem.

In any other location, radio would have been a very good choice. Radio is a proven technology capable of high-speed communication, and some PLC manufacturers provide radio network modules which plug directly into the PLC racks. In Seattle, however, it was feared that interference from city operations, aviation, maritime, and military radio traffic, would cause communications checking errors.

Although microwave had worked successfully on a state-owned bridge and was a very promising alternative, it required a clear line of sight for operation. Unfortunately, the state-owned bridge used as an example did not have the large ships to contend with that Seattle bridges, including this project, do. An additional problem with using microwave technology was possible inconsistency: At another location, a closed-circuit television camera on microwave sometimes acted on its own whenever a large ship would pass through the bridge. There was also concern about the effects of ship radar transmitting directly into a microwave dish. For these reasons, microwave was eliminated.

A telephone modem operating at 2400 baud was the safest, although slowest, means of communication; at 2400 baud we determined that there would be a delay of 1 - 2 seconds from the operator's command to a reaction on the other side of the bridge. Although this time span was workable, we felt that it was less than desirable.

The final design was a compromise. A PLC control system was designed with dual communication cables, each cable crossing the channel in a separate conduit. An automatic dialing telephone modem was also included as an emergency backup, should the conduits be damaged or destroyed.

Four 3-inch Schedule 80 high-density polyethylene pipes were installed. The pipes were installed in single pieces with no couplings or splices. The conduit trench was excavated to a depth of five feet below the mudline. The pipes were placed in the trench then covered with concrete drain pipe sections split

in half. Along with the communications cables, a multiconductor cable was pulled in for a new intercom system.

EMERGENCY OPERATING SYSTEM

Emergency operation in this case refers to operation during a power outage. Since operation of the bridge could not depend on the submarine cable, new electrical service was brought to the previously power-dependent side. Each side is fed by a different radial and substation so that if power is lost on one side it is not necessarily lost on the other. In addition, each side was provided with a diesel engine generator which is sized to operate the main drive motors at full power. In the event of a power outage on either side, this generator automatically starts and switches to online operation. Except for the indications on the control desk, the operator cannot tell the difference between emergency and normal power.

In addition to the diesel engine generator, an uninterruptable power supply (UPS) provides each side of the PLC system. The advantage of this UPS is two-fold. First, and most obvious, the system is not affected by variations in the service voltage. Second, by using a reverse transfer or inverter preferred UPS, the PLC and other sensitive equipment is protected from high voltage transients.

All of the I/O racks and processors were powered by the UPS. Motor control voltage originated from the individual starters.

IV. CONSTRUCTION AND FIELD MODIFICATIONS

Although most of the construction was carried out exactly as designed, there were some changes in the construction schedule. Because of these schedule changes, some wiring changes were made that were at first meant to be temporary. However, these "temporary" changes are part of the system today, and include modifications to the traffic gate interlocks and to the motor drives. The construction phase also revealed some "glitches" that needed to be worked out before the bridge could operate normally.

TRAFFIC GATE INTERLOCKS

During construction, the bridge operator's station was relocated from the south tower to the north. During construction, we envisioned that the new control desk and control panels would be installed on the opposite side, with all traffic signals, gates, and centerlock controls remaining intact until the north side was complete. Upon completion, the traffic signals and gate controls on the north side would be operated by the new system while those on the south side would be operated manually by a second operator until the appropriate panels on the south side were completed. Thus, for a period of several weeks, there would be two operators and there would be no centerlocks or interlocks for traffic.

Because the operators did not want the kind of responsibility the proposed design required, the system was modified instead to include a second wiring system to keep the existing interlocks intact. A new control cable was pulled into one of the spare conduits and contact blocks were added to the traffic gate controls on the new desk. The result of these modifications was a dual system, one controlled by the PLC the other is a hardwired system comprised primarily of the original wiring. This dual system not only provided all of the interlocks, but also provided another complete backup control system completely independent of the PLC. Although the dual system was intended to be a temporary fix, it was left in service.

MOTOR DRIVE MODIFICATIONS

The drive controller was actually an unexpected "bonus" which was not in the original specifications. Once the manufacturer's field engineer demonstrated the capabilities of the system, field changes were made to optimize these capabilities. Along with the interlocks for the traffic gates, the motor drive permissive interlock from the centerlock was also connected directly to the drive controller. In addition, the trunnion limit switches which were to be removed were connected to the drive controller to serve as a backup for the resolver and the PLC logic. This new control also served to provide safety interlocking for the emergency manual operation.

GREMLINS

Integration of automated systems for new construction usually takes several weeks to completely shake out all the bugs. On a 70-year-old movable bridge the task seems to take months. Had the construction schedule allowed the closure of the bridge as originally planned all of the existing connections and wiring could have been completely renovated. The field modifications for the traffic gates compounded an already difficult situation.

It was originally planned that the interlock wiring for the traffic signals, gates and centerlock would be replaced by software and that the limit switches in the gate operators would be connected only to the PLC. The second "temporary" wiring system now required that the "Manual-Off-Auto" selector switch not only switch the motor control circuits but also the limit switches from the PLC to existing interlock circuits. Contact blocks had to be added to these switches to switch the limit switch connections from one type of service to the other. The existing wiring on this bridge was typical of a 70-year-old bridge, as there were many modifications, repairs and unmarked conductors. It was also discovered during these field modifications that the as-built schematics of the existing circuits were not complete; there were some additional contacts on two of the gate operators which were previously unknown. These had to be traced and implemented into the PLC system as well.

At the same time the above field modifications were taking place, the new motor drives and PLC system were being brought online on the north side. Each system was checked out, first in manual mode without the PLC to assure proper operation, and then via the PLC. During the checkout for the various motors and sensors, only minor problems--which were expected--were encountered. The north side PLC system was working fairly well and the operator moved from the existing control desk to the new one. This is when the "gremlins" arrived.

At this point in construction, the north side of the bridge was operating via the PLC system, while the system on the south side was still being completed. The traffic system was operating in the secondary system mode. With this operation of the traffic systems, random PLC faults began occurring. The first conclusion was that there were alternate voltage sources from the existing traffic control circuits. Circuits were checked and rechecked for back-feeding. System grounds were checked. Different fixes were tried, and each fix seemed to help but with each new system that came online, it seemed something else went awry. One particular "head scratcher" was a fault that, every once in a while, shut down the PLC processors when the whistle was blown.

One false lead was from the PLC manufacturer who advised us that the communications transfer module had a firmware error which was being corrected and that new modules would be shipped shortly.

Assuming that the problem was a manufacturing error, construction continued and the operators and electricians learned to live with little annoyances. The situation, however, did get to point where the PLC was taken out of operational service and was used only for monitoring purposes.

Finally, the new modules arrived; with a great deal of fanfare, they were installed. Having made and remade virtually every connection on the bridge, everyone who had been involved in this chase witnessed the installations. All day the system worked without trouble and the foreman pronounced the system good. However, at midnight the second night after the installation, the operator blew the whistle and the PLC went to sleep.

Round two! Circuits were rechecked, grounds were disconnected and reconnected, signal protectors were added to the communications cable, and programming was re-examined to see if there was a software conflict. It was obvious that something was wrong, but what? The manufacturer was brought out to the bridge for consultation. There was no apparent design flaw in the system that he could see. (The author breathed a little easier now. At least he wasn't going down alone!) Having exhausted all other possibilities, the panel fabricator had a sudden inspiration. He had a local cable TV technician check the communications cable with a Time Domain Reflectometer. Within an hour a flaw in a short section of the communications cable was discovered. When the cable was removed there was evidence that it had been pulled into a tight "S" shaped kink. The length of cable was replaced and the bridge has operated flawlessly for over a year. Reputations and confidence were restored. However, the whistle connection remains a mystery.

V. SUMMARY

Successfully implementing solid state equipment and microprocessor-based controls requires careful planning in the original design, as well as a knowledgeable contractor who has previous experience in the installation of this type of equipment. It is equally important that the owner be aware of the amount of time required to integrate a system like the one detailed here into an existing movable bridge electrical system.

Although start-up for the University Bridge project was somewhat more complicated than expected, the system's nearly perfect operating record since completion bears witness to the reliability of the PLC on movable bridges.

VI. ACKNOWLEDGEMENTS

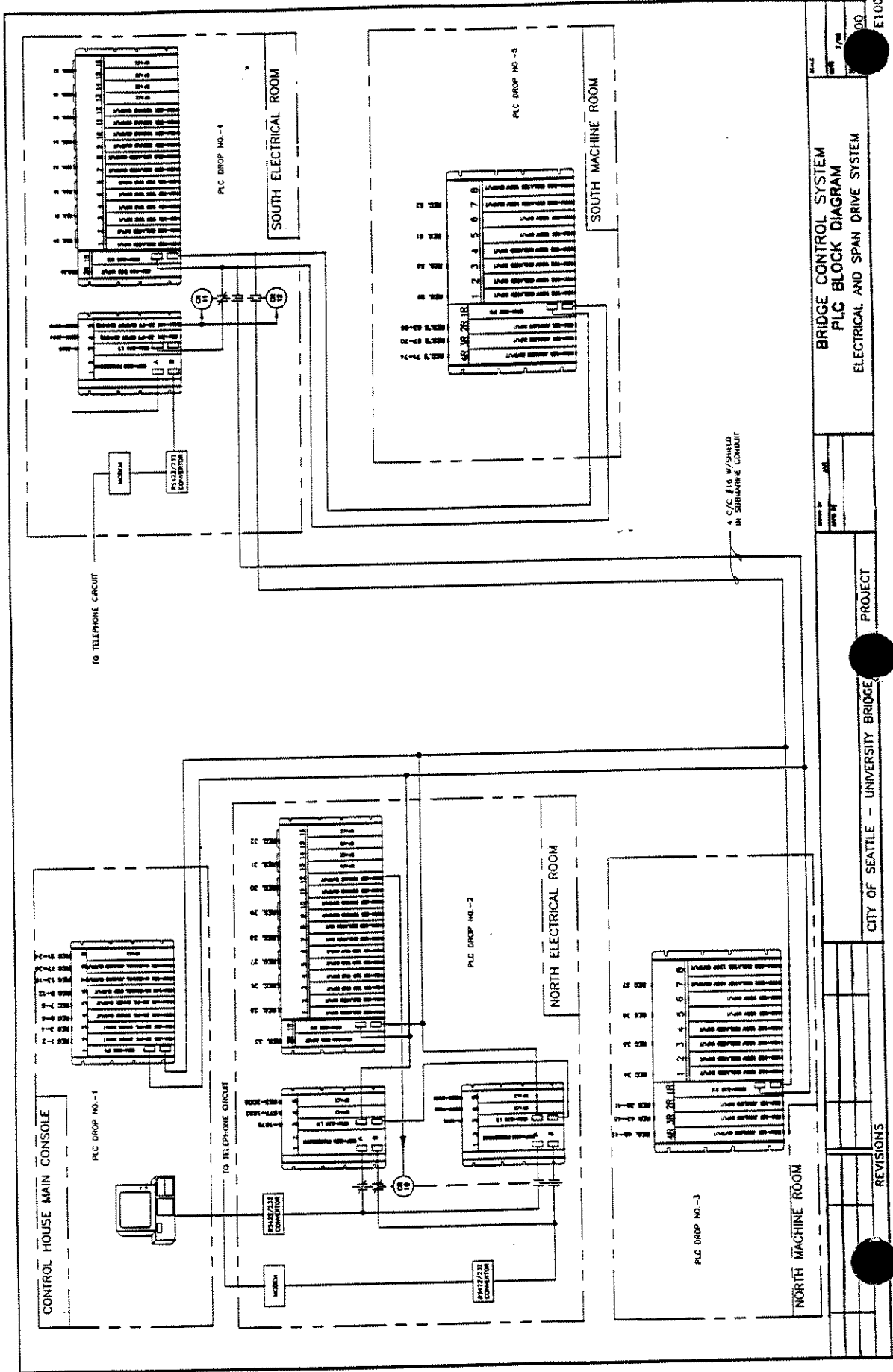
Sverdrup Corporation wishes to thank the City of Seattle Engineering Department for its assistance in the success of the University Bridge Rehabilitation Project, and also expresses appreciation to Centrac Associates, Inc. in Bothell, Washington, for its design contributions to the power distribution system for the project.

As special thanks is also extended to the following contractors and vendors whose cooperation and team spirit "got us through the rough spots."

- o Wright Shuchart Harbor Co., Seattle, Washington
- o Blessing Electric Co., Portland, Oregon
- o Technical Systems, Inc., Lynnwood, Washington
- o Reliance Electric, Bellevue, Washington

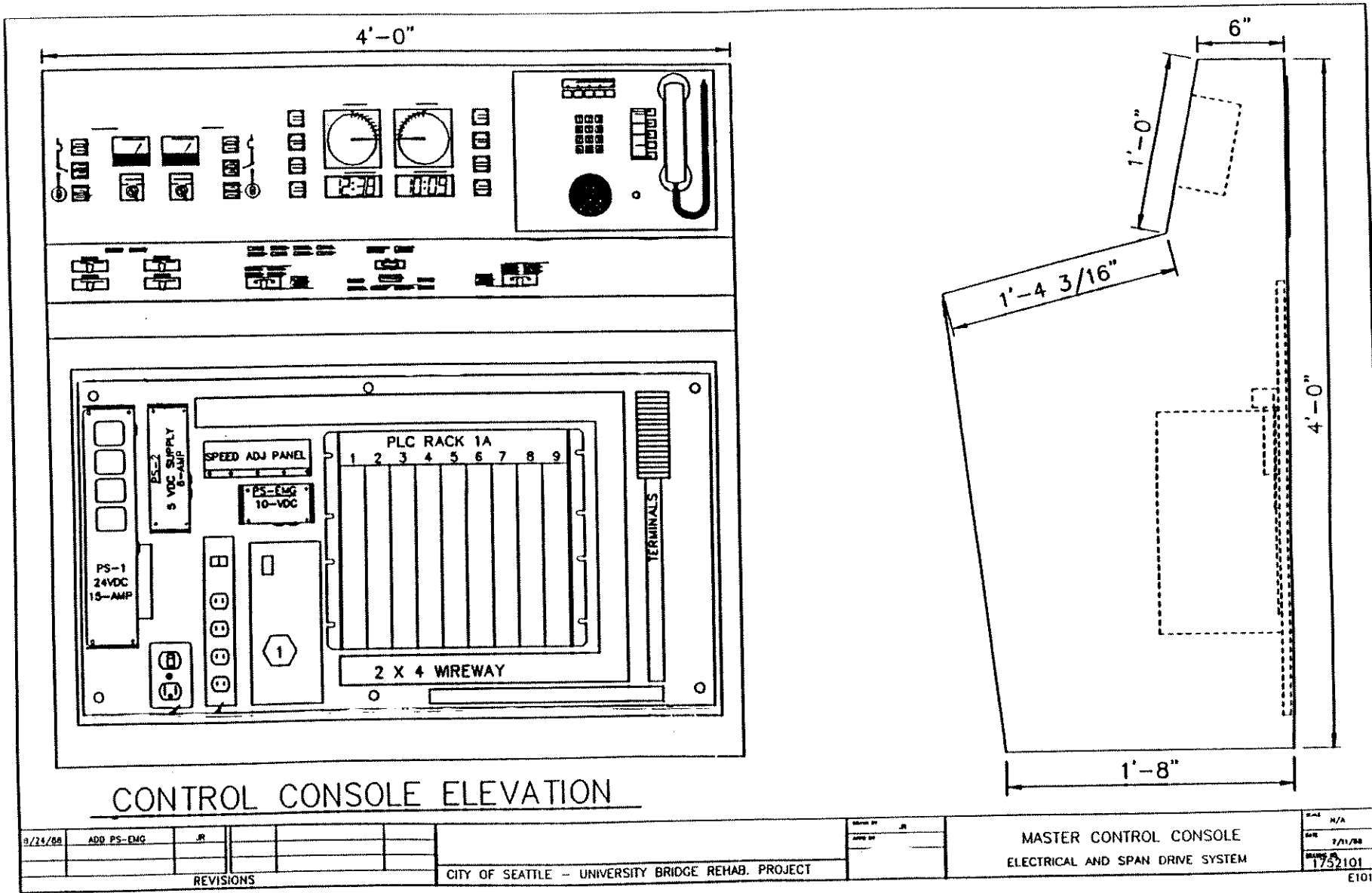
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Mr. Newcomb is the Instrumentation and Controls Section Leader in the Seattle Office of Sverdrup Corporation. He has provided both inspection and design services for 10 movable bridge projects throughout the Northwest. Since completion of the University Bridge, he has managed the control design of three more bridges in which PLC technology was applied.



CITY OF SEATTLE - UNIVERSITY BRIDGE PROJECT		DATE	7/88
BRIDGE CONTROL SYSTEM PLC BLOCK DIAGRAM ELECTRICAL AND SPAN DRIVE SYSTEM		SCALE	1/8" = 1'-0"
REVISIONS		NO.	00
		DATE	E100

Figure - 1



CONTROL CONSOLE ELEVATION

9/24/08	ADD PS-ENG	JR			
REVISIONS					

CITY OF SEATTLE - UNIVERSITY BRIDGE REHAB. PROJECT

MASTER CONTROL CONSOLE ELECTRICAL AND SPAN DRIVE SYSTEM	SCALE: N/A DATE: 9/11/08 DRAWING NO: 1732101 E101
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Figure - 2

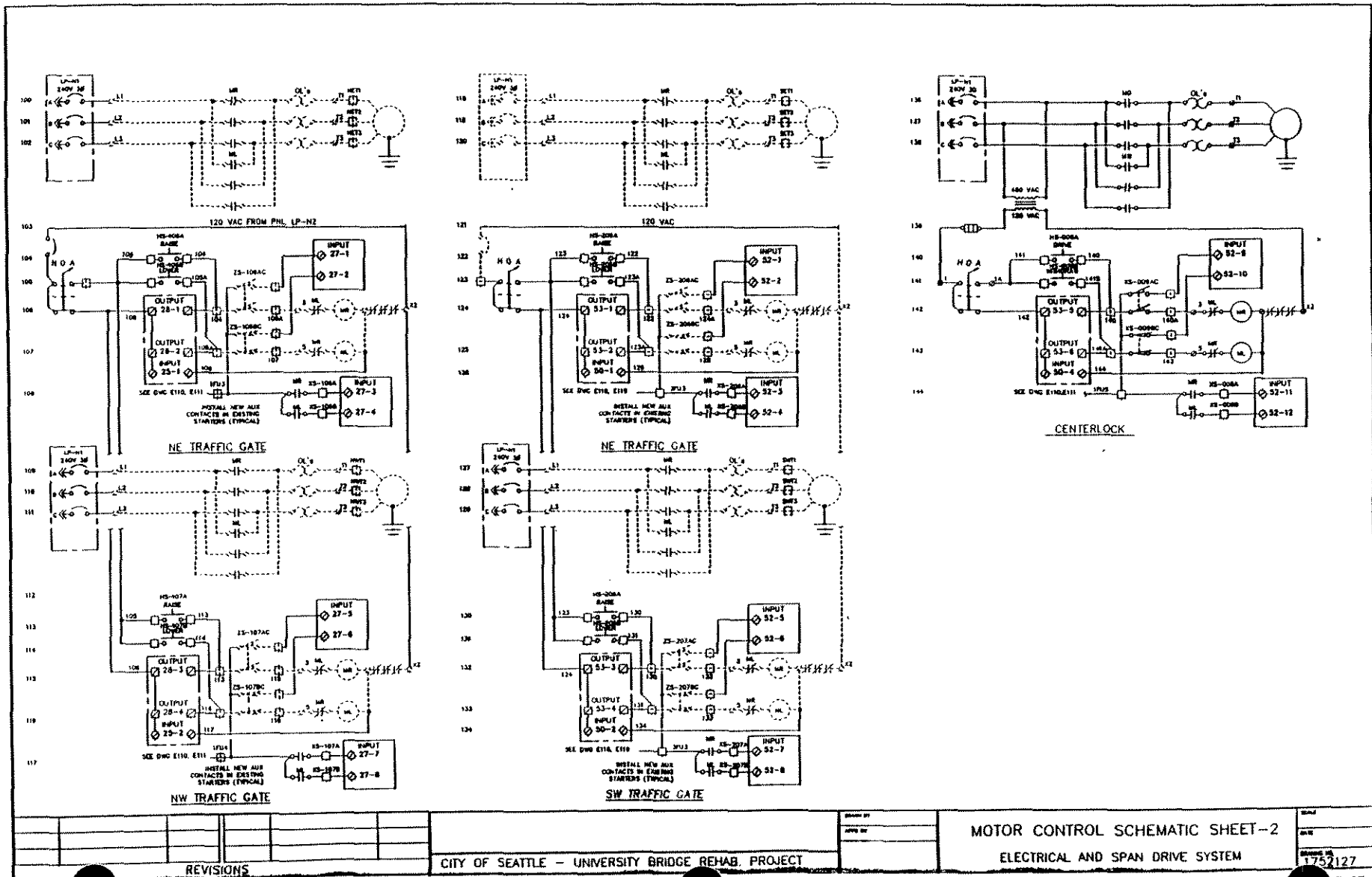


Figure - 3