A Distributed Smart Signal Architecture for Traffic Signal Controls

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Abstract— **This paper describes an architecture for traffic signal control based upon the IEEE 1451 plug and play distributed smart sensor network standard. The system integration with a commercial of the shelf traffic controller requires a minimum of software modifications. This demonstrates an incremental path to integration of smart signals with conventional traffic signal devices. The system design focused on countdown timers for pedestrian signals because the current designs can give incorrect times when the signal timing changes. The system also demonstrates the ability to provide remote access to the call button to assist visually and mobility impaired pedestrians.**

I. INTRODUCTION

MODERN traffic signal controls use highly capable microprocessor based algorithms to control vehicle movements through intersections. However, the infrastructure that provides the interface between the controller cabinet, which houses the traffic controller, and the signals and sensors continues to use technologies developed as early as 1912. These dated technologies limit intersection communication capabilities, thus resulting in construction practices that are costly to install, maintain and upgrade. The goal of this research is to investigate the suitability and advantages for safety and access of applying modern distributed control practices to controlling signal lights for not only vehicles, but also pedestrians who are often overlooked in the design of intersection control. Additionally, research on enabling technologies will improve service for vehicles and pedestrians. Current practices treat all vehicles the same regardless of stopping and acceleration capabilities. Pedestrians too are treated as if they have equal mobility, agility, and cognitive abilities. With current traffic controls there is little opportunity to tune traffic controller operations based upon individual user needs.

Unlike current intersection capabilities, distributed control architecture utilizes intelligent signals and sensor devices to collect significantly more information concerning their operating environment. This information can be used to modify signal timing for safer and more efficient traffic operations. Distributed control also supports a modular design that allows control capability to be added as required in much the same way the capability is added to modern personal computers (PC) using plug and play concepts.

II. BACKGROUND

The intersection traffic controller regulates vehicle movements based on two methods for signal timing. One method is fixed time control that allocates the amount of green phase based upon preset intervals.[1] The green phase can be changed during different periods of the day to better regulate traffic flow based upon traffic patterns. The second method uses actuated sensors to extend the green phase in response to real-time traffic flow. For both of these methods, the traffic controller like the one picture in Fig. 1 operates as a central processor, managing each input and output. In North America, signals are illuminated using 120VAC power that is switched in the traffic controller cabinet by load switches that are operated by parallel or serial outputs from the NEMA TS1, TS2 and similar traffic controllers.
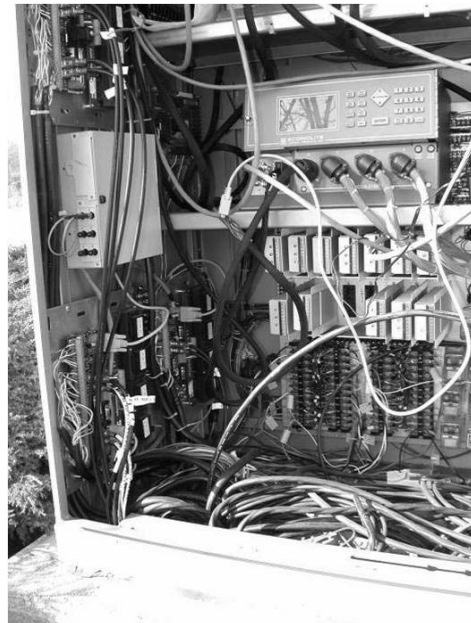

Fig. 1. Installed TS1 traffic controller cabinet

[1] In traffic control, the term "phase" denotes a specific movement of traffic or pedestrians through an intersection.

Every signalized intersection requires the installation of a controller cabinet like that shown in Fig. 1. Regardless of the type of controller used in the cabinet, individual conductors are required for each set of signal lights resulting in a plethora of conduits installed under the street. Should the signals need updating to provide additional controls or sensory inputs, additional conduits would need to be installed.

The inflexibility of the configurations makes traffic signals difficult to change during abnormal traffic conditions such as street maintenance, special events, and accidents. During such times, signals can and often do display information that is incorrect or conflicting with other streets signs, which can confuse drivers and be a contributing factor in vehicle accidents.

In theory, the distributed smart signals and sensors concept can be applied to every device currently connected traffic controllers. Our investigation started in 2005 by constructing a model four-approach intersection with each approach controlled by a set of processors arranged in a configuration to comply with IEEE 1451 standard for plug and play smart signals. [1] The model traffic system was controlled using a PC based limited functional model of a traffic controller. Since no smart signal devices existed, one the task of this project was to design hardware to support a distributed network and smart devices to interface with the traffic controller using this network. It is the focus of the remainder of this paper to describe the system and report on the successes and problems that we encountered that carried the initial work to the next level of full scale smart signal devices with TS2 NEMA traffic controllers.

III. SYSTEM DESIGN

A. System Architecture

For our tests, only the pedestrian signal and call buttons were implemented with smart signal design leaving the traffic lights under conventional traffic control operations. Fig. 2 is a block diagram of the distributed traffic system architecture that was built and tested for this investigation. It consists of two independent Ethernet networks: one to provide communications with the traffic controller and one network for the real-time control of the distributed smart signals.

The bridge node that interfaces with the traffic controller uses the National Transportation Communications ITS Protocol (NTCIP).[2] Also attached to the NTCIP network are two Windows based computers for simulation and configuration. The Traffic Operations computer generates messages to alter traffic signal timing representative of control from a traffic operations center. This computer was also used to implement preemption and setup the timing plans in the traffic controller.
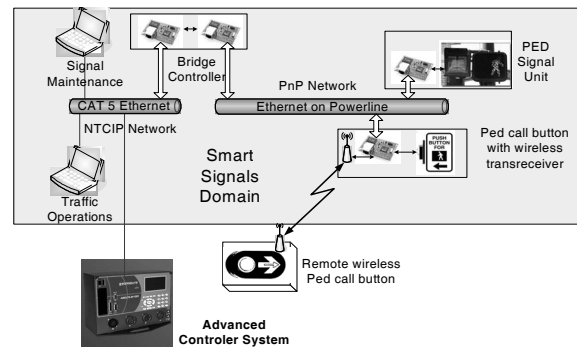

Fig. 2 The system block diagram for an IEEE 1451 compliant smart countdown pedestrian signal and pedestrian call button.

The Signal Maintenance computer is used to provide the connection logic between the traffic controller NTCIP objects and the physical smart signal devices. This logical connectivity implemented by this computer is equivalent to routing conductors from the traffic controller cabinet and the signal devices in the intersection.

The PnP Network was designed to comply to the IEEE 1451 standard for plug and play (PnP) smart sensor networks. The initial work on a scale model traffic system that discusses the elements of the IEEE 1451 network technology are reported by Wall and Huska. [3,4] The objective for a full-scale implementation was to make a drop-in replacement for existing pedestrian signals using distributed control technology that addresses the existing issues with countdown times and provides a demonstration for PnP as a path for integration.

Wall et. al. reported that correct countdown pedestrian signal operation requires that the countdown timer synchronize with the period of the pedestrian clearance interval.[4] The learning technique of existing countdown timers cannot provide accurate information in instances changes in fixed timing, actuated phase timing or preemption. To correct these issues, the timing information within the traffic controller must be communicated to the countdown signals in real-time. Apart from the parallel outputs, the TS2 traffic controller provides three communication ports: RS-232 serial asynchronous, RS-485 based Synchronous Data Link Control (SDLC), and Ethernet. However of the three communications protocols supported by current traffic controllers, only the Ethernet interface met these needs for multi-node, high-bandwidth, and transmission distance capability. It was also determined that the Ethernet interface is less invasive to existing traffic controller installations.

Real-time phase timing data is extracted using the NTCIP standard and Simple Network Management Protocol (SNMP). This data is then translated and passed to a second processor that rebroadcast the information as IEEE 1451 PnP compliant messages to the smart sensors and detectors.

The smart devices consist of a walk-wait display, a countdown display, and a closed-loop pedestrian call button. The embedded intelligence enables autonomous safe-fail

operations in the event of communications or detectable internal failure. These devices are discussed in greater detail below.

B. System Communications

Countdown timing and walk/wait state information are polled from the traffic controller by the bridge SNMP controller and are translated and rebroadcast to the PnP network controller that distributes this information to the smart signals and detectors. The service request information from the smart pedestrian call button uses the same route, but transmits minimal information which is translated by the SNMP bridge controller before reaching the traffic controller. In this implementation, the bridge node consists of two microprocessors, a SNMP translator and a PnP processor, operating in a master-slave configuration bridging the two Ethernet networks. Network communications with the traffic controller use SNMP employing a point-to-point User Datagram Protocol (UDP) transport layer. All other devices use standard network Transmission Control Protocol (TCP) and UDP broadcast communications where each network node uses dynamic host configuration protocol (DHCP) for a unique local internet protocol (IP) address allocation. The two networks can be replaced with a common network hub or switch. However, they are shown as two independent networks in Fig. 2 to give emphasis to the use of Ethernet over power line (EoP). Every smart signal and detector as well as the translator and bridge processors operate as a network node.

1) Translator Controller to Traffic Controller Communications

The primary function of the translator controller is to provide an interface between the traffic signal controller and the PnP traffic devices. We used Econolite's ASC/3 2100 series NEMA Type 2 traffic controller that follows the NTCIP standard. Data is exchanged between the translator and the ASC/3 traffic controller using SNMP packets which consist of management information base (MIB) codes as defined in the NTCIP standard. The translator uses MIB objects as specified by the NTCIP 1201 and 1202 standards to send and retrieve data from the traffic controller.[6][7] Table I. represents the MIB objects both read and set in management of the PnP nodes.

Upon startup of the bridge controller, critical information must be extracted for clock synchronization, proper signal configuration, and safe-fail operation. The first object includes the one from the 1201 standard representing the traffic controller clock value, *controller-localTime*. This time is used in time-stamping data log information on the bridge node. Secondly we use 1202 standard MIB objects which contain phase timing information, such as maximum phase values, phase cycle durations, safe-fail modes, and other indications associated with traffic controller operations.

Following startup initializations, the translator controller enters a continuous program loop where the traffic controller is polled every 250 ms. Standard objects received from within the *phaseStatusGroupEntry* MIB node provide state information for signal phases, and pedestrian service calls. This information initiates the smart signal transitions and verifies button operation. In support of this project, Econolite created a custom version of the ACS/3 firmware to process objects for the pedestrian timing data that was missing from the commercial off-the-shelf ASC/3 controller. The information contained in the custom objects consists of the pedestrian crossing state and walk timer. Near synchronous signal transitions and instantaneous countdown timing updates were achieved by using this proprietary information, thus improving information integrity and system reliability

TABLE I.
MIB OBJECTS USED FOR PEDESTRIAN WALK/WAIT STATE AND TIMING INFORMATION.

Standard	Object ID	Table Entries
1201	1.3.6.1.4.1.1206.4.2.6.3.6.0	controller-localTime
1202	1.3.6.1.4.1.1206.4.2.1.1.1.0	maxPhases
1202	1.3.6.1.4.1.1206.4.2.1.1.3.0	maxPhaseGroups
1202	1.3.6.1.4.1.1206.4.2.1.1.5.1.7	phaseControlGroupPedCall
1202	1.3.6.1.4.1.1206.4.2.1.1.4.1	phaseStatusGroupEntry: Red, Yellow, Green, PedCall, PhaseOns, PhaseNexts
1202	1.3.6.1.4.1.1206.4.2.1.1.2.1	phaseEntry: Walk; Pedestrian Clear; Minimum Green; Startup; Options; Ring
Proprietary	1.3.6.1.4.1.1206.3.5.2.1.19.1.2, 1.3.6.1.4.1.1206.3.5.2.1.19.1.3	PedStatusState, PedStatusTimer

A WEB based configuration program that is hosted by the SNMP translator processor, allows mapping of the phase groups to specific devices using a PC. Node power settings, phase, and safety critical data is configured using a standard HTTP web interface. The management control also has the ability to install or remove nodes from the intersection. Using WEB based control allows any computer with an Internet browser and Ethernet port to be used, avoiding the need for special application software on signal maintenance laptop or traffic operations system.

2) PnP Controller to NTCIP Translator Communications

Three categories of messages are sent from the translator controller to the PnP controller: a configuration packet, a traffic state packet, and a heart beat packet. The PnP controller error messages and detector trips data are sent to the ASC/3 controller via the translator processor. The PnP controller communicates with the translator controller using a high-speed eight bit bidirectional parallel data port using a master-slave mailbox data exchange structure supported by the RCM 3000 Rabbit Microprocessor series processors used for all embedded nodes.

3) PnP Controller to PnP Device Communications

The PnP controller communicates with all PnP devices on the PnP network using two types of messages: configuration packets and state update packets. The configuration packets are unicast messages used to notify individual nodes of changes in their configuration that originate from the signal maintenance PC or from the translator processor. Each configuration packet specifies a setting for the node's phase, power mode, and whether or not the data is safety-critical.

State-update packets are multicast to all nodes in the network by the PnP controller every time it receives new state information from the translator controller. After sending a state update, the PnP controller waits until all safety critical nodes in the system respond to the update before sending another broadcast message acknowledging the commanded state. This type of message is called an "implement packet" that instructs the nodes to change state instantly upon receipt of the message.

There are also three broadcast messages that do not contain traffic signal state information. There are heartbeat messages that simply indicate that the PnP device is still functioning. Another type of network message indicates that the PnP controller has detected a critical error in the intersection and instructs all of the nodes to transition into a safe-fail mode. The last type of network message is one that PnP controller sends when initializing to instruct all nodes on the network to transmit their electronic descriptions back so that the PnP controller can determine which nodes are connected.

The PnP controller periodically interrogates the status of each smart device. If the PnP controller receives an error message from a smart device or if a node does not respond in the appointed time window, the PnP controller passes that error message back to the translator controller to have that data saved in a log file. The error log is accessed from signal maintenance laptop through the WEB page hosted by the translation controller.

C. System Hardware

Rabbit Semiconductor RCM3000 series microprocessors with 10baseT Ethernet controllers were used for all PnP smart sensors. The embedded network system consists of two Ethernet networks each requiring a network switch and a data bridge in addition to one or more PnP networks nodes. When using EoP modems, no hub or switch is required for the PnP network. Two independent processors were used for the bridge consisting of an independent SNMP translator and PnP manager. It is possible to merge the communications of the bridge into one node, but for speed of development and microprocessor resource management the two remained separated thus providing two independent networks. The functionality of the two processors was allocated to level the processing burden for improved system response performance and development flexibility.

The smart pedestrian devices are a drop-in-replaceable

because no additional wires are required between the traffic controller cabinet and the devices because EoP technology is utilized. The conductors required to supply power for the devices also become the medium for network communications. Our PnP system communicated with DS2 200Mbps EoP modems and as a result provided sufficient bandwidth for managing system Ethernet communications.

1) Pedestrian Signal

Commercial pedestrian signals use a standardized housing. Therefore the PnP signal, which includes an EoP modem, light emitting diode (LED) array, and microprocessor, was intended to fit inside an MUTCD[2] compliant housing.

The signals were designed to allow individual LED control, monitoring, and variable display intensity. Each LED is now treated as a user specified pixel and can be controlled independently thus allowing the display of symbols other than conventional numbers. These smart signals are also able to detect and send alarms back to the bridge controller in the event of a signal failure. Possible failures include LED burnout or disconnect and state update timeout. LED monitoring was designed with analog to digital convertors that capture the returning electrical current as each column of LEDs is switched on. The display intensity of the LEDs is controlled by the pulse width modulation (PWM) output of the microprocessor. Possible uses of variable intensity control include adaptively reducing energy requirements, increasing LED longevity, and reducing light pollution or interference. The PnP feature of the smart signal technology makes it possible for the signal to have electronic descriptions of the signals capability and performance characteristics.

The display configuration of the new smart countdown and walk-wait signal are shown in Fig. 3 and Fig. 4. The countdown timer displays consists of two eight by sixteen LED arrays and the conventional hand and walking man icons. This design is intended to demonstrate the potential of smart signals concepts and is not intended to be MUTCD compliant.
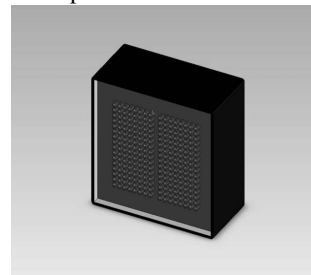

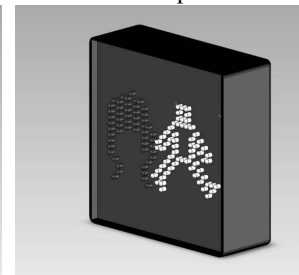Fig. 3 LED placement for the PED Countdown timer

Fig. 4 LED placement for the PED Countdown timer

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[2] The *Manual on Uniform Traffic Control Devices*, or **MUTCD** defines the standards used by road managers nationwide to install and maintain traffic control devices on all streets and highways.

2) Pedestrian Button

The smart PnP pedestrian buttons communicate with the traffic controller using the same Ethernet bus as the other signals. The controller can provide feedback to the pedestrian button when a request for service is registered. It is anticipated that a visual, tactile, or audio display of this feedback will discourage physical abuse of the call button and encourage pedestrians to wait for the walk indication in lieu of making a hazardous and illegal attempt to cross the street. The smart pedestrian call button is also equipped with wireless remote receiver. It can handle requests by special needs users who have difficulty locating or accessing the call button. A low cost 400 MHz short range radio implemented the call request and feedback communications. As such, the system is able to differentiate pedestrian calls and provide different service based upon the needs of pedestrians requesting service. The wireless receiver can reside anywhere in the system, for example within the countdown signal where the radio signal will be potentially more reliable.

D. Network Security Considerations

For network security measures, it is advisable to use a router between any wide area network (WAN) and the local area network (LAN). It is common for the traffic industry to secure a network by means of isolation or "air-gap". The physical network medium for transmitting control data includes proprietary radio, fiber optics, and metallic wires.

The architecture of the PnP smart signals system consists of two Ethernet network types. The PnP communication uses EoP which acts as a hub based network. The traffic controller communication uses category 5 Ethernet cable and utilizes switch based routing.

EoP was a convenient communication medium, but messages are broadcast across the entire intersection local network. Theoretically information could be accessed and possibly misused if this network does not employ security measures. Nevertheless the EoP modems implemented in this project include 256 bit Advanced Encryption Standard (AES) cipher algorithms developed by NIST for protecting sensitive federal information. AES was cleared for public use and is intended to be secure enough for US federal government use up to the "top secret" level.

IV. RESULTS

The system was demonstrated at the NIATT Smart Signals Conference in November 2006. With the constraints of very strict control over the network information flow, the system worked with no observed failures. The smart signal system countdown timer accurately displays the crossing time remaining during normal operations and dynamically updated for phase timing changes. The remaining clearance interval was also correctly displayed when the traffic controller timing

was changed due to preemption[3]. There were no observable transition lags in the walk/wait displays when compared to conventional units operating simultaneously.

Only a single smart pedestrian call button was implemented for all tests. This gave the conventional pedestrian signal the same call reference as the smart PnP pedestrian signal. Testing of inputs from a conventional call button was simulated using the signal maintenance PC as an SNMP client to set the pedestrian phase call object.

Problems did arise during testing resulting from limitations of the EoP modems. Power line noise generated from nearby devices made initial setup at the conference difficult. It is common for traffic intersections to use an isolation transformer, so we believe this would not be a problem in real world applications once the smart signals network was configured properly with appropriate isolation from interference generating devices.

The bridge has to request multiple large SNMP packets of information and then filter them to retrieve the correct information. There is considerable wasted time in retrieving information that has no use for the PnP system. A possible solution is to update the traffic controller configuration for dynamic objects to allow more precise information in one data broadcast. A dynamic object is a NTCIP standard minimal packet with only one byte of header information to accompany the raw ordered data.

Wireless Ethernet was also considered, however the associated security issues were beyond the scope of the project. Future developments could easily implement a 802.11 wireless standard into this design, perhaps even as a backup device for EoP modem failure. The project demonstrated that any medium for transmitting Ethernet messages could be used.

V. CONCLUSIONS

The project successfully developed proof-of-concept prototypes for a distributed-signal-network of PnP traffic signal devices. TS2 traffic controllers with minor modifications can support both conventional and smart PnP traffic signal devices. The continuation of research for implementing IEEE 1451 in signalized intersections demonstrated network communication over power line carrier, traffic controller integration, and improvements in accuracy and intersection services. The prototype IEEE 1451 compliant devices developed included a bridge controller for communication with traffic controller, variable intensity pedestrian crossing signals and countdown signals, and pedestrian crossing button with wireless button and feedback. Hosting a webpage for the maintenance of the PnP system does not require additional hardware or specialized software to be installed on PC for maintenance and installation. Testing of the PnP network makes it reasonable to anticipate

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[3] The term preemption is used in the traffic industry to define the state at which normally signal timing is superseded by an abnormal condition, such as an emergency vehicle requesting priority.

that continuing advances in EoP technology will resolve the issues addressed in the results above.

Traffic signals based upon PnP distributed sensor networks can support dynamic signage to facilitate temporal requirements for traffic control, thus providing better real-time traffic control that can result in safer and efficient traffic flow. Electronic descriptions in the smart transducer modules provided by the smart transducers simplify installations and provide a new multivariable array for user detection.

VI.   DIRECTION OF CURRENT RESEARCH

With the success of the smart signals research being able to correct the operations of the countdown pedestrian signal, the present research is focusing on pedestrian safety and access. Significant attention is being given to the making the system robust by including concepts of safety critical Ethernet and embedded network security. We are currently working with various groups representing pedestrians with disabilities to provide assistance in orientation and navigation. It is our intention to work with Federal Highway Administration researchers to integrate our pedestrian safety work with FWHA Vehicle Infrastructure Integration (VII) and Cooperative Intersection Collision Avoidance System (CICAS) initiatives.

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