WHITEPAPER

A Data-Centric System Architecture: What Robotic Surgery and Space Rovers Have in Common

DATA-CENTRICITY FOR CHALLENGING COMMUNICATIONS REQUIREMENTS

What do remotely-controlled Mars exploration robots and minimally invasive robotic surgery (MIRS) have in common? In many ways the technology and communication requirements for the two applications could not be more different. But in both cases, developers are benefiting from a common data-centric communications system architecture that helps abstract complexity and reduce the costs of connecting components, devices and systems across the Industrial Internet of Things (IIoT).

This whitepaper examines some of the challenges of designing modern robotic systems. It details the real-life lessons derived from NASA's Human Robotic Systems project, the European Space Agency (ESA) Telerobotics and Haptics Lab, and the development work being done at MIRO Lab, an advanced robotic assistance research laboratory at the Robotics and Mechatronics Center within the German Aerospace Center (DLR). Developers and system architects must address extreme communications challenges – including reliability, performance and scalability – when building robust systems for these and other telerobotics applications.

RTI worked closely with NASA and the MIRO lab on their implementation of the Data Distribution Service (DDS) communication standard to help address the challenges they were facing. Discussions center on key DDS contributions including decentralized architecture, real-time Quality of Service (QoS) and security capabilities.

THE COMMON COMMUNICATION CHALLENGES OF SPACE ROVERS AND ROBOTIC SURGERY

The most disruptive change in almost every industry, including robotics, is upon us. The era of smart machines is heralding the transition from a landscape of unconnected local infrastructure to one built on the IIoT where devices, machines and complete systems will be integrated into fully functioning systems of systems, and connected to the cloud.

Particularly for robotic systems, the real-time model of the environment will no longer be derived solely from the immediate surroundings of the robot and the input from the robot's own sensors. In telerobotics, semi-autonomous robots are typically controlled by people working across great distances and responding to unpredictable situations. Advanced data correlation and analytics will lead to enhanced situational awareness in robotic systems with data obtained from connected systems and even the public Internet.

The challenge across industries is how to handle the resulting data explosion and significant increase in network traffic. As just one example, consider that in the healthcare industry, successful patient treatment requires management of an exploding amount of digital data – monitoring a single patient can mean processing as much as 1.5GB of raw physiological data per day. To support this new model and the resulting data explosion, developers in almost every industry need common system architectures. An architecture that connects sensors, devices and systems together and to the cloud; an architecture that interoperates between technologies and that span industries.

The robotics field is already aligning with the IIoT, and the Internet has evolved to the point where it can deal with complex distributed systems. Opportunities abound to apply lessons learned across industries – a key reason why multinational organizations such as, the Industrial Internet Consortium (IIC) are focusing on defining common architectures for the IIoT. The IIoT will fundamentally change how robots interact and integrate, and common architectures will facilitate interoperability between manufacturers within and across industries.

To illustrate some of the challenges in finding architectural commonalities across systems and industries, think about the extreme communications problems that developers of both space rovers and surgical robots must solve. First, consider the challenges at NASA, where the human robotic systems team is experimenting with controlling robots on earth from the International Space Station (ISS) with an ultimate goal of controlling Mars-based robots from orbit. Traditional IP protocols like TCP/IP or UDP/IP do not work over the space-to-earth communication link that is inherently lossy, low bandwidth, intermittent and characterized by multi-second latencies. Unlike communications across a standard Ethernet network that can send Acknowledgements (ACKs) or Negative Acknowledgments (NAKs) within milliseconds or even dozens of microseconds, the space link would be saturated with just the metatraffic from the reliability protocol.

In similarly challenging applications, the ESA Telerobotics and Haptics Lab develops robotics technology for advanced human-machine interaction – that is, extending the human sense of touch to space and planetary environments. In 2015, the team demonstrated one of the first telerobotic control systems for use in space when Andre Schiele from

ESA shook hands with NASA astronaut Terry Virts, making a remarkable 5,000 kilometer connection between earth and the ISS.

In a completely different environment back on Earth, the MIRS technique involves surgical instruments that are held by specialized robot arms and remotely controlled by a surgeon who virtually regains direct access to the operating field through telepresence and telemanipulation techniques. The telesurgery scenario MiroSurge, developed by DLR coordinates three robots with the objective to perform delicate heart surgery on a beating heart, a procedure otherwise impossible for a surgeon attempting to make a precise incision. Through real-time image processing, the heart is displayed on a screen as a static surface and the surgeon uses haptic feedback to control the robot arms. The robot arms perform the actual surgery and compensate for the beating of the heart, dictating extremely precise control. To enable real-time control, the system closes a distributed loop between the robots and the remote surgeon's controls at 3kHz or 3,000 updates per second.

As disparate as their environments may seem, the three systems by NASA, ESA and DLR described above are implemented using the RTI Connext® DDS framework that helps overcome the communications complexities of tele-robotics systems. Connext DDS is based on the Data Distribution Service (DDS) standard.

THE LAYERED DATABUS ARCHITECTURAL PATTERN AND THE DDS STANDARD

In IIoT systems, a common architecture pattern emerges that is made up of multiple databases layered by communication QoS and data model needs. Typical IIoT systems are extremely complex and require sharing data across multiple networks from the edge to the fog to the cloud. For example, in a connected hospital, devices have to communicate within a patient or operating room, to nurses' stations and off-site monitors, to real-time analytics applications for smart alarming and clinical decision support, and with IT health records. This is challenging for many reasons: because the volume of streaming device data could easily overwhelm hospitals networks; patient data must be securely tracked; and all devices and applications must interoperate. A layered databus architecture is the ideal framework for resolving these challenges and developing multi-tiered IIoT systems of systems.

DDS is an international standard that implements this layered databus architectural pattern.

The IIC currently represents nearly 300 companies in more than 25 countries. IIC Members share a strategic interest in advancing connectivity between smart devices, systems and the cloud. A goal of the IIC is to identify and demonstrate common architectures across IIoT domains. It is important to note that the goal is not to design new standards, but rather to determine how existing standards and technologies can be integrated to enable development of IIoT applications.

The DDS standard is managed by the Object Management Group (OMG), an international, open-membership, not-for-profit technology standards consortium. The DDS standard specifies both an Application Programming Interface (API) that ensures portability of application code between DDS providers and a communication protocol for inter-operability between systems and devices implemented using different providers.

HOW RTI CONNEXT DDS IMPLEMENTS THE LAYERED DATABUS

As illustrated in Figure 1, the Connext Databus is used to integrate systems and devices. With a decentralized, serverless architecture, Connext DDS abstracts the com-

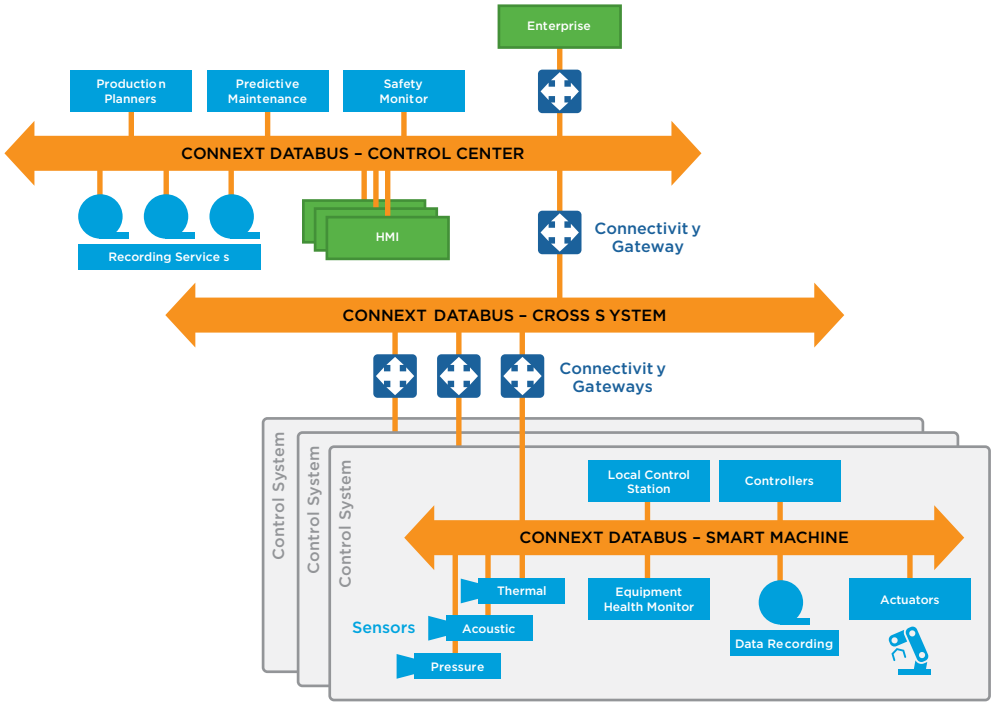


Figure 1: Peer-To-Peer Plug & Play Layered Databus

plexity of the direct point-to-point communication between devices and system components. Components that connect to the Databus act as publishers (providers) of data or subscribers (consumers) of data. Components can also act as both. Components have no direct dependencies between each other, but rather depend only on topics to which they subscribe and publish. Components publish data that they produce, and subscribe to data that they want to consume. In this example, a pressure sensor publishes pressure data. The control application subscribes to the pressure data and produces commands for the surgical robot (the actuator in this simple example system).

The important observation here is that, using the Connext Databus, the components are fully interoperable, and yet they have no hard-coded dependencies on each other. Connext DDS automatically discovers and connects components at runtime based on matching publications and subscriptions by topic. The resulting loose coupling between components offers a number of advantages. In this example, no code changes are required to the existing system components upon addition of a second pressure sensor or a equipment health monitor. New devices and system components can even be added at runtime without halting the system or any of its components.

The Mars Rover system is a great example of a Data-Centric Architecture enabled by using Connext DDS.

Each topic being published or subscribed to has an associated data type or schema, similar to the schema in a relational database. As shown in the Mars Rover example in Figure 2, the process might include giving each robot a unique name or number. In addition, the schema is populated with real-time data, such as each robot's position, direction and acceleration. Although the schema is defined centrally, the data itself is not stored in any one location. Rather, published data is replicated across all publishers and subscribers, and data is cached with each subscriber for near-zero-latency access.

Note how the data schema represents each robot's state, rather than messages or updates about the state. This is a fundamental difference between the layered databus architectural pattern and more conventional messaging patterns. By communicating state rather than messages, the layered databus architectural pattern is inherently robust to loss, duplication and reordering of published data.

SHOULD YOUR NEXT ROBOTICS PROJECT USE CONNEXT DDS?

Answering the following five questions can help determine if a robotics project will benefit from using Connext DDS:

1. Is it a big problem if your system stops working for a short time and you have to wait for it to recover?
2. Is the system's response time defined in terms of milliseconds or even microseconds?
3. Do you have more than 10 software engineers on the project?
4. Are you sending data to many destinations, as opposed to just one (like to the cloud or a database)?
5. Are you implementing a new IIoT architecture?

If the answer to at least three of these five questions is "yes," Connext DDS will likely be an appropriate choice for the project.

If a downtime of a few seconds would result in severe or even life-threatening consequences, the application will likely benefit from the use of the DDS communication protocol. Likewise, Connext DDS would be applicable for robotic projects with response time requirements on the order of milliseconds or microseconds, with a dozen or more developers contributing to the project, with communication patterns that share data with multiple destinations. Or perhaps the project is driven by modern IIoT requirements in general.

To date, more than 1,000 different system designs across a broad range of industries implement the layered databus architectural pattern using DDS. The Connext DDS standard itself is referenced by more than 15 other standards and reference architectures, including the OMG and IIC.

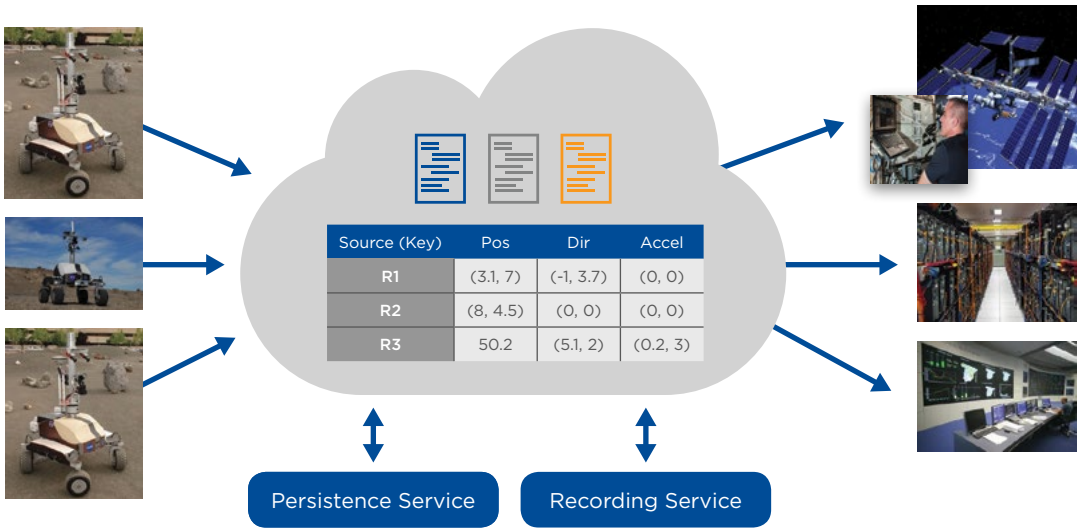


Figure 2. The Mars Rover Data-Centric Architecture

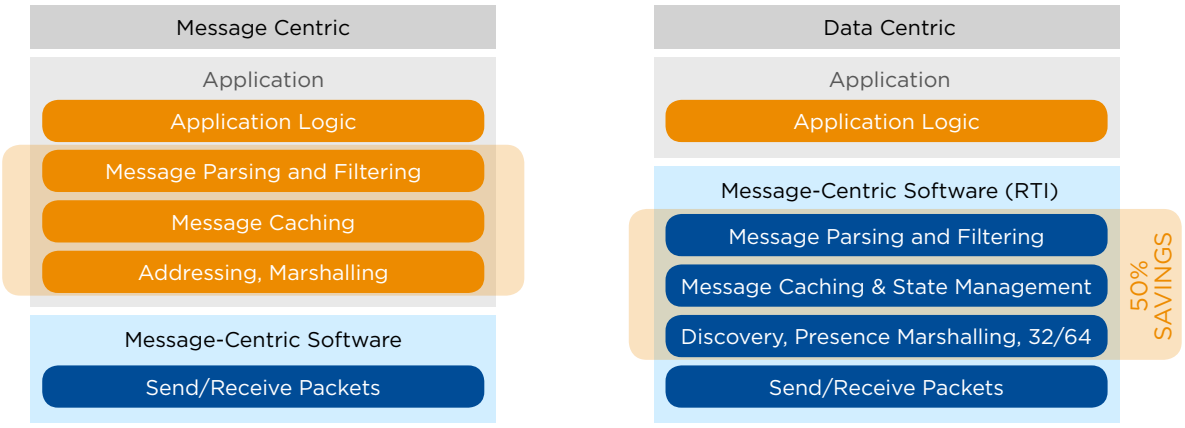


Figure 3. Reducing Application Development Workload by 50%

UNIQUE REAL-TIME QUALITY OF SERVICE

The NASA and ESA telerobotic systems as well as the DLR surgical robotics system use Connext DDS to implement the layered databus architectural pattern. Utilizing advanced real-time QoS, Connext DDS can be implemented across a space link as well as for the MIRS robot's 3kHz closed control loop. RTI Connext DDS includes a highly-tunable reliability protocol, offering per-subscriber best-effort or reliable data transmission to optimally balance throughput and latency across a wide variety of interconnections. For a sensor that outputs updates at a relatively high frequency, best effort may be the best option, while a high-latency, lossy connection, such as the space link likely dictates the reliable QoS policy. Connext DDS QoS is time-aware so timeouts that control when ACKs or NAKs are sent can be aggressively set to dozens of microseconds for the surgical robot system, or to seconds for the higher-latency space link. The DDS protocol is the only protocol that will work optimally in each of these very different scenarios. DDS subscribers can also specify time-based filters to sub-sample the data stream to, for example, conserve network bandwidth and CPU power.

Flexible QoS configuration makes Connext DDS the only connectivity framework that can be used across the entire breadth of the IIoT for communication between devices, machines and systems, and from devices and systems into the cloud for data analytics. Its protocol can be fine-tuned to work equally well across any communication media, including shared memory, LANs, WANs, LTE, satellite or radio links.

Implementing equivalent communication-protocol intelligence using standard message-centric software – including plain socket programming – requires significant work before developers can even address the application logic. In contrast, as illustrated in Figure 3, Connext DDS data-centric software integrates intelligence into the communication platform to reduce the application-development workload significantly.

SUITABLE FOR SAFETY- AND MISSION-CRITICAL SYSTEMS

Both the space rover and MIRS applications require robust security and safety. A surgical robot, for example, must be protected against vulnerabilities in the remote connection to prevent a hacker from taking control of the device.

Figure 4 illustrates the variety of data including remote commands, diagnostic data and patient data, and the different security policies required. Diagnostic data must be authenticated, for example, while it does not require the encryption that would be necessary with patient data that falls under HIPAA rules.

Traditional transport-layer security methods secure the communication channel and consequently require full encryption of all data. Such gross-level security can be unnecessarily compute-intensive and cause latencies and jitter that would be unacceptable in time-critical applications, such as with the MIRS technique. In addition, traditional transport-layer security requires robust network connections and lack multicast support. The DDS standard overcomes these issues by securing the data itself in real-time. The approach supports secure multicast and allows setting of per-topic security policies and access privileges, making it possible to apply different security policies to different kinds of data, even when they are sent on the same channel.

Safety certification is another consideration in choosing a connectivity framework. Developers must ensure, for example, that a medical robot never takes an action that would endanger a patient. The International Electrotechnical Commission (IEC) specifies requirements for the safety and effectiveness of medical devices in its IEC 60601 class 3 standards. Similarly, the DO-178C Level A standard describes requirements for flight management systems and ISO 26262 specifies road-vehicle functional safety.

Connext DDS has achieved DO-178C safety certification to provide a strong head start for developers building safety-certified medical robots. The safety-certifiable version is based on the DDS standard and its wire protocol and is fully interoperable with regular DDS implementations. To understand the benefit of using a safety-certifiable connectivity framework like DDS, consider that DO-178C Level A certification, for example, can cost more than $100 per executable line of code – and this only includes the cost of developing certification evidence, not the cost of writing certifiable code in the first place. Relative to non-safety critical code, certifiable software is more expensive to develop because it must be deterministic in both execution time and memory, traceable to requirements, and fully testable.

Using DDS reduces the amount of code one has to develop and certify in two ways: it eliminates the need to create a custom

Security Example



DATA ITEM	AUTHENTICATION	ACCESS CONTROL	INTEGRITY	NON-REPUDIATION	CONFIDENTIALITY
Device diagnostic data	X		X		
Remote commands	X	X	X	X	
Patient data	X	X	X		X

Figure 4. Examples of Types of Data and Required Security Policies

connectivity infrastructure and its high-level interfaces reduce the amount of communication and integration logic required by typical lower-level connectivity interfaces. Thus, it is not unusual for DDS to reduce the amount of custom lines of code in a system by 20,000 to hundreds of thousands. This results in a certification cost savings of $2 million or more, in addition to the reduced cost of software development and integration.

With Connext DDS, the certifiable code base is derived from a scaled-down DDS implementation for resource constrained environments. Characterized by a very small memory footprint and a reduced source-code line count, the solution makes it feasible to develop certification evidence. The implementation follows the DDS specifications and the DDS wire protocol, but implements a subset of the standard DDS API that that is most amenable to certification and relevant to safety-critical systems and devices.

The developed DO-178C Level A certification evidence can be used as a starting point for medical-safety certification. The evidence includes 940 high-level requirements, more than 3,000 low-level requirements, and a body of 3,000 test files that altogether achieve 99.88% code coverage. The solution can be used for safety certification in robotic systems. Already developed and tested, such evidence also reduces the risk and time required for certification — on top of the millions of dollars of savings from the overall reduction in custom code and evidence.

THE FUTURE OF THE IIOT

Connectivity is key to the future of many industries including robotics. In time, the IIoT will be as pervasive as the regular Internet is today. Common reference architectures and connectivity standards, such as DDS are expected to rapidly replace custom connectivity solutions across systems, as well as across entire industries.

FOR MORE INFORMATION

RTI Connext DDS Professional, the first connectivity framework designed for the demanding requirements of the IIoT.

For more information about RTI Connext DDS Professional, please visit: www.rti.com.

You can also download a free trial of RTI Connext DDS at www.rti.com/downloads.

ABOUT RTI

Real-Time Innovations (RTI) is the largest software framework provider for smart machines and real-world systems. The company's RTI Connext® product enables intelligent architecture by sharing information in real time, making large applications work together as one.

With over 1,500 deployments, RTI software runs the largest power plants in North America, connects perception to control in vehicles, coordinates combat management on US Navy ships, drives a new generation of medical robotics, controls hyperloop and flying cars, and provides 24/7 medical intelligence for hospital patients and emergency victims.

RTI is the best in the world at connecting intelligent, distributed systems. These systems improve medical care, make our roads safer, improve energy use, and protect our freedom.

RTI is the leading vendor of products compliant with the Object Management Group® (OMG) Data Distribution Service™ (DDS) standard. RTI is privately held and headquartered in Sunnyvale, California with regional headquarters in Spain and Singapore.

Download a free 30-day trial of the latest, fully-functional Connext DDS software today: https://www.rti.com/downloads.

RTI, Real-Time Innovations and the phrase "Your systems. Working as one," are registered trademarks or trademarks of Real-Time Innovations, Inc.
All other trademarks used in this document are the property of their respective owners. ©2020 RTI. All rights reserved. 50037 V2 0820

Your systems. Working as one.

CORPORATE HEADQUARTERS
232 E. Java Drive, Sunnyvale, CA 94089
Telephone: +1 (408) 990-7400
Fax: +1 (408) 990-7402
info@rti.com

rti.com
rti_software
rtisoftware
company/rti
connextpodcast
rti_software