SMART INTERFACES FOR DUMB DEVICES

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Many economic and design challenges face the embedded Internet solution provider in creating and controlling a network of potentially tens of thousand of switches, sensors, and TCP/IP embedded devices over the Internet. To implement these systems, the designer must consider five key system requirements: **S**calability, **M**anageability, **A**vailability, **R**eliability, and **T**ransparency. An application example of a vineyard management system is outlined.

INTRODUCTION

As the world becomes more and more IP connected, the devices being connected are simpler than ever. For example, during the development of the Internet, the "simplest" machines on the Internet were full function minicomputers hosting a multitude of applications and users, maintained by professional staff and located in controlled and secure environments.

In contrast, the desire today is to use the Internet as a connection service to simple "single function" machines. The TCP/IP interface itself can be more complex than the function being performed by the machine. (For example, the embedded control software of a kitchen refrigerator may be far simpler than the TCP/IP interface). Going a step further, it is now possible to connect simple sensors and control devices to the Internet. But is this economically feasible? Is the cost and complexity of connecting dumb devices over IP justifiable?

The more information monitored and remote control exerted via an IP interface, the greater the complexity of processing required at the connected device to support the IP connection. At some point, the complexity of the monitoring program will consume more computing resources than the local function being monitored, and the monitoring program itself will become the most expensive and unreliable part of the system.

From the server's perspective, the number of connected devices requiring monitoring can easily run into the millions for typical consumer application. In addition, if for cost reasons these simple clients employ very simple control software and a very rudimentary machine understandable only information exchange interface, the greater the complexity required of the server to interact with the multitudes of connected devices, as well as the ability of the server to extract meaningful information of the state of the "network" and to present it in a human understandable format. Simply stated, the simpler the clients, the more complex the server required.

This paper will explore the economical and design challenges facing the embedded Internet solution provider in creating and controlling a network of potentially tens of thousand of switches, sensors, and TCP/IP embedded devices over the Internet. We will attempt to make sense out of what the real value of managing a network tens of thousand devices is:

1) Is it to control each node individually?
2) Or is it to see the whole system from a simple view. Seeing the picture, not the pixels.

After establishing a better understanding of why one would want to connect tens of thousand devices, we will discus the **SMART** method to developing a workable and robust solution in controlling and monitoring a distribute system of tens of thousands of devices. For the system to work, the interface must meet an acceptable level of five performance requirements:

1) **S**caleable: The system must be designed to be easily expanded as new remote devices are added
2) **M**anageable: The system must be able to manage potential thousands of simple device
3) **A**vailable: A connection must be locally available
4) **R**eliable: The interface must be reliable (system dependent).
5) **T**ransparent: To the greatest extent possible, the data exchanged must be as untainted as possible by the transport mechanism itself and the data presented to the server must be timely.

We will then present a practical example and apply the SMART method in developing a multi device manage-at-distance solution for a sensor management system. Finally we will conclude the paper by summarizing our findings.

OPPORTUNITY

Widespread proliferation of intelligent interconnected embedded systems and devices on Internet and Ethernet is now a reality. What formerly required entire systems, is now possible with system-on-chip components and integrated networking software (embedded TCP/IP and 10/100 Ethernet MAC). Further, devices like sensors and valves can now be integrated with simple I/O control, ROM & RAM. Any sensor could potentially have its own home page because it is individually Web addressable.

Whether it makes senses for individual sensors and simple devices to be connected directly through IP depends on the application. A viable alternative is to use local data concentrator hubs to gather and relay data from any appropriately equipped mechanical or electronic device to the IP network.

Though it is relatively easy to connect devices to IP, the real challenge is in making sense out of the tens of thousands of devices making up the network and creating real economic value out the resulting system. Device networking creates the opportunity for fast access to real world information to enable better decision-making. However, monitoring an isolated device node like a sensor, in a complex system, doesn't provide tremendous information in of itself. It is the resulting picture or map, created by connecting all of these devices into a single view, where the value is derived.

As more and more simple appliance type devices are connected to the network, there will be an increase in complexity of the network and collective intelligence, but an overall decrease in the intelligence of the individual nodes of the network. In many cases, at the node level, the network interface control may be far more complex than the application itself. In fact, some applications, such as remote temperature sensing, may be so simple, that as stand-alone they contribute very little information, and only when viewed collectively do they make "sense." In particular, these types of networked systems quickly become too complex to be understood let alone controlled at the human level without some intervening data concentration and processing.

THE SMART APPROACH

Clearly then, for ease of use, a hierarchical system will naturally evolve out of the chaos. The question is, when we implement these systems what are the important criteria we need to examine? We believe five criteria must be considered during the design phase.

Scalability.

The utility of the Internet as a common connection method would be severely limited if the network had to be reconfigured every time a new device was added. Incremental additions of devices should not result in degradation or failure of the network operation.

Ideally, adding a new device should as simple as plugging it in and using available network services such as DHCP, ARP etc… to automatically configure the device and announce its presence on the network. Additionally, some other protocol such as JINI or UPNP would be available to announce to the network the capabilities of the new attached device.

At the upper levels, the system needs to be able to adapt and learn as new capacity and capabilities are added. Implicitly, this is a two-way street; just as new components are physically added, new applications may be downloaded to the existing component creating new capabilities.

Manageability:

Hand and hand with scalability is manageability of the network as the number of attached devices increases. The management system must provide at least two major functions, a "global view" of the operation of the whole system, and second a means to interact at the individual device level. As a practical means, management may be distributed between two or more layers. Take for example, the case of a remote temperature sensing application, which deploys thousands of sensors: it may be more effective to use a number of inline data concentrators to reduce the network traffic.

Managing and interpreting the data stream from thousands of simple sensors is a major challenge in itself. A trade-off must be made between complexity of view and ease of understanding. Taking the example of the temperature sensors above, it may be both more meaningful and easier to interpret a plotted graphical thermal map versus a complex table of individual temperature sensors values. Trends which can be extracted from the data and entered into a predictive model may be much more important than the absolute temperature at a specific sensor (see example below). In such a case, it may not be necessary to know the exact value at a particular sensor point – although for things like test and service, the ability to do so should not be precluded. In most cases, automatic data logging at inline clusters can significant reduce the amount of traffic with little or no loss in significance of the data.

Availability:

TCP/IP is ubiquitous and it is a good backbone to build a distributed network, but it may not be as pervasive as we like to believe it is, or if available at the local connection point, as flexible as we require. For example, in the case of an array of thousands of simple sensor in a vineyard application, even a POTS connection may not be available. Additionally using SLIP/PPP, the overhead consumed just in establishing a connection at the individual sensors level would be enormous. In this case it would make more sense to use a data concentrator to connect the sensors and a wireless interface (of which there are several good alternatives) between the data concentrators to the main network.

TCP/IP contains a very flexible set of protocols. When deciding upon the method of connection, availability of a sufficient level of QoS to support the protocols selected must be a major consideration (McGourty et al. 2000). This is primarily a cost issue. Within the system itself, there may be multiple connection paths with different costs. For example, a high cost high reliability but low traffic connection can be maintained primarily for transmission of system alert status, while the bulk of the sensor traffic could be transmitted over a lower cost less reliable connection. If the system is relatively slow changing, lower QoS in return for lower connection costs is a reasonable tradeoff since missing a particular data sample will have little impact overall. On the other hand missing an alert may have a major impact.

Finally, when considering manageability issues, such as reprogramming the system, the implementation must support the management requirements. For example, in the case of the requirement of remote program update control, if e-mail is used as a vehicle to send program updates, it may theoretically be possible to mass-mail an update to all sensors, but an entire client-server infrastructure must be put in place to do this. It may be simpler and cheaper to individually connect to individual sensors (or sensor sub-nets) via a simple telnet interface for example, and update at a slower rate.

Reliability:

The utility of the networked system is a function of its reliability. There are three important aspects of reliability we need to consider. First is the Quality of Service, second is the Robustness of the system to point failure and the third is the Security of the network.

QoS describes the level required to support proper functioning of the application(s) running on the network (McGourty et al. 2000). It is useful as measure of the performance of the "common carrier" connections used to network the distributed subnets of the system. At the local subnet level we have complete control of the network, and we can implement any networking topology we care to pay for. However, it is important to have complete understanding of the response time demands of the application to ensure that the chosen interconnecting network topology (and or provider for that matter) itself will support a high-enough QoS for the application to function properly. Real time interfaces such as VOIP need a higher QoS rating than our example of slow reacting temperature sensors.

If the system is restricted to transmitting slow changing data, almost any level of QoS will suffice. However, if the system must track fast changing data in real-time, then higher levels of QoS are required. It should be noted that local data caching is not necessarily a panacea for low QoS. Finally, if the system supports online reprogram ability at the concentrator or node, the issue of reliability of transmission is very important.

Robustness of the networked system is the ability of the system to tolerate point failures at the node and perhaps subsystem level yet still continue to function, albeit perhaps in a gracefully degraded failsafe mode. For example failure of a simple sensor should not take the entire network down. A means to partition and remove mal-functioning nodes and even subnets must be built into the system. In addition, proper feedback perhaps using protocols such as SNMP should filter up to the highest management levels of the system. The system should react by continuing to function and give proper output by adjusting as best as it can for the error, and logging the problem so that it can be resolved in a timely fashion.

Security may be the sleeper issue. It is only obliquely addressed, but what would happen for example if a hacker broke into a network of refrigerators and reprogrammed them as ovens? The liability issues are enormous. Restricting access to vital functions such as system reprogramming is a requirement. Further steps such as data encryption maybe warranted depending upon the sensitivity of the system. However if the system is very sensitive, one must question why it is online in the first place?

Transparency

To the greatest extent possible, the management system should appear to be in direct contact at all times to the lowest level of component in the networked system. The means of connection should not be apparent, and the data and response time of the network should not be compromised by the means of connection. In simple terms there needs to be assurance that what is being measure at any point in time is the response of the system, not an artifact induced by the network.

This should not imply that we need T1 level connections between the all the components of the network – although a very few applications may demand that level. We classify applications into 4 classes, where class 1 is very time response demanding, and class 4 is the least demanding (McGourty et Al. 2000). In reality the response time requirements of most systems fall into the class 2 and 3 levels and are easily accommodated by very modest connections schemes.

If the system is primarily a data collection and reporting system, achieving workable levels of transparency is relatively easy. On the other hand, if the system is an active control system, a reasonable level of transparency to effect a required response time to a command may be difficult to achieve even at high cost.

SMART IMPLEMENTATION: The Vineyard Management System

The goal of the vineyard management system is to provide the grower the tools and controls to maximize the yield of the vineyard while reducing operational and management cost.

The customer is a wine vineyard with approximately 100 acres of Cabernet Sauvignon and Zinfandel grape vines. The customer's objective is to achieve gross revenue per acre of more than $7500 at a production cost of less than $2700. (High quality vineyards are capable of generating significant cash flow, and the customer is highly motivated to maximize his returns.)

There are two yield components the customer is concerned with: maximizing the quantity (measured in tonnage per acre) and quality of the grape (measured by sugar and acid composition.) Vineyards can trade off quantity for quality, depending on the vineyard's market niche and business objectives. The vineyard management system provides the grower a method to optimize on specific parameters to meet their objectives. For this customer, increasing quality is the primary objective.

Reducing operating cost is equally important for the customer. Most of the cost in managing and operating a vineyard is associated with labor cost, though other cost including irrigation, chemical management and asset management contribute significantly to the overall operational cost. Table 1 summarizes major vineyard activities and cost, the degree of automation that can be applied, and how the activity affects the quality and quantity of the vineyard. Activities (systems) that are prime candidates for automation are the irrigation and frost protection system. The other activity addressed is the automation of data collection in the areas of labor and material tracking providing hard metrics to better utilize and manage resources through the vineyard's management resource planning (MRP) information systems.

It is theoretically possible to monitor and manage every vine in the vineyard; however, the resulting data collected may not be particularly useful. A key system tradeoff to consider is the density of data points versus resulting information value and cost per data collection point. While it might be nice to have lots of data, the effort required to extract information from the data may have little value to the vineyard's operational efficiency. For this customer, we implemented zone measurements, but provided the capability to add additional sensors and controls to the system without incurring significant cost and integration headaches. (Scalable, manageable and transparent)

Frost Management System:

The greatest potential negative impact to vineyard yield is frost damage. The greater the likelihood of frost conditions, the greater the need for a frost management system. From the grower's perspective, the value of the frost management system is directly proportional to the probability of a frost and the economic impact of losing a crop for the year. In areas of high frost probability, losing a years crop to a deadly frost is a critical concern and requires a fail-safe system that works when it needs to work, every time. These systems are typically installed right-up front and are part of the fixed infrastructure cost. As a consequence, it is important not to over design the system and inflate the cost beyond benefit, nor under design the system so that it will not perform adequately when needed.

System requirements:

The frost management system must be 100% fail-safe and with 100% coverage of all vines within specific “at-risk” frost zones. The system shall be proactive and anticipate deadly frost conditions before damage occurs. It will also provide the necessary feedback to alert the grower if system failures occur, allowing the grower time to manual correct the fault and save the vine.

1) Controls and sensors:
    a. Temperature sensor, overhead sprinkler system, reservoir and pump (pump to fill reservoir and pump to deliver pressure to sprinkler system). Alternatively, blower systems can be used in replacement of sprinkler systems for frost protection, requiring specific monitoring sense points for the blower system.
2) Information system and alerts.
    a. National weather forecast for regional area. Provide early warning of killer frost conditions, in addition to localized data collection points.

Irrigation System:

System requirements:

The irrigation system must provide 100% assurance that individual vines receive the right amount of water, and must optimize the water delivery to reduce cost of evaporation and associated electrical pump cost. Management information based on historical, present and forecasted data shall be used to optimize irrigation schedules.

1) Controls and sensors
    a. Drip irrigation system (Directly from well pump, pipe distribution system & moisture sensors).
2) Information system and alerts.
    a. Optimize irrigation schedules to
        i. Deliver the right amount of water to optimize quality and quantity of the crop; based on historical records, present conditions and future weather conditions.
        ii. Best water times per day in relationship to evaporation and electrical power. (Water and energy savings)
    b. System performance monitoring: flow rates, pressure changes, filtration systems.

Data collection, geographic information system (GIS) and management resource planning (MRP) information system:

System requirements.

The primary purpose of this system is to provide physical checkpoints throughout the vineyard to optimize labor and material cost. The system must be able to sense tractor locations, consumption rate of chemicals and minerals applied to the vineyard, and integrate with handheld data collection devices used by the vineyard workers the vineyard’s management resource planning (MRP) information systems. Real-time collection is not a requirement for this customer.

1) Control and sensors:
    a. Row tags: RF tags, minimal one per row. Possible to tag individual vines for specific data collection points if more accuracy is required.
    b. GPS/GIS system to map physical locations of vines with RF tags (position and altitude). Ideally GPS/GIS interfaces are integrated into the initial design of the vineyard.

c. Flow sensors and container measurement systems for individual chemical and material delivery systems (i.e. pesticide and weed sprayers, pathogens (disease) and fertilizer delivery systems, etc.)
d. Collection terminal/PDA used to log RF tag proximity and chemical/material dispensing.
e. Database integration into MRP information systems.

2) Information systems and alerts
   a. Labor utilization – data integration into
      i. Time and attendance, payroll systems
      ii. Resource planning and management system
      iii. Asset tracking

Activity	*Cost/ acre*	*Comments*	*Field automation*	*Affects on*	
				Quality	Quantity
General Vine Care	$322	Pruning, train vines, etc. Mostly manual labor.	Labor tracking	Yes	Yes
Weed Control	$50	Spray, disc and hand hoeing.	Labor & material tracking	Minor	Yes
Mildew Control	$110	Dusting and spraying	Labor & material tracking	Yes	Yes
Insect & Mite Management	$35	Spray	Labor & material tracking	Yes	Yes
Frost Protection	$25	Does not account for actual crop damage and replacement cost.	Fully automated: Temperature and automatic sprinklers	Yes	Yes
Irrigation	$38	Typically drip system	Fully automated: Moisture and sprinklers	Yes	Yes
Fertilize	$48	Spray and cultivate	Labor & material tracking	Yes	Yes
Leaf Removal	$217	Labor intensive	Labor tracking	Yes	Yes
Harvest cost	$720	Harvest cost increases as tonnage increases. Mostly labor cost	Labor tracking	Possible	Possible
Other cost	$1113	M&A, overhead, depreciation, repair maintenance equipment and vineyard infrastructure.	Labor & asset tracking	Possible	Possible
Total Cost	$2678				

Table 1: Vineyard activities and typical associated cost per acre.

APPLYING SMART:

Productivity should not be confused with profitability! There is a cost/benefit tradeoff for any specific implementation level of the five system requirements. Finding the implementation level to support the goal of the system is the key to achieving an acceptable return on investment for the system.

Scalability

Vineyards typically incorporate a trellis system to support the vines. The trellis can function as a structure to support a communication cable. In addition, since vines are living plants, other than normal weather, the environment is not likely to be subjected to harsh chemical attack. A simple twisted pair wire with multi-drop connections is the most cost effective means of networking the sensors, though RF technology is another viable solution. Additionally, a power drop, or local source is required (solar power). Since the communication rate requirements are very modest, data and power could be multiplexed on to the same cables

For practical reasons, a trellis system rarely extends beyond 500 meters long; a simple serial topology such as RS485 or 1-wire (Nelson, 1995 & Awtrey 1997) is a practical networking method. In the case of temperature sensors, assuming a linear spacing of approximately 30 meter apart, 15 sensors would be required along the communication line. Since RS485 allows up to 32 load-drops, this leaves plenty of expansion for other types of sensors along the communication line (Nelson, 1995).

An acre is roughly 64m x 64m. Depending upon the geometry of the vineyard, at 30 meter center-to-center spacing, a mesh of 3 to 5 sensors will give complete coverage per acre. A 100-acre vineyard requires 500 sensors maximum. At 15 sensors per subnet, approximately 30 subnets are required to monitor the vineyard.

Manageability

Temperature change rates are not particularly fast (tens of minutes per change), so a single data collection unit could be used to manage the 30 subnets. Assuming 100kbps data rate, a simple 64 bit packet protocol (8 bytes of data) exchange per transactions, and two transfer per sample, a complete sample of the system would take under 1 second.

Alternatively, the system could be split into a number of separate stand-alone sub-nets, which in turn link to a more sophisticated master controller. For flexibility, the link here is a simple 900mhz wireless connection.

It is highly unlikely that the sensor function would ever be reprogrammed. Reprogramming would be at the data concentrator point(s) or master controller. These are very few in number; so individual update via telnet type services would be appropriate.

Availability

A complete upload data packet is 500 bytes of data. The data rate of the upload link is very minimal. If available, a POTS interface is the simplest, but a RF connection such as a cell phone, or even pager interface is more than adequate to support the system.

Reliability

The master controller continuously runs a background diagnostic comparing readings to determine if a particular sensor is not responding, or reporting out of range. At the sensor subnet level, the only reliability issue would be the requirement that a non-functioning sensor not be able to hang the system up, it must be able to be partitioned out of the system in the case of a failure.

The greatest reliability issue is the final uplink. If QoS is an issue, this link could be implemented as redundant system to insure that at least one uplink is always available. The primary concern is the ability of the system to send out an alert signal for frost protection. Of course, the controller can be programmed to run in automatic mode if no uplink is available as a final fail-safe.

Transparency

A complete data scan will take about 1 second. By way of contrast, a temperature change will take minutes. The sampling rate is significantly faster than the process change rate. For all intents and purpose this is an ideal class 1 system, the instantaneous state of the entire system can be determined with precision.

Value Added Through a Comprehensive Vineyard Management System:

The real-time systems provides the vineyard manager high level of assurance that time critical operations, such as irrigation and frost control, are optimized and properly executed, while reducing cost by eliminating physical labor. Eliminating crop damage from frost and under and over watering vines provides real value. Though the cost per acre of water is relatively modest (table 1), water cost and energy cost continue to be an issue, especially for California vineyards. Automation provides the opportunity for the vineyard manager to operate systems during off peak power times.

Within a typical vineyard, soil composition varies which directly affects the moisture conditions. Using GIS and other mapping techniques, the grower can adjust for different soil gradients. Using direct feedback through moisture and temperature sensors, the grower will know within reasonable accuracy, if the vines are receiving the right amount of water to eliminate over or under watering. Equally important, the grower can control the water consumption to optimize the ultimate grape quality, where often times, less water results in a higher quality fruit.

In addition to zone measurements, the system provides the grower the ability to monitor reference vines within sectors to provide plant specific information. Important reference plant measurements include plant sap pressure (moisture measurement), canopy (leaf) temperature, pruning weights and grape cluster weights (provides a direct measurement of quality and quantity). As new plant sensor technology evolves, the grower can simple attached the sensor to the existing network infrastructure (scalable & manageable).

The data collection system provides the manager direct feedback and status as to how efficiently vineyard work orders are executed including labor, material and asset planning and tracking. As seen in table 1, labor represents the highest cost in operating a vineyard. The data collection system reduces general management and administrative cost by automating basic data entry into the MRP system including time and attendance and payroll processing. With accurate and real-time data loaded into the vineyard MRP systems, the manager can execute purchase orders of basic materials when inventories need replenishing avoiding over stocking and shortages.

But the real-value added will come from the collection and processing of data over time. Real-time and historical data integrated into GIS software systems such as ArcView, provides the grower “precision farming” capabilities to better plan and manage vineyard activities and resources. Converting the raw data, including historical, present and predictive data, into an understandable information and management tool is the ultimate purpose and added value of the vineyard management system.

Observing and anticipating change and conditions early help the grower adapt the operational conditions to yield highest quality and quantity results. For example, if the grower observes consecutive hot temperature days as the harvest season approaches, he will have the historical knowledge to know the optimal time to deploy the harvesting crew. Over time he may discover that certain zones within the vineyard (mapped and layered in a GIS system) yield specific qualities that result in premium wines. With the vineyard management system in place, it is now possible to zone pick and tag specific grapes that can be bottled or sold as premium grapes to maximize revenue per acre. The manager will also have the ability to apply specific material resources to any zone to optimize the growing conditions throughout the growing season.

CONCUSION:

As the world becomes more and more IP connected, the devices being connected are simpler than ever. As more and more simple appliance type devices are connected to the network, there is an increase in complexity of the network and collective intelligence, but an overall decrease in the intelligence of the individual nodes of the network. At some point, the network interface itself can be more complex than the function being performed by the networked devices.

However, there are potentially great productivity gains to be made by connecting simple inexpensive sensor devices into monitoring and control networks. The example provided of the vineyard management system is typical. But, productivity gains can be realized only by first defining the goals of the system, and second analyzing the system requirement implementation cost/ benefit. The five key system requirements are:

Scalability: The system must be designed for easy expansion
Manageability: The system must be able to manage potentially thousands of simple device
Availability: A connection must be locally available to support the goals of the system
Reliability: The interface must be reliable at a reasonable cost
Transparency: To the greatest extent possible, the data exchanged must be as untainted as possible by the transport mechanism itself and the data presented to the server must be timely

The key to achieving an acceptable return on investment is to not over design the system, but to implement to just the level of performance required. Device networking creates the opportunity for fast access to real world information to enable better decision-making. However, monitoring an isolated device node like a sensor, in a complex system, doesn't provide tremendous information in of itself. It is the resulting picture or map, created by connecting all of these devices into a single view, where the value is derived.

For the vineyard, the IP accessible sensor and data collection network enables data to be shared and monitored with consultants, wineries, offsite managers and university people involved with collaborative research. Integration of real-time and real-world data with GIS and vineyard MRP tools provide the big picture we are looking for to create value in managing tens-of-thousands of sensors and devices to improve overall industry knowledge and efficiencies.

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