Resource-Conscious Customization of CORBA for CAN-based Distributed Embedded Systems*

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Abstract

The software components of embedded control systems get extremely complex as they are designed into distributed systems consisting of a large number of inexpensive microcontrollers interconnected by low-bandwidth real-time networks such as the controller area network (CAN). While recently emerging middleware technologies such as CORBA and DCOM can partially deal with such complexity, they cannot be directly applied to embedded system design due to their excessive resource demand and inadequate communication models.

In this paper, we propose a new CORBA design for CAN-based distributed embedded control systems. The design goal of our CORBA is to minimize its resource need and make it support group communication without losing the IDL (interface definition language) level compliance to the OMG standards. To achieve these goals, we develop a transport protocol on the CAN and a group communication scheme based on the well-known publisher/subscriber model. This transport protocol realizes a subject-based addressing scheme to support the anonymous publisher/subscriber communication model. We also customize the method invocation and message passing protocol, often referred to as the general inter-ORB protocol (GIOP), of CORBA so that CORBA method invocations are efficiently serviced on a low-bandwidth network such as the CAN. This customization includes a packed data encoding scheme and variable-length integer encoding for compact representation of IDL data types.

The new CORBA design clearly demonstrates that it is feasible to use CORBA in developing distributed embedded systems on real-time networks possessing severe resource limitations. We are currently implementing the ORB of our CORBA design using the GNU ORBit and the result is promising.

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1 Introduction

There is a growing demand for distributed computer control in sophisticated embedded control systems such as high-end passenger vehicles, numerical control machines, and avionics fly-by-wire systems. These systems are often equipped with tens of microcontrollers which oversee diverse functional units connecting hundreds, sometimes thousands, of analog and digital sensors and actuators. There are significant merits in designing such complex embedded control systems in a distributed fashion. First, it is more cost effective to build an embedded control system with several customized, inexpensive microcontrollers than to do so with a single high performance microprocessor. For example, a passenger vehicle consists of various functional components including engine control, anti-lock brake, and cruise control units. Since each of these units requires specific functionalities such as digital signal processing or interrupt driven event processing, functional units with dedicated microcontrollers can reduce the overall hardware cost. Second, a distributed embedded control system is more reliable than a centralized one since it is possible to isolate the breakdown of one subsystem from others in a distributed control system.

The distributed control systems architecture, if properly designed, offers additional benefits: (1) *composability*: large systems can be built in an incremental manner by integrating a set of well-specified and tested subsystems; (2) *extensibility*: existing systems are open to incremental modification and extensible without some predefined upper limit; and (3) *maintainability*: it is possible to implement well-defined error-containment regions and to achieve fault tolerance by replicating nodes.

Unfortunately, such benefits come with a serious cost – increased software complexity. This makes software systems in a distributed embedded control system get extremely complicated to handle the added complexity as well as inherent one. Note that embedded control software must operate in a harsh environment, run on a wide variety of microcontrollers, and interface with heterogeneous I/O devices. Thus, it is very difficult, though not impossible, to design a distributed embedded control system without supports from real-time operating systems, well-defined network protocols, and component-based middleware systems.

Such software complexity can be partially addressed with recently emerging component-based middleware technologies such as CORBA [6], DCOM [4], and Java RMI [16]. They can provide embedded system designers with platform independence and component reuse through interface inheritance and software bus abstraction mechanisms. However, these technologies cannot be directly applied to embedded control system design without careful customization and tuning since they were originally conceived and developed for use in a general purpose distributed computing environment.

In this paper, we propose an environment specific CORBA for distributed embedded control systems on the CAN (controller area network) bus. The CAN [3] is a rapidly emerging standard for embedded real-time network substrates and widely used in the automotive industry worldwide. In designing the new CAN-based CORBA, we put our emphasis on meeting three key requirements inherent to the CAN-based embedded systems. First, the ORB implementation on each processing node should have a small memory footprint not exceeding a few hundred kilobytes. Second, the message traffic per service invocation should be kept low. Note that on the CAN the highest network bandwidth is only 1 Mbps and the payload of each message is only eight bytes long. Last, the ORB should support group communication to facilitate easy dissemination of sensory data. The standard CORBA lacks group communication capabilities.

To meet these requirements, we redesign the general inter-ORB protocol (GIOP) into an environment specific IOP (ESIOP) for the CAN bus and define a compact common data representation (CCDR) format. We name the protocol the embedded inter-ORB protocol, or EIOP. We also develop a new transport protocol on the CAN to support group object communication. The proposed CORBA design is compliant to the OMG (object management group) standard at the IDL (interface definition language) level and strictly follows the guidelines on ESIOP as given by OMG.

1.1 Related Work

Three areas in CAN-based systems and middleware come close to our work: (1) high-level protocol designs for CAN, (2) object-oriented modeling schemes on CAN, and (3) group communication supports for the standard CORBA.

Since the CAN standard specifies protocols only up to the data link layer, it lacks high-level protocol services such as distribution of media access identifiers and establishment of communication transports. Thus, it is laborious to build a distributed application, even with modest size and complexity, on the CAN. To address this problem, several commercial, high-level protocol suites have been developed and widely used in industry [1, 10, 9]. DeviceNet [1] by Allen-Bradley is one of such protocols for the CAN. One of noticeable features of DeviceNet is a high-level abstraction called device profiles. A CAN node in DeviceNet is assigned one of the standard device profiles, e.g., a photoelectric sensor profile, which specifies the type and behavior of a software component in the node. Together with many other features of DeviceNet, device profiles provide a desired level of abstraction for CAN programmers. These profiles are systematically defined by the Open DeviceNet's Vendor Association (ODVA) and distributed to end users by the vendors.

In a distributed real-time control system, it is typical that sensor data are periodically produced without specific requests from its consumers and then disseminated among different controllers. In such an operating environment, subscription-based group communication is more important than connection-oriented point-to-point communication. In the literature, group communication for real-time systems has been well studied on various network media [17, 18]. Particularly, in [13, 14], Kaiser *et al.* propose a real-time object invocation scheme and a publisher/subscriber scheme on the CAN 2.0B bus. These are one of seminal attempts to develop systematic paradigms for real-time object models on the CAN. Their approach in [14] uses an abstraction called an event channel, which establishes a virtual connection between publishers and subscribers. Each event channel is identified with a global event tag which takes up 14 bits in the 29-bit CAN 2.0B identifier. The remaining 15 bits are used for a message priority and a node identifier. A drawback of this approach is that it cannot be effectively applied to the CAN 2.0A bus which has only 11-bit identifiers: it would be able to offer at most 64 event channels in CAN 2.0A even if only five bits were used for a message priority and a node identifier. This poses an important practical problem. Note that the CAN 2.0A bus is preferred to the 2.0B bus since the extended 2.0B identifiers increase bus arbitration overhead [1]. Though our approach uses a similar abstraction called an invocation channel, it differs from the event channel since publishers access an invocation channel via their own port. Under a given upper layer protocol, our group communication scheme can support up to 512 ports in CAN 2.0A.

DeviceNet also supports group communication. However, it requires that an explicit bidirectional connection should be established between producers and consumers. Such a bidirectional connection is created by combining two one-way connections in reverse directions. This requirement makes it impossible to support anonymous communication such as the publisher/subscriber model.

There are several research results which address the group communication problem for CORBA. In [8], Harrison *et al.* present the implementation of the CORBA event channel [5] for real-time systems. The CORBA event channel is an intermediary object which accepts event data from a supplier and retransmits it to related consumers. The event channel has the responsibility of grouping consumers and multicasting messages to them. It may well increase the communication overhead since every message is transmitted at least twice due to message indirection. Though our approach also relies on an intermediary object for managing subscriber groups, it does not incur message redirections since each subscriber receives messages directly from a publisher.

In [15], Maffeis presents the Electra ORB (object request broker) which supports reliable multicasts in CORBA. In Electra, required multicast services are provided by sophisticated lower-level toolkits such as Horus and Isis [20, 2]. In order to incorporate a group communication semantics into Electra ORB, the approach extends the definition of CORBA object references so that object groups are addressed in a uniform manner. While Electra provides valuable features such as group objects, reliable multicast communication, and object replication, it is not appropriate for embedded systems built on a broadcast network with low bandwidth such as CAN.

The remainder of the paper is organized as follows. Section 2 introduces the target system hardware model on which our CORBA is developed. Section 3 briefly overviews the layered configuration of CORBA and outlines the proposed approach. Section 4 presents the design of the CAN-based transport protocol and our publisher/subscriber scheme. Section 5 explains our embedded inter-ORB protocol. Finally, Section 6 concludes this paper.

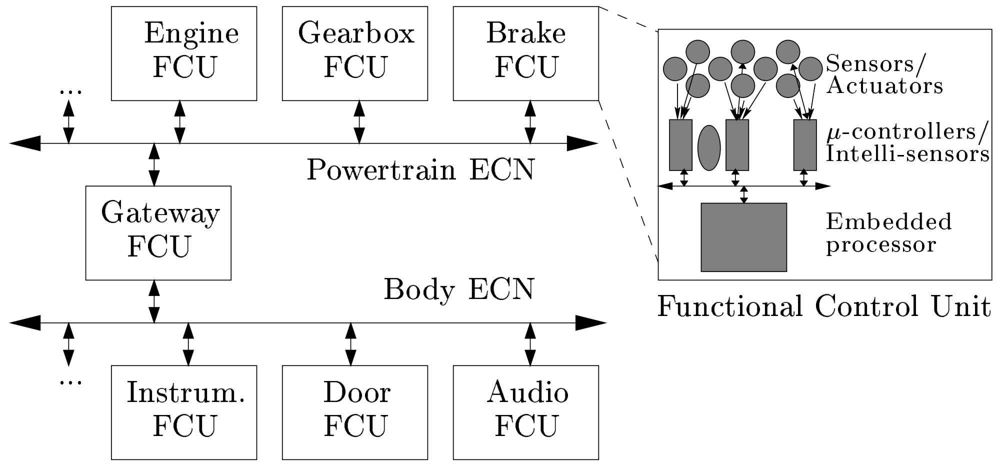


Figure 1: Example distributed embedded control system: Passenger vehicle control system.

2 Target System Hardware Model

A typical distributed embedded control system consists of a large number of function control units interconnected by embedded control networks. In this section, we present our distributed embedded control system model. We design the CAN-based CORBA on this system model.

2.1 Functional Control Unit

Figure 1 demonstrates a typical distributed embedded control system which makes the electronic control system of a passenger vehicle. It consists of several functional control units (FCU) which are interconnected by embedded control networks. Each FCU conducts a dedicated control mission by interfacing sensors and actuators and executing prescribed control algorithms. As shown in Figure 1, it has one or more microprocessors and microcontrollers attached to an on-board system bus. It is also equipped with a bus adaptor which enables the FCU to participate in communication via embedded control networks (ECN). Depending on configuration, an FCU works as a data producer, a consumer, or both.

2.2 Embedded Control Network

As shown in Figure 1, embedded control networks (ECN) connect FCUs through inexpensive bus adaptors. Such embedded control networks usually operate in an extremely harsh environment such as on factory floor, in a machining tool, and in a vehicle. Also, they are often required to provide real-time message delivery services, and subject to very stringent operational and functional constraints. In this paper, we have chosen the CAN [12] as our embedded control network substrate since it is an internationally accepted industrial standard satisfying such constraints.

The CAN standard specifies physical and data link layer protocols in the OSI reference model [3]. It is well suited for real-time communication since it is capable of bounding message transfer latencies via predictable, priority-based bus arbitration. A CAN message is composed of identifier, data, error, acknowledgment, and CRC fields. The identifier field consists of 11 bits in CAN 2.0A or 29 bits in 2.0B and the data field can grow up to eight bytes. When a CAN network adaptor transmits a message, it first transmits the identifier followed by the data. The identifier of a message serves as a priority, and a higher priority message always beats a lower priority one.

The CAN possesses two important characteristics. First, it offers a consistent broadcast mechanism in a straightforward manner via a serial broadcast medium and non-destructive priority-based bus arbitration. Second, it supports the anonymous producer/consumer model of data transmission which is often referred to as the publisher/subscriber communication model [14, 1]. In the CAN protocol, a producer of a message is totally unaware of its consumers and simply broadcasts messages over the bus without specifying their destinations. A CAN bus adaptor can be programmed to accept only a specific subset of messages that carry predefined identifier patterns with them. This filtering mechanism, which is made possible via a mask register mounted on a CAN interface chip, allows consumer nodes on the CAN to select desired messages among all the broadcast messages. This addressing method, also known as subject-based addressing [14, 1], renders the CAN suited to the publish/subscriber communication model.

In this paper, we intentionally consider only the CAN 2.0A standard. While some CAN controllers support both 2.0A and 2.0B, the 29-bit identifier format gains little support from most of commercial high level protocol products such as DeviceNet. This is because CAN 2.0B networks incur a compatibility problem with already installed 2.0A networks. More importantly, the extra 18 bits of 2.0B messages increase the bus arbitration overhead and reduce determinism by increasing potential jitter during message transmission.

3 Overview of the Proposed Approach

The proposed CAN-based CORBA design stems from the standard CORBA and possesses most of essential components of it. Figure 2 illustrates layer-to-layer comparison between the standard CORBA and the proposed one. Specifically, Figure 2 (b) shows our new CORBA design. Both architectures consist of four layered components.

At the top of both hierarchies lies an application layer. While the standard CORBA provides the client/server model for application programmers, the proposed one offers the publisher/subscriber model. The object abstraction layer just below the application layer encapsulates computational processes into CORBA objects. A CORBA object is a building block, or a component, of a distributed application. While the implementation of a CORBA object is hidden from clients, its services are publically announced through an OMG IDL interface. A client process invokes a

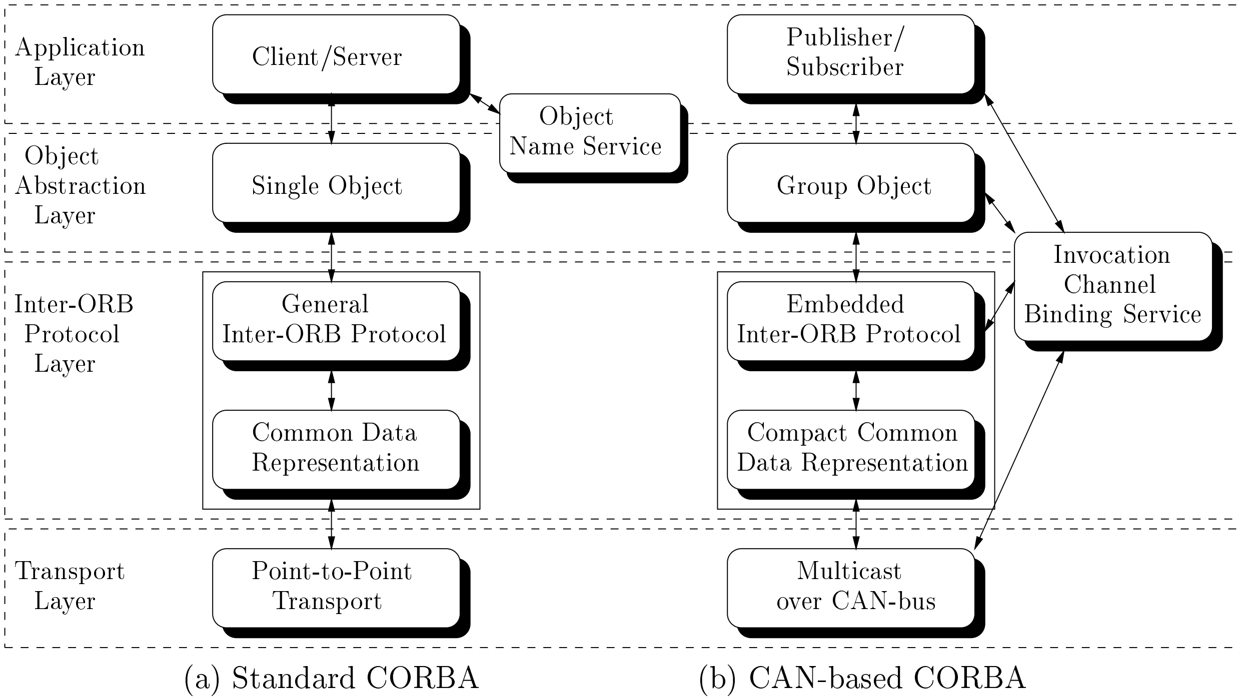


Figure 2: Comparison between two CORBA configurations

CORBA object using an object reference, which serves as a handle used to identify and locate a CORBA object.

At the inter-ORB protocol layer, a remote method invocation is transformed into a networked message representation according to a syntax called common data representation (CDR). The general IOP (GIOP) defines the contents of CORBA messages. For example, a CORBA service request message contains a message header, method parameters, and optional contextual information. The transport layer at the bottom actually delivers these messages over the network.

CORBA is based on the connection-oriented transport model and an object reference denotes only a single CORBA object. In order to extend CORBA to accommodate group communication, we extend the object reference and develop a new publisher/subscriber protocol on the CAN bus. In order to make CORBA affordable on low-bandwidth embedded networks, we customize the GIOP and CDR of the standard CORBA. We summarize the noticeable features of our new CORBA as below.

- **Group object reference:** An object reference in CORBA refers to a single object. It is internally translated into an interoperable object reference (IOR) denoting a communication end-point the object resides on. In our design, an object reference may refer to a group of receiver objects. An intermediary object named a conjoiner is responsible for managing object groups and implementing the internal representation of their references.

- **CAN-based transport protocol:** A new CAN-based transport protocol is designed to support group communication in CORBA. This protocol makes use of the CAN identifier structure to realize a subject-based addressing scheme, which supports the anonymous publisher/subscriber communication model. In this protocol, a sender is totally unaware of its receivers and simply sends out messages via its own communication port.

- **Publisher/subscriber scheme:** A new publisher/subscriber communication scheme is also designed on top of the transport protocol. This scheme relies on an abstraction named an invocation channel. It denotes a virtual communication channel which connects a group of communication ports and a group of receivers. Since each port is owned by a publisher, this scheme supports the one-way, many-to-many communication model. In this scheme, a conjoiner object takes care of group management, dynamic channel binding, and address translation. An invocation channel is uniquely identified as a channel tag in an IDL program.

- **Compact common data representation (CCDR):** Common data representation is a syntax which specifies how IDL data types are represented in CORBA messages. In CDR, method invocations often take up tens of bytes in messages. Since a CAN message has only an eight-byte payload, a method invocation may well trigger a large number of CAN message transfers. To deal with this problem, we define the compact CDR. It exploits packed data encoding which avoids byte padding for data alignment, and introduces new data types for variable length integers to encode four-byte integers in a dense form.

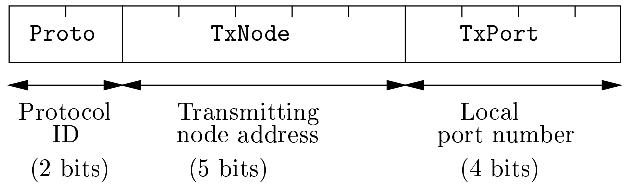
- **Embedded inter-ORB protocol (EIOP):** In addition to CCDR, we customize GIOP by simplifying messages types and reducing the size of the IOP headers of messages.

4 CAN-based Publisher/Subscriber Protocol for CORBA

While CORBA relies on the point-to-point transport service provided by standard protocols such as TCP, distributed control systems require group communication capabilities. In this section, we design a publisher/subscriber protocol for our CAN-based CORBA. We first define the protocol header format using the CAN identifier structure. We then present the conjoiner-based announcement/subscription mechanism which allows for dynamic binding between publishers and a group of anonymous subscribers.

4.1 Defining the Protocol Header

In order to overcome the limitations of the standard CAN protocol, several vendors offer commercial high-level protocol suites for the CAN [1, 10, 9]. These protocols define packet fragmentation schemes, types of service including client/server, master/slave, and peer-to-peer communications,



$$\text{Protocol ID} = \begin{cases} 00, 01 & \text{reserved} \\ 10 & \text{EIOP} \\ 11 & \text{binding} \end{cases}$$

Figure 3: Protocol header format using CAN identifier structure

and sometimes object models. In doing so, they invariably use the CAN identifier as a network identifier to denote a connection, a message, or an object group. In our design, we also make use of the CAN identifier structure for this purpose.

The greatest challenge in defining the protocol header using the 11-bit CAN identifier structure is in its limited size. We put the greatest emphasis on making efficient use of the bits in the identifier. Also, we attempt to simplify the protocol design to warrant the small execution overhead and code size of the protocol stack as long as it can provide desired services for higher level CORBA layers.

Figure 3 shows our protocol header format. We divide the CAN identifier structure into three sub-fields: a protocol ID, a transmitting node address, and a port number. They respectively occupy two, five and four bits amounting to 11 bits. The `Proto` field denotes an upper layer protocol identifier. The data field following the identifier in a CAN message is formatted according to the upper layer protocol identifier by `Proto`. In our current design, among four possible values of the `Proto` field, only 10_2 and 11_2 are used for the EIOP and the channel binding protocol, respectively. The other two are reserved for potential user-defined protocols.

The `TxNode` field is the address of the transmitting node. In our design, one can simultaneously connect up to 32 distinguishable nodes with the CAN bus under a given upper layer protocol. The `TxPort` field represents a port number which is local to a particular transmitting node. Since `TxNode` serves as a domain name which is globally identifiable all across the network, `TxNode` and `TxPort` collectively make a global port identifier. This allows ports in distinct nodes to have the same port number and helps increase modularity in software design and maintenance. As the `TxPort` field supports the maximum of 16 local ports on each node, up to 512 global ports coexist in the network under a specific upper layer protocol.

Note that the header does not include any form of destination addresses and that receiving CAN nodes can select and accept messages sent from a specific set of ports, using the message filtering mechanism of the CAN bus adaptor. In this way, anonymous publisher/subscriber communication is effectively supported.

The layout of the CAN data field is determined by `Proto` which designates the upper layer protocol. A CORBA object invocation message longer than eight bytes should be fragmented into multiple CAN messages. Since the CAN offers reliable and ordered message transmission based on physical error detection and recovery, message re-assembly at a receiving end is done in a straightforward manner.

4.2 Conjoiner-based Channel Binding Mechanism

Our publisher/subscriber model relies on an intermediary object we name a *conjoiner*. A conjoiner is a pseudo-CORBA object which establishes an invocation channel from publishers to a collection of anonymous subscribers. It must be started right after network initialization, and then operational during the entire system service period. It maintains a global binding database where each CORBA object in the system has a corresponding entry. One of important roles of the conjoiner object is to translate a CORBA object name string into a global port number consisting of `TxNode` and `TxPort`. This is done by looking up the global binding database. Figure 4 illustrates the conjoiner-based publisher/subscriber framework and the global binding database.

As shown in the figure, an entry in the global binding database is a quadruple consisting of a *channel tag*, an *OMG IDL interface identifier*, and `TxNode` and `TxPort`. The channel tag is a unique symbolic name associated with each invocation channel. An invocation channel is a virtual broadcast channel from publishers to a group of subscribers. Each publisher is attached to an invocation channel via its own port. A channel tag is statically defined by programmers when they write the application code. Both publishers and subscribers use it as a search key in the global binding database later on. The OMG IDL interface identifier is a unique identifier associated with each IDL interface in the system. The IDL compiler generates IDL interface identifiers. The CORBA run-time system uses these identifiers to perform type checking upon every method invocation. This ensures strong type safety as required by the CORBA standard. The channel tag and the interface ID together work as a unique name for each invocation channel. It is programmers' responsibility to define a system-wide unique name for an invocation channel.

The conjoiner object oversees object registration, consumer subscription, and dynamic channel binding between publishers and subscribers. When a publisher wants to get attached to an invocation channel, it first obtains a communication port from its local free port pool, and then registers it to the conjoiner object. This procedure is illustrated in Figure 4 by an arrow labeled as (1) `announce()`. Such a registration process leads to the creation of an entry, or the modification of one if it exists, in the global binding database. Thus, a publisher's registration message contains all necessary information to construct a database entry such as a channel tag, an OMG IDL interface ID, and a global port number.

A subscriber wishing to subscribe to an invocation channel also accesses the conjoiner object, as depicted in Figure 4 by an arrow labeled as (2) `subscribe()`. A subscriber's message contains

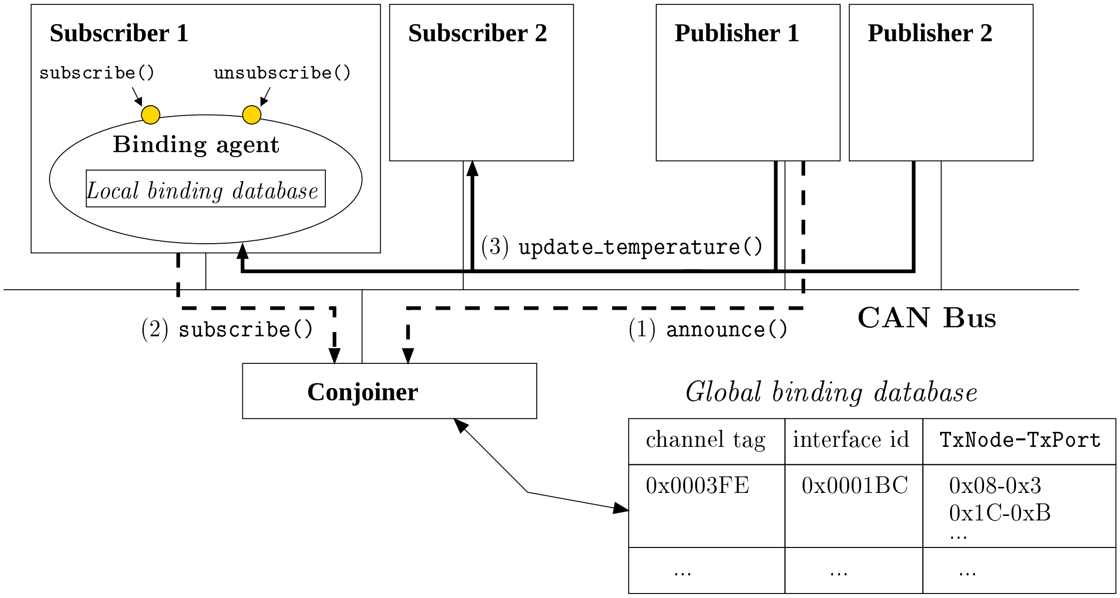


Figure 4: Conjoiner-based object binding scheme.

a channel tag and an IDL interface identifier. If a matching entry is found in the global binding database, the conjoiner provides the subscriber with the binding information of the invocation channel. The subscriber ends its subscription process by updating the mask register of the CAN bus adaptor so that it can accept subscribed messages later on.

After subscription, subscribers are asynchronously informed of changes in invocation channels. Note that a publisher may be dynamically attached to an invocation channel or detached from it. As shown in Figure 4, a binding agent in a subscriber reacts to such asynchronous updates.

A subscriber maintains its own local binding database, which contains the binding information of all the invocation channels it currently subscribes to. Unlike the group communication scheme in [8], subscribers in our scheme receive messages directly from publishers using the local binding databases. As an example, consider `update_temperature()` method in Figure 4. The publishers of temperature data invoke this method to send out messages via an invocation channel. The subscribers receive the temperature data when their `update_temperature()` methods are executed. Since a subscriber knows the port addresses of all of its publishers using its local binding database, it can conveniently pick up subscribed messages from the broadcast bus. Note that every subscriber intending to receive the temperature data should possess the `update_temperature()` method. The common interface of such subscribers is defined in an IDL program.

```
// IDL

interface TemperatureMonitor {
    // Update temperature value for a location.
    oneway void update_temperature(
                  in short locationID, in short temperature, in int time);
}
```

Figure 5: IDL program for subscriber interface.

4.3 Example Publisher/Subscriber Code

We present an example program which demonstrates the usage of our publisher/subscriber scheme. The program consists of publisher and subscriber objects which respectively perform temperature sampling and updating. The source program consists of an IDL interface definition and subscriber/publisher code. Figure 5 shows the IDL code which defines the interface of the subscriber objects. It specifies the signature of method `update_temperature()` which updates temperature values in the subscriber objects. This method is defined as a `oneway` operation which does not have output parameters.

Figure 6 shows the publisher/subscriber code in C++. In both source files, there exist a unique channel tag `TEMP_MONITOR_TAG` and an IDL interface identifier `TEMP_MONITOR_IFACE`. Note that `TEMP_MONITOR_TAG` is defined by programmers, while `TEMP_MONITOR_IFACE` is generated by our OMG IDL compiler.

5 Embedded Inter-ORB Protocol

Remote method invocation in CORBA is handled through the general inter-ORB protocol which allows for interoperability among various CORBA implementations. The CORBA 2.2 GIOP defines a transfer syntax called common data representation (CDR) and eight messages types which cover all the ORB request/reply semantics. However, the GIOP is not suitable for our embedded CORBA since it triggers a large number of CAN message transfers upon every method invocation. In this section, we present a new inter-ORB protocol by defining a new transfer syntax and two message types. They are called the embedded inter-ORB protocol (EIOP) and the compact common data representation (CCDR).

5.1 Compact Common Data Representation

CDR is a transfer syntax which maps data types defined in OMG IDL into a networked message representation so that GIOP sends IDL data types over the network. It also addresses inter-platform

```
// Subscriber code in C++

// Define a channel tag for temperature monitoring.
#define TEMP_MONITOR_TAG 0x01

// Initialize the object request broker (ORB).
CORBA::ORB_ptr orb = CORBA::ORB_init(argc,argv);

// Get a reference to the conjoiner.
Conjoiner_ptr conjoiner = Conjoiner::_narrow(
    orb->get_initial_reference("Conjoiner"));

// Create a servant implementing a temperature monitor object.
TemperatureMonitor_impl monitor_servant;

// Assign a local CORBA object name to the monitor object.
PortableServer::ObjectId_ptr oid =
    PortableServer::string_to_ObjectId("Monitor1");

// Register the object name and servant to a portable object adaptor (POA).
poa->activate_object_with_id(oid, &monitor_servant);

// Bind the monitor object to the TEMP_MONITOR_TAG.
conjoiner->subscribe(TEMP_MONITOR_TAG, &monitor_servant);

// Receive temperature values
while(1) {
   ...
}
```

```
// Publisher code in C++

// Define a channel tag for temperature monitoring.
#define TEMP_MONITOR_TAG 0x01

// Initialize the object request broker (ORB).
CORBA::ORB_ptr orb = CORBA::ORB_init(argc,argv);

// Get a reference to the conjoiner.
Conjoiner_ptr conjoiner = Conjoiner::_narrow(
    orb->get_initial_reference("Conjoiner"));

// Obtain a reference to the temperature monitor group
// TEMP_MONITOR_IFACE is an interface identifier generated
// by the IDL compiler.
HeatMonitor_ptr monitor =
    conjoiner->announce(TEMP_MONITOR_TAG, TEMP_MONITOR_IFACE);

while(1) {
    ...
    // Invoke a method of subscribers.
    monitor->update_temperature(placeA, value, currentTime);
}
```


Figure 6: Publisher/subscriber code

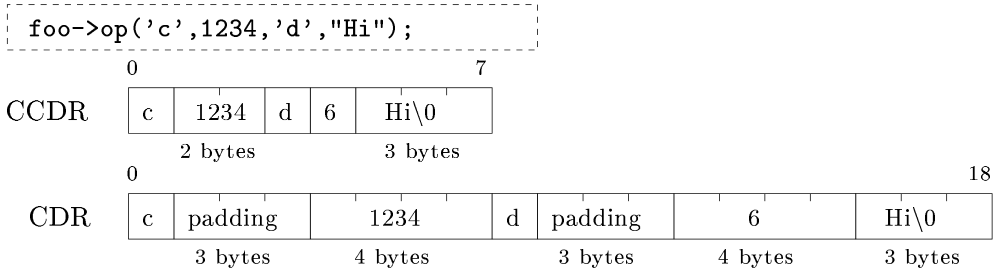


Figure 7: Example encoding

two MSBs	Size (bytes)	Max. Value (unsigned)
00	1	2^6-1
01	2	2^{14}-1
10	3	2^{22}-1
11	5	2^{32}-1

Table 1: Variable-length integer representations

issues such as byte ordering and memory alignments in such a way that it can support fast encoding and decoding of IDL data types. Specifically, CDR aligns integers on 32-bit boundaries and supports both little and big endian byte orderings rather than mandating a common network byte ordering. As a result, marshalling and unmarshalling of a GIOP message becomes very fast if it is performed on processors supporting the same ordering and alignment. Clearly, the generality and efficiency of CDR are achieved at the expense of increased network load.

In order to make CDR affordable on a slow network such as CAN, we propose compact common data representation (CCDR). We optimize CDR in two ways. First, we add packed data encoding into CCDR in that integers need not be aligned on 32-bit boundaries. This saves padding bytes. Figure 7 illustrates the saving when method invocation `foo->op('c',1234,'d',"Hi")` is encoded in CCDR. In this example, we can save six padding bytes which are needed to align two integers `1234` and `6` in CDR. (Integer `6` is internally used to specify the string length.) This packed encoding scheme may increase the processing overhead of message encoding and decoding and require extra buffer space on nodes. This drawback can be minimized if the encoded message fits in a single CAN message, which is often the case in an embedded control system.

Second, we introduce a variable-length encoding scheme for integers. While an integer is stored in four bytes in CDR, most of integer instances in IDL programs are smaller than $2^{32}-1$. For example, in CDR, integers are very frequently used to represent the sizes of `string` and `sequence` data types of IDL. Obviously, these integer values are very small in most cases. We thus devise a

Message type	Originator	EIOP support
Request	Client	yes
Reply	Server	no
CancelRequest	Client	yes
LocateRequest	Client	no
LocateReply	Server	no
CloseConnection	Server	no
MessageError	Client or Server	no
Fragment	Client or Server	no

Table 2: CORBA 2.2 GIOP message types

variable-length integer encoding scheme in that an integer occupies one to five bytes depending on the actual value it represents. As shown in Table 1, we use first two MSBs to denote the actual byte-length of an integer. We decide to support only the big endian byte ordering in CCDR to reduce the encoding/decoding overhead. Revert to the method invocation example in Figure 7. We observe that extra five bytes are saved through the variable-length encoding scheme and that these two schemes together yield total eleven-byte saving in this simple method invocation. As a result, the method invocation can fit in a single CAN message in CCDR while it needs three CAN messages in CDR.

5.2 EIOP Messages

In CORBA, every message transmitted over the network starts with a GIOP header. A GIOP header is subdivided into a 12-byte common prefix and a type-specific header which varies in size depending on message types. Table 2 shows eight message types supported in the CORBA 2.2 GIOP. We make two customizations on GIOP.

As the first customization, we reduce the number of supported message types into two in EIOP. To do so, we eliminate from GIOP `LocateRequest`, `LocateReply`, `CloseConnection`, and `Fragment` messages which are meaningful only in connection-oriented point-to-point communication. We also eliminate `Reply` and `MessageError` messages since our CORBA supports only asynchronous communication. As a result, EIOP supports only `Request` and `CancelRequest` messages, as summarized in Table 2.

The second customizatin we make on GIOP is to reduce the length of the message header of the `Request` type. Note that messages of this type are most frequently seen in the system since they carry method invocation information. Figure 8 shows both the common prefix and the type-specific header of the `Request` message in GIOP. Since the header is included in every `Request` message, it is crucial to reduce its size. We first modify the common prefix by reducing the 4-byte `magic`

```
module GIOP {
  ...
  struct MessageHeader_1_1 {
    char                    magic[4]; // The string "GIOP"
    Version                 GIOP_version;
    octet                   flags;
    octet                   message_type;
    unsigned long           message_size;
  };
  struct RequestHeader_1_1 {
    IOP::ServiceContextList service_context;
    unsigned long           request_id;
    boolean                 response_expected;
    octet                   reserved[3];
    sequence<octet>         object_key;
    string                  operation;
    Principal               requesting_principal;
  };
}
```

Figure 8: GIOP message format

```
module EIOP {
  ...
  struct MessageHeader_1_0 {
    octet           magic; // 0xE0
    octet           flags; // Includes bit fields for
                           // version number and message type.
    unsigned long   message_size;
  };
  struct RequestHeader_1_0 {
    unsigned long   interface_id;
    unsigned long   operation_id;
  };
}
```

Figure 9: EIOP message format

field into one-byte magic code and merging `GIOP_version`, `flags`, and `message_type` fields into the one-byte `flags`. `MessageHeader_1_0` in Figure 9 defines this new header format.

We then modify the type-specific header of the `request` message in two ways. First, we remove optional and reserved fields such as `service_context` and `requesting_principal` from the GIOP request header. They are used to store information required only when add-on services such as `Security` and `Transaction` are provided. Second, we encode name strings appearing in the GIOP request header into integer identifiers. As shown in Figure 8, `RequestHeader_1_1` includes string fields such as `object_key` and `operation`. The `object_key` field contains an interface name, an object name, an object adaptor name, etc, and the `operation` field holds the method name. Since programmers tend to use long and self-explanatory strings for these names to enhance the readability of programs, string fields in a request message header may well occupy excessively large space. We use integer-encoded `interface_id` and `operation_id` fields in EIOP. EIOP relies on the IDL compiler to obtain proper identifiers for them. Finally, we remove `request_id` and `response_expected` fields since the `Reply` messages are not supported in EIOP.

6 Conclusion

We have presented the design of an environment specific CORBA for distributed embedded systems built on the CAN bus. The design goal we had in our mind during the development of the new CORBA was to minimize its resource demand and make it support anonymous publisher/subscriber communication without losing the IDL level compliance to the OMG standards. To achieve these goals, we have developed a transport protocol on the CAN and a group communication scheme based on the well-known publisher/subscriber model. This transport protocol makes efficient use of the CAN identifier structure to realize a subject-based addressing scheme, which supports the anonymous publisher/subscriber communication model. In the proposed communication scheme, publishers are completely unaware of its subscribers and simply send out messages via their own communication ports. This scheme uses an invocation channel to establish a virtual broadcast channel which connects publishers and a group of subscribers.

We have also customized GIOP and CDR so as to reduce message traffic generated for each method invocation. Specifically, we have defined the compact CDR which exploits the packed data encoding scheme and the variable-length integer representation. In addition to the CCDR, we have simplified messages types and reduced the size of the header of GIOP messages. We have shown that the proposed EIOP along with CCDR contributes to significantly reducing the size of request messages. In spite of these vast modifications, the new CORBA is still compliant to CORBA at the application program and IDL level.

The new CORBA design clearly demonstrates that it is feasible to use CORBA in developing distributed embedded systems on real-time networks with severe resource limitations. We are currently implementing the embedded ORB of our CORBA using the GNU ORBit [11] on the Arx real-time operating system we have developed at Seoul National University [19]. The ORB implementation complies with the minimum CORBA specification [7]. The code size of the preliminary implementation is less than 70 Kbytes. We plan to report its performance numbers in future reports.

We are currently looking to extend our CORBA such that it is interoperable with the standard ORB implementations running on conventional transport networks such as the TCP/IP on Ethernet.

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