Networking —*Part 2*

In theory, the concept of a "three-cable boat" should simplify marine-systems installations and monitoring. In reality, builders and boat owners now face a new complexity: different protocols at variance with each other.

Part 1 of this three-part series looked at the emergence of whole-boat networking systems for integrating engine monitoring and control, navigational electronics, and power distribution. These systems have the potential to dramatically reduce the amount of wiring in boats, moving toward what I call a "three-cable boat."

To get a better sense of how the available systems differ, and of their benefits and drawbacks, we'll consider them in more detail in Part 3. There, we'll look at how these networking systems are being applied to general-purpose boat wiring—what's known as a "distributed-power system." But before doing this it will be useful to have an understanding of how they work.

The two networking systems that presently have the highest visibility—SmartCraft and NMEA 2000—are both based on the Controller Area Network (CAN) protocol, which has come out of the automotive industry but is also now widely used in industrial controls. So, it makes sense to start by discussing CAN.

Before we begin, I wish to state that I have at one time or another been hired as a consultant by several of the companies mentioned in this series; however, I have no ongoing arrangement with any of them.

For a list of companies mentioned in the article, see the source list on pages 74–75.

Text and photographs by Nigel Calder

(except where noted)

Core CAN Concepts

CAN defines a message-sending pipeline and the mechanisms to be used to transport messages through it. It does not say what those messages will be. Every device, or *node*, connected to a CAN-based system (commonly referred to as a CANbus) must include a *transceiver* for transmitting and receiving the CAN-based messages, and a *link controller* for translating those messages into and out of an appropriate format for the device. The two processes are often conflated, and the hardware—a small microprocessor—that performs them is referred to as either a *transceiver* or *chip* (also known as an *Applications Specific Integrated Circuit*, or ASIC).

The contents of the messages on any CAN system are customized for the specific purposes of that system, which makes the CAN approach extremely flexible. Engine manufacturers can design a system in which the messages relate to engine performance, such as rpm, temperature and pressure measurements, and exhaust analysis; in industrial controls, different messages will be used—a grain-elevator system, for example, would include information on how full the hoppers are, the state of the elevators, etc.

For the marine world, MotoTron (among other companies), a subsidiary of the Brunswick Corporation tasked with developing and managing SmartCraft, has devised a set of messages that relate primarily to engine operations; and the National Marine Electronics Association, the creator of NMEA 2000, has devised a set of messages that relate primarily to marine electronics (latitude and longitude, heading, depth, etc.). *[For background on SmartCraft and NMEA 2000, see Part 1 in PBB No. 97—Ed.]* Other companies—notably EmpirBus and Moritz Aerospace—have developed messages relating to power distribution on boats. All these systems have the capability to be expanded, and are being expanded, with new messages as new types of equipment and functions are supported or developed. Various engine manufacturers also have proprietary, CAN-based systems for electronically controlled engines, most of which now include throttle control and transmission shifting, with Volvo Penta's approach including an interface with some autopilots. As far as I know, though, there are no plans to extend any of these into whole-boat applications.

Left—*In networking, heavy or light cable and connectors are necessary, depending on the amperage requirements of the devices to be connected to a given system.* ***Below***—*Note the relative difference in the heavy and light connectors used with the two different sizes of NMEA 2000 cable.*

Addresses

Unlike some other networking protocols, CAN-based messages need not contain the address of the sending node (although the NMEA version does include an addressing system), and need not be addressed to a particular station or device. Instead, the content of a message—wind speed, water temperature, revolutions per minute—is given an identifier that is unique within the system. All devices then send their information to all nodes on the system. Each node "decides" on the basis of the identifier whether or not the information is relevant to that particular node, and thus whether or not to process the message. This decision is programmed into the transceiver chip; in the NMEA version, if the message is addressed to a specific device, all devices—other than the device to which it is addressed—will ignore it.

In a message-based system of this kind, every node must have the chip needed to send and receive signals. No central controller, or *master*, is needed (a *masterless* system), so the failure of any node or device will not crash the system. In fact, one of the requirements of NMEA 2000 is that any node can fail in just about any way without adversely affecting the system. A corollary to this is that equipment can be added to and removed from the system at any time without shutting down the system, and without having to reconfigure it every time it's booted up. If there have been any changes since the last time it was powered up, the addressing system is used to assign a new address to all nodes. This is known as *automatic dynamic addressing*.

CAN Kingdom

The basic CAN approach described above is sometimes modified to include a master, resulting in what is known as CAN Kingdom. Here, there *is* a central controller, which acts as a system "king" to allow or disallow access to the system; there is no automatic dynamic addressing. SmartCraft takes this approach, designating the engine as the main controller of the system. If some component in the system causes trouble, it can be shut down without affecting the engine, which is, in essence, treated as the most important piece of equipment on the boat. If the master crashes, the engine crashes, although it can still be configured to operate in a fail-safe, "limp home" mode.

Phil Gaynor, business manager for MotoTron, writes, "Safety-critical systems for throttle/shift/steering must have 100% redundancy and fail-safe allowances. This is the primary reason SmartCraft exists." The Brunswick Corporation/MotoTron uses the king approach as a mechanism to maintain control over all non-engine-related devices that will be put on the SmartCraft bus(es). With respect to NMEA 2000, he comments, "There are a lot of unanswered questions about merging critical safety systems with an 'all-purpose network.'" Advocates of NMEA 2000 challenge the notion that the king approach provides greater security for engine controls, as well as the implied assumption that the broader-based NMEA 2000 provides any less security for mission-critical functions.

There is not yet enough real-world data to see how these differences in philosophy play out in practice, and in fact whether there is anything at all to be concerned about.

Collisions and Errors

What happens if two nodes transmit information simultaneously, leading to a "collision"? CAN's response is an approach known as *Carrier Sense, Multiple Access with Collision Detection* (CSMA/CD) combined with *non-destructive bitwise arbitration*.

The way this works is as follows. All messages within any given system are assigned a priority. When two collide, the higher-priority message gets through with no delay (as opposed to Ethernet, for example, on which both messages get delayed). The lower-priority message does not get lost, as can happen on other kinds of networks such as Ethernet. Instead, the message gets put in a queue and waits its turn. CAN's ability to guarantee

Top left—*A section of the heavy NMEA 2000 cable, which can carry up to 8 amps, is readied for the installation of a connector.* ***Top right***—*A closer view of the connector shows where the five distinct small cables attach that together make up the larger package.* ***Below left***—*Four competing cable and connector options currently available are, from left: NavNet, SeaTalk2, NMEA 2000, and SimNet.* ***Below right***—*A Maretron NMEA 2000 cable kit includes an array of Ts and connectors for installation.*

SIMNET

that the highest-priority messages (throttle, gear-shifting, and steering commands) get through in real time—that is, immediately—is critical to the safety of a vessel and its crew. It is one of the main reasons NMEA, Brunswick Corporation, and others have settled on CAN.

CAN also has built into it a number of error checks that enable faulty messages to be rapidly recognized and sidelined, and that also prevent a node that may be outputting a stream of junk—from fouling up the system. It is, in short, an extremely reliable and robust messaging protocol that has proven itself over many years in the automotive and industrial fields.

The Physical Layer: NMEA 2000

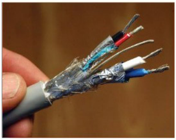
Of course, the CAN system is not of much use if the cabling and connectors—the physical layer through which messages are transmitted—fail to provide an adequate framework to carry the messages. One of the problems with NMEA 0183 (NMEA's earlier messaging protocol) has been that NMEA only *recommended* a particular physical layer instead of *requiring* it. Device manufacturers and installers can use less-robust approaches than those recommended and still claim NMEA 0183 compliance.

The NMEA 2000 standard *requires* a very specific physical layer comprising an extremely sturdy cable that is fully shielded against electrical interference, with cabling and connectors that are waterproof—they can be submerged in bilgewater and still work. These components have been developed for industrial controls and come out of a widely used CAN-based system known as DeviceNet. Two cable sizes are specified: NMEA 2000 heavy cable and NMEA 2000 light cable. Even the light cable is built to the same rugged standards; essentially, all that changes is the size of the wires within the cables, and the size of the connectors.

An NMEA 2000 cable contains a negative and a positive power cable, two data cables, and a ground cable—five cables in all. The NMEA 2000 heavy cable has AWG 16 power cables, which can carry up to 8 amps, and AWG 18 signal cables; the light cable has AWG 22 power cables, which can carry up to 4 amps, and AWG 24 signal cables. Power is supplied to the power cables from the boat's batteries or from a dedicated power supply, and connected into the network cable via a *Powertap T.* If required for redundancy, power can be taken from two or more different sources, using blocking diodes to keep the sources isolated from one another.

Those devices that require less than 1 amp to operate, such as a depthsounder, can be powered directly from the power cables within the NMEA 2000 cable. The NMEA cable would be the only cable connected to the device. Those that require more than 1 amp, such as radar, are powered from separate power cables. In this case, there would be the usual negative and positive power feeds to the device, plus the NMEA 2000 cable. A basic NMEA 2000 chip draws 15 mA to 20 mA; display screens draw more power. The 8-amp and 4-amp limits of the heavy and light cables result in a limit to the number of physical connections that can be made to a bus. This limit will vary according to the power draw of the various devices.

When installing an NMEA 2000 system, a cable called the *backbone* or *trunk* is run through the boat to all locations at which devices will be plugged into the system. At both ends of this cable there is a terminating



NMEA 2000 heavy cable is really a bundle of five smaller cables: two for data, two for power, and one ground wire.

Top—*A T fitting in light cable,* ***left****, compared to one in heavy cable,* ***right****. Both examples shown terminate with a resistor on the right-hand side.* ***Below left***—*A heavy connecting terminal being made up along with a heavy T.* ***Below right***—*Getting progressively more complicated, a heavy cable steps down to light cables at two Ts, and ends with a terminating resistor at right.*

resistor—a piece of hardware needed to stop signals "reflecting" back onto the network. Wherever a device is to be attached, a "T" is inserted into the backbone and a cable known as a *drop cable* is run to the device. The drop cable and its device constitute a *node*. The Ts and all other pieces of hardware inserted into the backbone, as well as the drop cable, must be NMEA certified, although the means of connecting the drop cable to its device is left up to the device manufacturer.

Every device is individually wired to the backbone with no daisy-chaining (connecting in series) of devices, so they can be added or removed without affecting any other device on the network. Where a number of devices connect to the backbone in close proximity to one another, a *multiport box* can be used to consolidate the connections into a single drop cable onto the backbone.

NMEA 2000 requires that communication can still continue, albeit at a degraded level, with no permanent damage done, with either of the two signal wires broken, and either signal wire shorted to the power supply or to ground. In other words, any device can be miswired in any conceivable way for any length of time without causing permanent damage to the system or any device on it, although this may well render the network inoperative until the fault is corrected.

The NMEA 2000 physical layer is expensive. The T required for every drop onto the NMEA 2000 heavy cable costs more than certain sensors or pieces of equipment that someone may want to add to the system! This high cost is a bone of contention with many device manufacturers, and a source of hot debate within NMEA. It has led to several manufacturers developing their own physical layer, which is not NMEA certified, and then providing access to the NMEA 2000 bus via a single NMEA 2000–certified "gateway" of some kind. Discussion persists within the NMEA over whether or not to certify, and under what circumstances, a less-expensive physical layer.

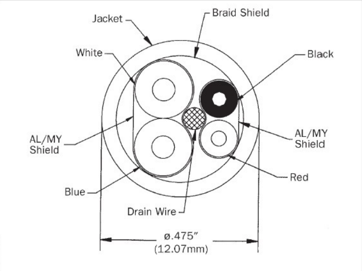
The Physical Layer: SmartCraft

As you would expect, the physical layer for SmartCraft has many similarities to that of NMEA 2000, including: the linear layout; the resistors at each end; the limit on the number of physical connections that results from the size of the power cables and the power demands of connected devices; and others. The big difference lies in the fact that SmartCraft is designed around three data buses, "X," "P," and "V" (as opposed to the single data bus in the NMEA 2000 cable), with a different core function for each bus, sometimes resulting in different information running on each.

CAN X is a bus reserved exclusively for safety-critical systems, such as throttle and transmission shifting, with access tightly controlled by MotoTron (it is essentially reserved for Mercury Marine and Cummins MerCruiser Diesel). It entered production in 2004 as the control system for Mercury's fully electronic Verado and MerCruiser DTS engine platforms. CAN P carries propulsion and extensive system-diagnostics data, and also acts as a fully redundant bus to CAN X, providing a backup for mission-critical data transfers. CAN V is reserved for all other vessel devices, such as generators, switching systems, and bilge systems. It began to carry its first generator and system diagnostic data in May 2005. It is the bus most suited for a distributed power system, but is the least developed at present and has yet to be deployed for distributed power.

The triple-bus design of SmartCraft is intended to separate the vessel into its major functional areas and to preserve bus integrity through division. One defective bus will not bring down the others. SmartCraft buses can be combined at the helm and elsewhere, so devices such as displays or switches can have access to all the information and control on the boat.

Typically, the physical layer may contain only one of the three buses (CAN X in engine applications, or CAN V for distributed power) or perhaps



Inside a section of NMEA 2000 cable, we find ample shielding to prevent radio frequency interference. The blue and white data cables are wrapped together in an individual Mylar shield. The same is true for the red and black power cables, while the ground wire remains uninsulated. The entire package is enclosed in large braided shield and finally a waterproof jacket.

two (CAN X and CAN P), but almost never all three. The buses are likely to be routed together from the engine-room to the helm, but then separated to suit specific installation criteria. Each bus consists of a twisted pair of cables. The physical layer also includes a set of power cables (positive and negative) and a switched power lead for powering devices from the keyswitch. As with NMEA 2000, power for SmartCraft buses can be supplied from multiple, isolated sources via blocking diodes, with those devices that draw less than 1 amp operating directly off the network power supply. In some cases, there also is an uninterrupted power supply (hardwired to the batteries, to maintain memory functions when a system is shut down), and ignition cables. The standard SmartCraft engine connector ends up with 14 pins, including connections for redundant power and data cables.

Shielding and Grounding

NMEA 2000 positive and negative power cables are wrapped in a shield, as are the two data (signal) cables. The fifth (ground) cable is laid in separately, and then another shield (made of Mylar), and a braided shield, surround the cable as a whole. That's a lot of shielding! There is considerably less shielding with the SmartCraft physical layer, and less expensive, automotive-like connectors. As such, the installation is less costly than that for NMEA 2000, and less robust.

NMEA's focus on shielding for radio frequency interference (RFI) is a reflection of the fact that NMEA 2000 has come out of the navigational side of the marine industry, where RFI is a big issue, and the device manufacturer has limited control over the installation. The backbone, for example, may be run close to a "noisy" fluorescent light or CRT display screen. By contrast, SmartCraft has come out of the engine side of the industry, where the manufacturer has a high degree of control over the bus and its installation, and where RFI is less of an issue.

As noted above, MotoTron/Brunswick is maintaining a tight control over CAN X and CAN P, but will have a different level of control over CAN V when it is extended to distributed power systems, which will require the bus to be run all over the boat. It remains to be seen whether this results in problems. If it does, the triple-bus nature of SmartCraft will keep problems on CAN V from disrupting the CAN X and CAN P buses.

Shielding is another of those issues on which strong opinions are expressed by the advocates for the differing network approaches. Once again, there is not yet enough real-world data to see how these differences play out in practice, and in fact, whether there is anything to be concerned about.

With all networked systems, single-point grounding on the network side is necessary to prevent "ground loops" that could destroy the integrity of the system, causing messages to get lost. On those devices that require more power to operate than can be pulled from the network backbone—a radar, for example—and that therefore require an additional power supply to the device, for safety reasons it is essential to isolate the grounded (negative) side of this power supply from the network ground. If this is not done and the main power ground to the device gets broken externally, the full operating current of the device will run to ground down the data ground. The relatively high current flow will likely melt the small grounding cable in the network cable, disabling the system and possibly starting a fire. Ground isolation can be achieved within devices either via an optical isolator (with an OEM cost of \$1.50 to \$9.00, depending on the required level of robustness) or at a lower cost through "current loop isolation." This added layer of complexity and expense is another bone of contention for some manufacturers.

Practical Limitations

The data-carrying capacity of any network is a function of such things as the length of the network, the speed of data transmission, the number of nodes on the bus, and the message structure.

The longer a data cable, the longer the time it takes for data to travel from one end to the other, and therefore the longer another device must wait to get its data transmitted down the bus. The NMEA has determined that a backbone cable length of 200m (656′) is adequate for marine purposes. SmartCraft currently limits bus length to 40m (131′), but is extending this to 70m (230′), and could, in all probability, handle 200m, depending on the bus loads and/or whether the information is safety critical. (The 40m comes from the J1939 standard from which SmartCraft and NMEA 2000 are derived, which in turn has come from the automotive industry where long cable runs simply do not occur.)

CAN-based equipment is nominally designed to operate at data rates of 1 megabit (Mb) per second, but on a 200m backbone this drops to 250 kilobits (Kb) per second—the designed speed of NMEA 2000 and SmartCraft. This is still 50 times faster than NMEA 0183. Where NMEA 0183 can deliver 6 to 8 messages a second at 4.8 Kb per second, NMEA 2000 can deliver 300 to 400 messages at 250 Kb per second. However, the greater the number of nodes on a bus, the lower the message rate will be. The SmartCraft people use this fact to argue in favor of breaking up the messages and putting them on more than one bus. The response from the NMEA 2000 advocates is that it is irrelevant, because the NMEA 2000 bus has plenty of capacity.

Data (messages) on CAN-based systems are transmitted using a 29-bit identifier. The way this is configured effectively limits the number of functional connections to a network to 252, meaning 252 devices can be uniquely addressed on the network, although the physical layer can support a maximum of only 50 electrical connections to the bus (see above). One physical connection, however, can support multiple addresses to multiple logical devices. For example, an autopilot may integrate a GPS, heading sensor, fluxgate compass, and other devices, all of which can have separate addresses but with one connection to the network. In terms of power distribution, a number of circuit breakers may be clustered together, each with its own address, but with a single connection to the network. If more than 50 physical connections, or 252 nodes, are needed, a second network can be added with a "bridge" between the two.

The messages themselves are short, being limited to 8 bytes (64 bits; 1 byte = 8 bits), with the actual data content being less than 50% of the message. The rest consists of the identifier and various error-checking mechanisms. With NMEA 2000, messages larger than 8 bytes, but less than 256 bytes, are broken up and sent sequentially, using something known as a *fast packet transmission*. Longer messages (the limit is 1,785 bytes) are sent in blocks, when there is available time on the bus, and reassembled in an "envelope" that is "opened" once the message is complete—what's known as *transport protocol*. Currently, all NMEA 2000 messages greater than 8 bytes have been designed to use the fast packet transmission. There are two types of messages: status messages, which are sent at some periodic rate to update any device that cares about that particular information; and control messages, which are sent only when needed—for example, to turn a breaker on or off.

CAN-based systems are not designed to carry large streams of data such as video. For large-volume data, some other approach is needed. Ethernet is rapidly becoming the dominant technology (see the sidebar on page 66). With Ethernet, our three-cable boat actually becomes a four-cable boat consisting of the negative and positive power cables, a relatively low-volume CAN-based messaging system (or a rival system), and a high-volume Ethernet-based data-transfer system.

Benefits of CAN

A CAN-based network allows multiple electronic devices to be connected together, via a single cable connection, in order to share information. Its message-sending and -receiving protocols, and the physical layer, have been well tested in literally millions of vehicles and thousands of industrial applications, and have proven to be reliable, rugged, and error-free. The content-based nature of CAN allows users to define messages appropriate to their application, making it extremely flexible.

The fact that CAN-based systems are now so widespread means that there are numerous chip manufacturers producing the necessary transceiver (transmitting and receiving) chips for any device in a CAN-based system. Once a set of messages has been devised, it's easy for a chip manufacturer to program them into a chip, allowing any device with this chip to be added to a network and immediately begin sending and receiving messages to and from all other devices on the network. The existing mass market for CAN chips means that the cost is relatively low; the wholesale price ranges from $2 to $5.

As for the physical layer, a number of manufacturers are already supplying to industry the DeviceNet type of hardware specified by NMEA. (Maretron is the first to have had NMEA 2000–certified products.) This, too, helps keep the cost down, although, as noted, the high quality of the hardware in the backbone required by NMEA 2000 does drive the cost up over that of some competing hardware. Manufacturers getting on the SmartCraft bus work with MotoTron to establish a suitable physical layer.

From a device manufacturer's standpoint, the R&D that has already been put into a CAN-based system such as NMEA 2000 or SmartCraft, and the availability of the necessary chips, can significantly reduce design

Open vs. Proprietary Standards

NMEA 2000 is an open standard for marine electronics and engine data in the sense that it has been developed by a broad range of organizations over a period of nine years. NMEA grants certification to any manufacturer who purchases and meets the requirements of the NMEA 2000 standard. These requirements are a result of the efforts and input of NMEA members, including manufacturers, installers, and the U.S. Coast Guard. NMEA has also been working with international standards–setting bodies such as the International Maritime Organization (IMO), the International Electrotechnical Commission (IEC), and the International Organization for Standardization (ISO), as a result of which NMEA 2000 will likely be adopted as a worldwide standard.

NMEA's automatic dynamic addressing approach requires every product to be capable of negotiating its address and position in the hierarchy, enabling devices to be added and removed at any time, and enabling the system to function regardless of the state of any time for new products. From a boatbuilder's and installer's perspective, the single-cable installation and compatibility of all devices programmed for a particular CAN-based system greatly reduce installation complexity, time, and cost, as well as the likelihood of post-installation problems. From a boat owner's perspective, the considerable reduction in cabling and connections is almost certain to result in greater reliability. If the system permits any compatible device to be plugged in and unplugged without having to reconfigure the system or the device (what is commonly known as "plug and play"), the boat owner can buy best-in-class devices from any manufacturer, rather than being locked into one manufacturer's proprietary system. NMEA 2000 is configured this way; SmartCraft is not (see the sidebar on page 58).

Non-CAN Approaches: ED&D's E-Plex

Although CAN-based systems have received the lion's share of publicity to date, there are a couple of non-CAN networking systems that have entered the marine world from left field, and that have considerable potential. These are ED&D's E-Plex, and Victron's VE.Net. Both focus on power distribution rather than propulsion monitoring and control or navigation, although both have interfaces with just about any other conceivable system. (In May 2005, ED&D was acquired by Airpax Corporation, a manufacturer of circuit breakers and engine sensors.)

E-Plex utilizes a relatively slow (20 Kb per second, Kbps) master/slave messaging protocol. In essence, the master (which ED&D calls a *clock*, or *E-Plex Control Module* [ECM]) samples all the nodes sequentially. The nodes use the position of the data in the sequence to determine if it is directed at them. This dramatically reduces the amount of activity on the bus as compared to a CAN-based system. For example, a simple "on" or "off" instruction with CAN requires the 29-bit identifier in a 64-bit message, as opposed to a single bit at a particular point in the sequence with E-Plex. At 250 Kbps, a 64-bit CAN message will take 256 microseconds, whereas a single E-Plex bit at 20 Kbps will take 50 microseconds. Despite the slower bus speed, E-Plex is five times faster in this instance! Most E-Plex messages are, in fact, only 1 bit in length, although some may be 8, 10, or 16 (for example, engine rpm is 16). A 16-bit E-Plex message will take 800 microseconds, as opposed to 256 microseconds for the equivalent CAN message (E-Plex is more than three times slower), but, asks David Bateman, president and lead designer at ED&D, "how many engines outputting rpm do you have?"

The nature of the E-Plex protocol is such that there are no collisions; the clock controls the messaging sequence. But, there can be no prioritizing of messages. Some messages are not particularly time sensitive. Depth information, for example, is not needed in most situations more than once every second, maybe much less. Others are time sensitive—throttle, transmission shifting, and steering individual device. If a manufacturer has a device for which there are not currently appropriate messages built into the system, the manufacturer can approach the regulatory committee (NMEA's standards committee) and work with it to devise the necessary messages, according them an appropriate priority level within the priority hierarchy.

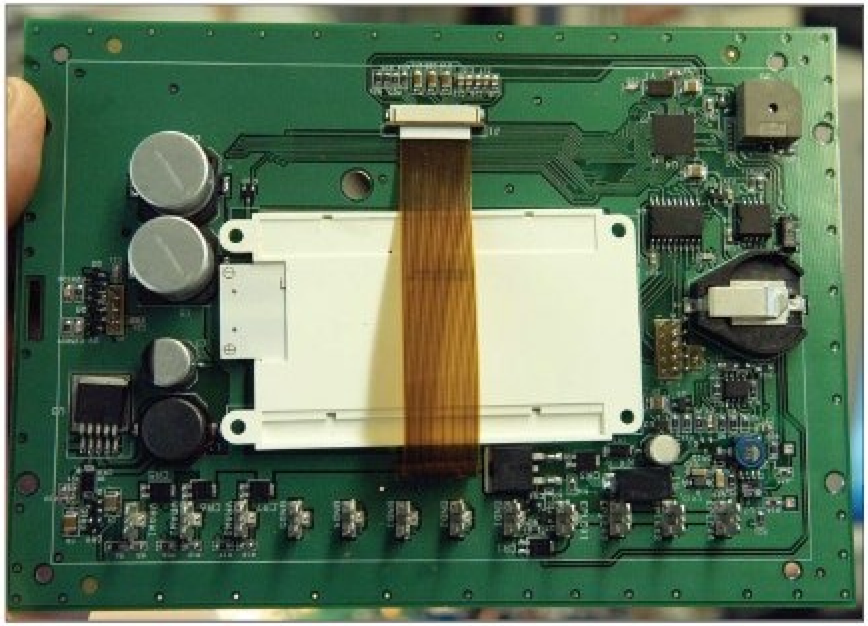
In order to obtain NMEA 2000 certification, a device is tested by its manufacturer to ensure that it will communicate and behave properly on the NMEA 2000 bus and that it has the necessary self-configuring capabilities to meet the plug-and-play characteristics of NMEA 2000. The device manufacturer purchases both hardware and software from NMEA to carry out all the required tests. These generate an encrypted test-data base file that is sent to NMEA for validation.

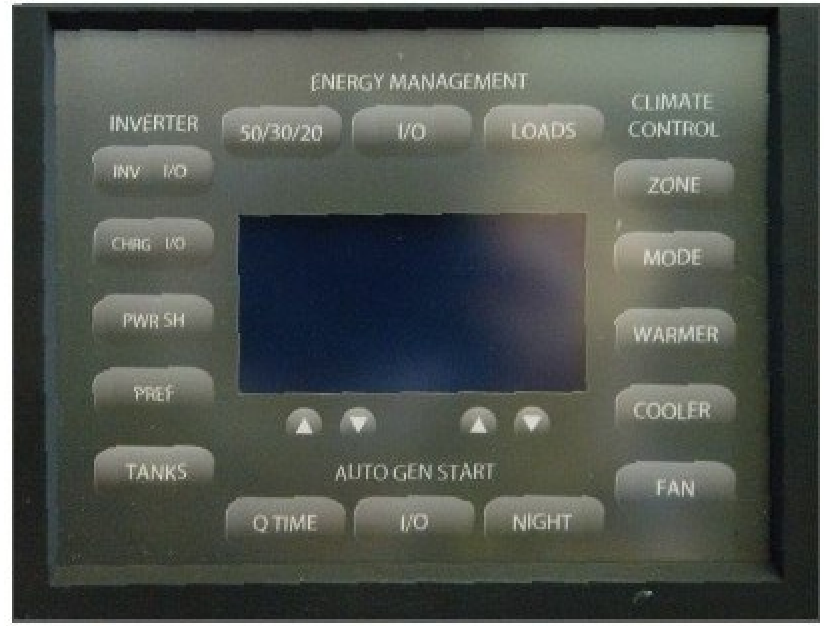
To avoid unnecessary development costs, the NMEA has two levels of certification: "A" and "B." Simple devices, such as a speed sensor that needs to output only a simple message, do not require the capabilities of sophisticated devices such as an autopilot, which will be receiving and processing information from several sensors, and then outputting messages to a chart plotter and other devices. The speed sensor can be certified to level-B compliance; the autopilot will need to be certified to level-A compliance.

A consumer should be able to buy any NMEA 2000–certified product and plug it into an existing NMEA 2000 system—true plug-and-play versatility, allowing the consumer access to an ever-widening range of mutually compatible electronic devices. And the more information there is on the system, the more powerful the uses to which this information can be put. One of the things an open standard tends to do is release the creative juices of software writers and engineers, resulting in novel and unforeseen applications of the available data. A list of NMEA 2000 Certified Manufacturers/Suppliers/equipment can be found at www.nmea.org/about/news.cgi?article_id=177.

SmartCraft, by contrast, is a proprietary system controlled by the Brunswick Corporation, via MotoTron. In developing the system, MotoTron has worked with Kvaser AB, a leading CAN Kingdom developer, as well as the U.S. Navy.

MotoTron is primarily responsible for developing the messages on the SmartCraft system, determining message priority, and so on. If a manufacturer wants to get on the bus (CAN X, P, or V) there is a process by which the manufacturer and MotoTron define the project, develop the messages and the necessary hardware, and test and validate the application, at which point the product becomes certified. As with NMEA, MotoTron sells hardware and software to the manufacturer to help with the development and validation process. Unlike NMEA, MotoTron is much more actively involved at every step, including bench-testing





Left—*An E-Plex "clock" or "control module" is the center of ED&D's system, which employs a master/slave messaging protocol.* ***Right***—*The company provides a variety of screen sizes and layouts for its clock face.*

commands. When it comes to distributed power, signals such as switching lights on and off are time sensitive: if there is a delay, the operator is likely to think the switch is not operating, and will try switching again.

ED&D's goal is to ensure that all address points on the system are sampled at least 10 times a second. Doing a little simple arithmetic, if we assume all messages are 1 bit long, at 20 Kbps (20,000 bits per second), sampling 10 times a second, the system can handle 2,000 messages per second (20,000/[10 x 1]); this would be more than adequate for even a superyacht. However, if we assume the average message is 10 bits long, at 20 Kbps, sampling 10 times a second, the system can handle 200 messages per second (20,000/[10 x 10]), which would significantly limit the number of devices on the bus.

As noted, most messages are 1 bit

of models and validating the application in real-life boat tests. MotoTron charges for its time by the hour, and then collects a royalty fee for every validated device that is sold.

Given the CAN Kingdom nature of SmartCraft and the lack of automatic dynamic addressing, an applications engineer is needed to add or remove devices to an existing network. The infrastructure for this is provided by Brunswick Corporation builders, distributors, and field technicians. As the message base becomes more fully developed, and recognition of more certified nodes is built into the King (the controller), it will be possible to add or remove, in a plug-and-play fashion, many devices for which messages have already been developed.

MotoTron's approach is more restrictive and more tightly controlled than that of NMEA. Phil Gaynor, business manager at MotoTron, argues in favor of it as follows: "A free and open network [such as NMEA 2000] is, by definition, not a field-supported or 100% pre-tested network like SmartCraft. Without management, it's very difficult to create the consumer benefits that an 'integrated' network system of products should deliver.... When issues arise from connecting devices together, members of the free network are only responsible for verifying that their products are transmitting/receiving messages successfully. Without management over how each company displays and controls another company's products, quality to the customer is at risk. A very likely result is that product warranties, such as those for complex digitally controlled engines, will have limitations placed on them because of the risk an unmanaged network imposes." NMEA 2000 advocates challenge those statements.

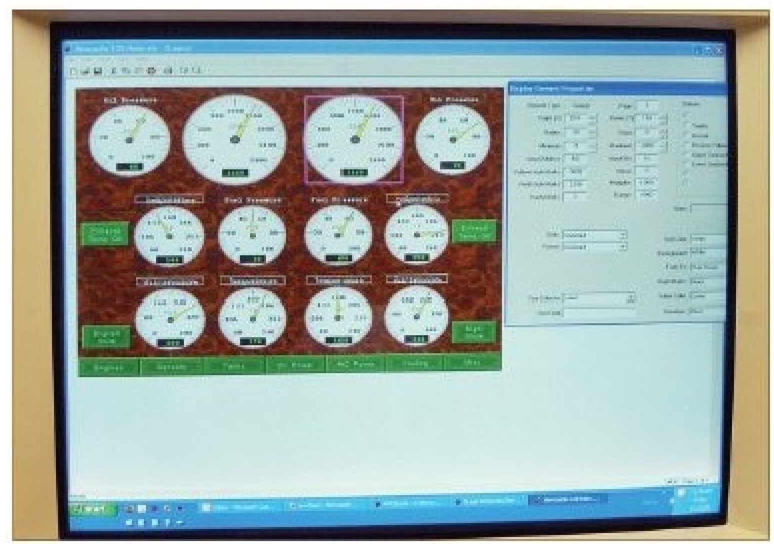
Gaynor notes that "management costs money, and even though royalties are generally viewed with skepticism, without them the databus management and implementation responsibilities will fall mainly on the customer.... Both Mercury and Cummins MerCruiser customers expect more from us than that, and so we are providing SmartCraft in this way to them."

There are clearly some deep-seated philosophical differences between NMEA and the Brunswick Corporation in terms of how accessible to make the bus, and how to provide protection to mission-critical functions (bus redundancy and strictly controlled access versus a "bulletproof" physical layer). Given the lack of real-world experience with any of these systems, it remains to be seen how serious those differences may be.

As with NMEA 2000, SmartCraft has two levels of licensing. Certified manufacturers can be found at www.smartcraftnetworked.com.

—Nigel Calder

Right—*An E-Plex tank-level sensor has a "core" or circuit board inside it that communicates the information from the tank to the "clock."*
Far right, top—*A second type of tank-level probe with an embedded E-Plex core.*
Bottom—*An E-Plex system displayed on a computer monitor. Most additions to an E-Plex bus require reprogramming through a personal computer with a simple software package called E-Logic.*



A temperature gauge converted to operate on an E-Plex system. The twisted wires will be the only connection.

in length. Analog sensors, such as voltage, current, or frequency, typically require 10 bits, or "addresses"; each bit constitutes an address. A recent installation on a 41′ (12.5m) powerboat uses about 600 address spaces, and, as a result, updates over 30 times a second. That includes AC and DC power monitoring, engine start and stop, an engine monitoring system, bilge controls, trim tabs, lighting, wipers, and other distributed-power functions.

It would be an interesting exercise to take the entire electrical system on a large yacht and see what the sample rate would be if it were fully configured to run on E-Plex. Bateman is

Wireless Technology

We have recently seen some marine wireless entries into the low-volume/data-transfer field, including Bluetooth, using short-range radio to communicate between compatible devices (each of which must include the necessary chip). Bluetooth has become popular enough to be incorporated into an international standard. It connects a wireless mouse and keyboard to a computer, wireless headphones to a stereo system, and so on.

A similar technology has been developed by Tacktick for a range of wireless, solar-powered boat instruments—for example, a masthead-mounted wind-speed and -direction sending unit that communicates wirelessly with a display device in the cockpit. It draws significantly less power than Bluetooth, while operating 16 times faster than NMEA 0183.

There is also WiFi and similar broadband (high-speed) wireless technologies found ashore that enable huge amounts of data to be transferred wirelessly over relatively short distances.

It remains to be seen whether or not wireless technology will become popular for transmission of critical data such as steering commands. There is always the fear that powerful outside interference, or other problems, will drown out the signals. —*N.C.*

confident that E-Plex can handle just about any boat. Julian Potter, manufacturing and engineering supervisor at Sealine, a British boatbuilder implementing E-Plex on the production line (Sealine calls it "SeaPlex"), noted that as boats get larger the number of devices does not go up exponentially. The engine bay, for example, has more or less the same number of "modules" over a broad range of boat sizes.

With NMEA 2000 and SmartCraft, the number of addresses is limited by the possible permutations of the address portion of the 29-bit identifier. With E-Plex there is no theoretical limit—it's just a matter of adding another address to the clock's address list. But, there is a practical limit inasmuch as each new address lengthens the time it takes the clock to cycle through all the addresses, and as such slows down the sampling rate.

The ED&D approach is proprietary, including the design of the clock, the software that runs the system, and the transceivers, which ED&D calls a "core." At the time of this writing,

Ethernet

When we get to really large data requirements, such as video, we are into the realm of Ethernet-based systems such as Furuno's NavNet, Northstar's N2, Garmin's MarineNet, and Raymarine's HSB2.

Ethernet, a protocol for high-speed communication, was invented by Robert Metcalfe at Xerox in 1976, but subsequently has become so popular that it is now an internationally regulated network technology. Data can be transmitted and received at a rate of 1,000 megabits per second through a network of up to 300′ (91m) between nodes/switches. NMEA 2000 can transmit and receive 250 Kb per second over 656′ (200m); SmartCraft, over 130′ (40m). Ethernet is 4,000 times faster. Ethernet does not have a distance limitation—provided there are hubs/switches every 300′, which is an advantage over CAN on large yachts and ships.

A major difference between CAN and Ethernet is the size of data packets. On CAN the data packets are relatively small, primarily the data from one sensor at a time, whereas Ethernet packets can contain hundreds or thousands of sensor data all within one packet. The result is greater efficiencies of transmission, with only one interrupt per packet of multiple data. In addition, the large packet sizes allow Ethernet to be less restrictive in terms of data format.

Ethernet also wins over CAN in the number of nodes it can support. A large yacht can have thousands of sensor points, while a large ship might have up to 50,000 sensor points. The large number of nodes and data packets fit easily within an Ethernet framework; however, the cost of adding the Ethernet chip at each device is higher.

As with NMEA 0183, Ethernet is *point to point* (see Part 1 of this series), which means a separate cable must be run from each sensor or device to the control panels. This returns us to the existing system of multiple parallel cables in a boat and consequent large wiring harnesses. These cables can be consolidated by running them into an intermediate hub, with one wire connecting the hub back to the panels, but that adds another device and more cost. Standard Ethernet hubs start at $20.

As with CAN-based messages, Ethernet protocol specifies a set of rules for constructing and sending messages. Ethernet has two forms of transmission: Universal Datagram Protocol, or UDP; and Transmission Control Protocol, or TCP. UDP messages are sent in a broadcast mode to all nodes, while TCP uses a specific address for transmission. With CAN, the microcontroller at each device interrogates the message to determine if it has data for its processor. With Ethernet, employing TCP communications, two devices form a direct peer-to-peer connection that guarantees data delivery.

In the event of a collision between two Ethernet messages, the two sending nodes back off and then retransmit the data after a randomly chosen delay period. The messages may collide again, or collide with another message, in which case the process is repeated. In theory, given the randomly generated delay periods, sooner or later (we are talking nanoseconds here) the messages will be timed such that no collisions occur and all get through. In UDP there is the potential for one or more messages to get lost, but not in TCP. However, Ethernet can sustain a maximum continuing utilization of only 30% before the performance of the network will begin to degrade. CAN, though, continues to operate flawlessly at 100% utilization.

Ethernet does not have the same capability as CAN to take offline a defective node that is outputting junk. In fact, a node can send a stream of junk that will block all other nodes from sending and receiving messages. As with CAN, the physical layer is highly variable from application to application. In a home office, it is not very rugged. But, cables and connectors can be purchased to meet very demanding physical needs, including waterproof connections and waterproof hubs/switches. Ethernet has been used quite successfully in manufacturing facilities that are wet, dirty, and electrically noisy.

When it comes to high-volume data flows, such as those generated by many modern radars and chart plotters, or by high-resolution video (such as from closed-circuit TV), Ethernet provides an extremely cost-effective network. On larger boats and superyachts, which may have full-scale office-style networks that integrate several computers, printers, scanners, and other devices with shipboard electronics and a mass of data input sensors, Ethernet has become the predominant networking technology, including for relatively low-volume, monitoring, alarm, and control circuits. A good example is provided by the SiMON (Ship's Information Monitoring System) from Palladium Technologies.

—*N.C.*

the transceivers had not yet been miniaturized into a chip [ASIC], but instead are built on a printed circuit board. Once a system is set up and the clock programmed, if any module fails and is replaced, the clock will program a replacement module for the specific application. In other words, in terms of switching-out parts, this is plug and play. At the planning stage for a given system, if future needs can be identified, these needs can be built into the software, which will require no further adjustment when the additional equipment is installed. Otherwise, additions to, or deletions from, the bus require reprogramming via a personal computer. E-Plex includes a highly intuitive software package called "E-Logic" that greatly simplifies this process and that adds considerable value in terms of the ability of an end user to customize a system (more on this in Part 3 of the series). Nevertheless, it is not a fully plug-and-play system in the sense of NMEA 2000.

In terms of the physical layer, E-Plex uses a single twisted-pair bus with the data signals running on the power cables (in contrast to NMEA 2000, with its five cables, and SmartCraft, with its up to three twisted-pair buses plus power cables). As opposed to a CAN-based system, in which the backbone must be installed in a linear fashion with a resistor at each end, the E-Plex backbone can be installed in any fashion—a linear and/or a "star" pattern (a central connection point with cables branching out)—with a single resistor somewhere in the system, and individual "branches" up to 500′ (152m) in length. Sealine's "clock" has connections for four branches; the company uses three of these at the present time, with one bus going forward, one aft, and one to the bridge.

ED&D exercises no control over the physical layer, its installation, or connections to it. Connections can be made by splicing in at any point. That makes the installation side much more economical than NMEA 2000 (and also more economical than SmartCraft) but makes it more likely that poor installations will result in poor performance that negatively impact the system. It's up to the installer to see that the job is done right.

The data bus on CAN-based systems is typically operating on plus or minus 1.5V, resulting in a 3.0V swing (from 1.5V to –1.5V); since ED&D is sending the data signals down the power bus, it is operating at battery voltage—that is, a 12.0V swing (from 0.0V to +12.0V) on a 12V system, and a 24.0V swing on a 24V system. The greater the swing, the easier it is for devices on the bus to distinguish between a true signal and "noise" or interference of various kinds. Dave Bateman claims that the high swing on the E-Plex bus makes it possible to achieve reliable communications with less RFI suppression, and therefore lower cost.

Individual physical connections to the bus will draw from a low of 15 mA to a high of 1 amp. The E-Plex clock is current-limited to 3 amps, which means the maximum number of physical connections is 200 (3 amps/15 mA), and will likely be considerably lower than this. But, as

Networking Technology and the ABYC

Over the past 50 years, the American Boat & Yacht Council (Edgewater, Maryland) has carved out a preeminent role for itself as the principal standards-writing body for the recreational boating industry. Its standards-writing process is based upon Project Technical Committees, or PTCs—composed of dedicated volunteers, and coordinated by ABYC staff. It is these committees that have dealt with evolving technology, and changing public concerns regarding safety, in a manner that has served both the industry and the boating public well. Perhaps the best testament to this is that when the Europeans decided, not long ago, to get into the recreational-boating standards-writing business themselves, the ABYC's standards were selected as the model and starting point.

Right now, the rapid introduction of three new technologies is confronting the Electrical PTC:

1. Cogeneration, meaning the ability of inverters and other AC power-supply and conditioning devices to parallel themselves with shore power or onboard generators. (Parallel operation is presently not allowed under ABYC standards.)

2. The introduction of high-voltage DC electric motors and propulsion systems. Some will operate on DC voltages up to 800 volts. (The present DC standard covers applications only to 50 volts.)

3. The use of electronic devices for DC and AC power distribution and circuit overload protection. (The existing standards presuppose traditional air-gap-type technology.)

The third item on the list above is especially challenging. Why? Because it is now possible to combine traditional fuse and circuit-breaker technology with electronic circuit-control devices in a way that passes all present ABYC standards for branch-circuit protection—and yet the equipment is vulnerable to failures from sources never envisioned by the ABYC. Consider that, in one case, the electronic circuit breakers on a boat were randomly turning on and off at erratic intervals. It was eventually determined that a defective battery installation kept intermittently dropping the voltage on the DC system below the minimum 5.0 volts required to keep the electronic circuits functional. In another case, random operation of circuit control devices was attributed to high radio-frequency interference from a radar and single-sideband installation.

The latter situation ties directly into the intense debate over what kind of shielding is required for data cables (control cables) in networked electronics and power distribution systems. Based on assumptions derived from the automotive field, and other assumptions about boat usage, plus some testing, under the NMEA 2000 protocol, of unshielded cable (and bombarding it with electric field strengths of 50 volts per meter), Rich Gauer of Maretron—a proponent of the NMEA's conservative physical layer—writes: "Once we have a hundred thousand boats with these systems using unshielded cable, then every seven minutes a boat somewhere will experience an undetected error: inadvertent transmission shift, a breaker turning 'on' or 'off,' a windlass or winch turning 'on' or 'off,' an inadvertent alarm, a throttle glitch, a steering glitch, and the like. Is this acceptable?"

Gauer's comments raise a number of complex issues for a standards-writing organization such as the ABYC. For instance, do electric fields of this strength occur on boats? What is an acceptable undetected error rate? How is it calculated? Does the acceptable error rate vary according to how safety-critical an application is? What, if any, language and/or test requirements in the ABYC standards are necessary to address these issues? Gauer reports that the automotive industry requires safety-critical systems (throttle controls, say) to be tested to 60 volts per meter, while some applications are routinely tested to 100 volts per meter. Perhaps the ABYC should adopt similar language.

This is just one example of several emerging areas of concern, raised by the new technologies, that need to be addressed. The challenge is to adapt existing ABYC standards in a way that will continue to protect and enhance the safety of the boating public without creating unnecessary obstacles to the development and implementation of those very technologies, and to do so in a timely manner. It will take the active participation of industry professionals in the standards-writing process—precisely when most of them are working long hours to refine their own products while battling for market share.

The ABYC Electrical PTC recently created several ad-hoc subcommittees to look into these matters and bring proposals back to the PTC. Those companies in the forefront of product development must get involved to ensure that the necessary questions get asked. In so doing, they will help establish a level and consistent standards-based playing field for the introduction of these critical new technologies, which can only benefit manufacturers and consumers alike.

Having personally observed the Electrical PTC for more than 15 years, I know it can rise to the occasion. And when it does, the recreational marine industry as a whole should give the committee the technical support and resources it needs to fulfill its mission.

—*N.C.*

with CAN, each connection can include multiple addresses.

E-Plex has several layers of error protection. Matt Bush, ED&D's lead programmer, reports, "Given the bus's high degree of noise immunity [as a result of the high voltage swing], a typical system will run for hours without generating a single data error. Any time an error is generated, all modules throw away the data just received and prepare to retransmit. Even if the bus was generating one data error a second, if the update rate was 30 times a second, this would just drop to 29 times a second."

Non-CAN Approaches: Victron's VE.Net

As with ED&D, Victron's focus is on power distribution rather than engine control or navigation. Additionally, Reinout Vader, the founder of Victron, is a sailboat owner who is particularly interested in boats with intermittent generating sources, and which therefore need to minimize the load on the DC system. Matthijs Vader, Victron's principal systems designer, notes that although "CAN is a beautiful network…that is very suitable for navigational integration," it requires more power to operate than is necessary for a distributed-power system. "Since CAN is a network that has been designed for cars, which have short cable runs and power from an alternator always available, this is not a real surprise."

On a boat, the power-distribution network will often be in use when there is no generating source online, including when the boat is anchored or in harbor. So, the network must be designed to minimize energy overhead. As opposed to a navigational system, which will have a limited number of devices, the power distribution system will include a large number of sensors and devices—quite possibly hundreds on a larger boat. As the number of devices on a network rises, and thus the total electrical load, the network cabling must be increased in size to handle the load, which drives up the cost. A difference of a few milliamps per connection can make a significant difference in both the overall energy consumption *and* the cost of installation.

All of which raises some interesting considerations that do not seem to have caught the attention of other systems designers. Traditional circuit-breaker and fuse technology imposes no energy overhead on a boat, except in cases where distribution panels include LED annunciators. Distributed-power systems, however, require energy to power up the chips at each node, and to operate the display screen if this is the mechanism used to control the system. (Some low-end systems employ keypads with minimal energy consumption.) The load occurs whether or not a device is turned "on" or "off"; it is a constant parasitic load that comes with the technology. When a traditional circuit breaker is in the "on" state, there is still no energy cost in terms of operating the breaker (assuming no voltage drop through the breaker), whereas the switching devices used in electronic circuit breakers create some power loss that is dissipated as heat. All in all, a distributed-power system on a moderately complex boat could easily draw 1 to 3 amps at 12V continuously. For an energy-conscious boat owner, those values represent a significant overhead.

Victron's VE.Net starts from the following premises: power consumption is related to data speed of transmission; and mission-critical data need to move in near real-time, but some, such as voltage displays, do not. Victron's approach is to use the lowest data speed possible, combined with the ability to send data at different speeds so that where high speed is necessary it can be accommodated, albeit with higher energy consumption. To this end, Victron has developed a variable-speed system that ranges from 9,600 bps to 115 Kbps.

This is a master/slave system. On startup, if two or more nodes transmit at the same time, resulting in collisions, then each backs off and retransmits at a random interval until no collision occurs. (Ethernet transmits in a similar fashion—see the sidebar on page 66.) The node with the highest processing power now becomes the master. After the initial exchange, the master takes over, sampling all the nodes in a sequence that varies according to priority needs (some nodes get sampled more often than others), and with the speed varying according to the speed of the node being sampled. This avoids further collisions. Nodes can communicate directly with one another, with the master controlling their time on the bus, but to do so an addressing system is needed based on a 32-bit identifier. The addressing system drives up the content of messages during the initial contact phase and, as a result, slows down the message rate. However, messages are sent only on an as-needed basis, which keeps down the message volume—as opposed to E-Plex's cycling through all addresses at each cycle. There is no message prioritization.

As with CAN-based systems, the backbone has two power cables and two data cables. When the voltage on one data cable is higher than the other, it signifies a "1," and when the second is higher, a "0." (This is also how CAN operates.) The microprocessors in the nodes synchronize on the slopes—that is, when the voltages cross. Any transient voltage spikes tend to occur on both cables, so the higher one remains higher, making the system relatively immune to interference.

Up to 256 nodes can be connected to the net. The maximum length of the net is 500m (1,600′).

Aside from the chips at each node, the single biggest load on a distributed-power system is likely to be the screen (or screens) used for command and control. This load will vary according to screen size and display technology. Victron minimizes it by the inclusion of a "sleep" mode that kicks in if no activity takes place for a given length of time.

Victron has concentrated on minimizing the installation cost by utilizing commonly available RJ 45 connectors, and—as with NMEA 2000 and E-Plex—ensuring that the installation can be done by regular boatyard workers rather than requiring expensive networking professionals. VE.Net has interfaces to NMEA 2000, Ethernet, and other systems in order to be able to create a fully integrated "tiered" networking approach on boats of any size.

A phased rollout of components necessary for a whole-boat VE.Net began in 2005.

The Tiered Approach

It would seem that in a perfect world the entire marine industry would embrace a single networking standard with a plug-and-play capability, such as NMEA 2000. Boatbuilders and boat owners would be able to buy any networked electronic equipment or digital-switching (power distribution) device they wanted and simply plug it into the system via a drop cable and network T.

But, because of the different benefits and drawbacks of one approach over another—cost, bandwidth, power consumption, reliability, ease of installation, redundancy, protection for mission-critical functions—a case can be made for what is known as a tiered approach. The most cost-effective setup is applied to a given subsystem—for example, a CAN-based propulsion control system, Ethernet for large-volume navigational data, and a non-CAN-based distributed-power system—and then the various systems are interfaced such that data can be shared, and command and control can take place from common display screens.

We are already seeing the development of interface boxes (referred to as "bridges" and "gateways") that can take the messages and data streams created by one system and translate them into the language of another system, enabling a fair amount of communication between systems. For example, an engine and its controls can be operating on the SmartCraft system, with the boat's navigational electronics using both NMEA 2000 and Ethernet, and the remotely operated circuit switches controlled by E-Plex (or perhaps the EmpirBus variant of CAN that is now being installed by a number of boatbuilders in Europe, or the Carling/Moritz variant that is starting to be deployed in the U.S.). Among them, these four systems will have literally dozens of sensors providing data that is initially inaccessible between systems. With appropriate bridges and gateways, most of the information can be made accessible to all four systems. With careful design, the redundant cabling and redundant systems can be minimized.

One way or another, the three- (or four- or five-) cable boat is close to being a reality, although it is not at all clear which particular networking variants are likely to come out on top in the shakeout that is just beginning to occur.

About the Author: *Nigel Calder, author of* Boatowner's Mechanical and Electrical Manual *and other marine titles, is a contributing editor of* Professional BoatBuilder *and an active participant on the ABYC's Electrical Project Technical Committee.*

See* SOURCE LIST *on the following pages.

Source List of Companies Mentioned in the Text

Bluetooth SIG
7300 College Blvd., Suite 200
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Tel. 913-317-4700
www.bluetooth.com

Brunswick New Technologies
1 North Field Ct.
Lake Forest, IL 60045-4811 USA
Tel. 847-735-4700
www.brunswick.com

Carling Technologies Inc.
60 Johnson Ave.
Plainville, CT 06062-1177 USA
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www.carlingtech.com

Cummins MerCruiser Diesel
Cummins Inc.
Box 3005
Columbus, IN 47202-3005 USA
Tel. 812-377-5000
www.cmdmarine.com

DSS
(Digital Switching Systems)
DNA Group Inc.
P.O. Box 31727
Raleigh, NC 27622 USA
Tel. 919-881-0889
www.dnagroup.com

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www.megatechelectro.com

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www.mercurymarine.com

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