# SPACEWIRE, A BACKBONE FOR HUMANOID ROBOTIC SYSTEMS

**Session: Missions and Applications**

**Short Paper**

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## ABSTRACT

The DLR Hand Arm System is an anthropomorphic system with 52 actuators and 430 sensors of different types. In order to maintain good performance the application must have the most direct access to all actuators and sensors. Therefore, a SpaceWire network connects FPGAs and CPUs and acts as real-time communication backbone. This publication focuses on the SpaceWire protocol implementation and the dedicated extensions that are defined for that system.

## 1 INTRODUCTION

The DLR Hand Arm System (see Fig. 1) is an anthropomorphic system that is aimed to reach its human archetype regarding size, weight and performance. It features intrinsic compliance implemented as variable stiffness actuation [1].

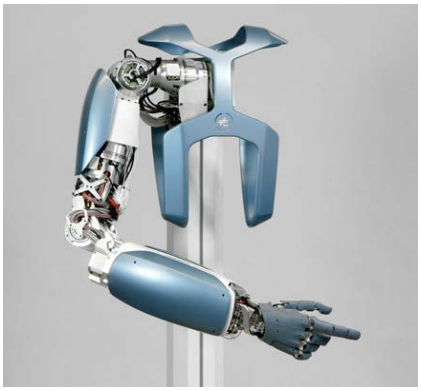

Fig. 1. The DLR Hand Arm System

The hand arm system has in total 26 DOF, thereof 19 DOF in the hand, 2 DOF in the wrist, and 5 DOF in the arm. To implement all those DOF, the hand arm system comprises 52 actuators and 430 sensors of different types. To operate that many actuators and sensors precisely for a certain control application the complexity of the system needs to be hidden from application designers. On the other hand, in order to maintain good performance the application must have the most direct access to all actuators and sensors.

In other words, a valuable means of abstraction with only minimal execution overhead is required. This is the task of the Computing and Communication Architecture. It incorporates the operating software and the computing and communication infrastructure of the DLR Hand Arm System. The aim is to provide a convenient high-level hardware abstraction that still allows high-performance feedback control with cycles beyond 1 kHz.

To balance the opposing requirements of flexibility and high integration, the DLR Hand Arm System's computing and communication platform is laid out hierarchical: At the top are general purpose, commercial-of-the-shelf (COTS) components. The footprint decreases towards the bottom end which is defined by the dedicated physical interfaces of sensors and motors. The available computing power and communication bandwidth decreases along with the decreasing footprint. A modular layout on each level together with the aggregation of components on successive levels by the means of suitable communication creates the desired platform flexibility (see Fig. 2). This hierarchy is not driven by a functional separation but only by the requirement of small footprint sizes at the physical interfaces. The functionality of an application can be flexibly mapped onto this hierarchy as required.

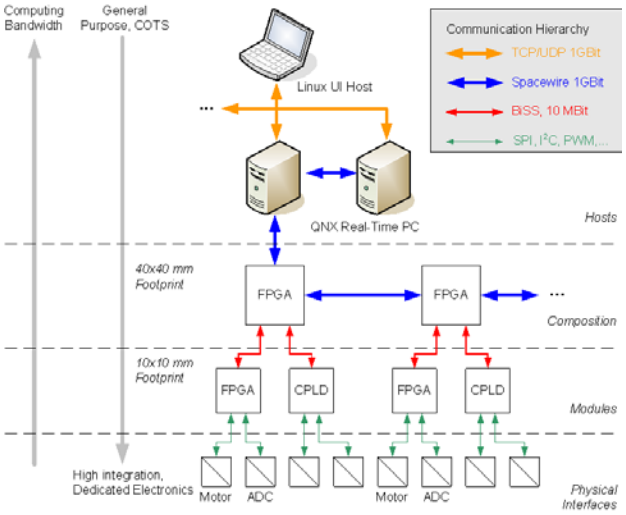

Fig. 2: The DLR Hand Arm System's hierarchical computing and communication platform

A SpaceWire network provides the necessary flexibility within the architecture and acts as a real-time communication backbone that connects FPGAs and CPUs. This publication has the focus on the SpaceWire protocol implementation and the dedicated extensions that are defined for the DLR hand arm system. A more detailed description of the entire Communication and Computation architecture is given in [2].

## 2 THE PROTOCOL STACK

### 2.1 PHYSICAL LAYER, CHARACTER LAYER, AND LINK LAYER

Inspired by the IEEE 1355 specification for fibre optical links as well as the Gigabit Ethernet and the FiberChannel specifications, the character-layer is realized with 8b10b [4] encoding. Therefore, a commercial GigE physical-layer interface circuit from Texas Instruments (TLK1221) is used, which has a dedicated ten-bit interface suitable for 8b10b encoding. The 8b10b encoding is implemented on FPGAs. This design allows SpaceWire links with data-rates of 1Gbit/sec and heterogeneous networks with fiber and copper.

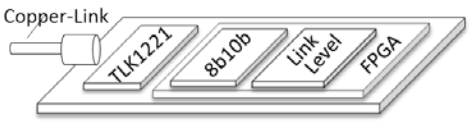

Fig. 3: SpaceWire Link with 8b10b encoding

The link-layer implementation meets the SpaceWire specification. It is adapted to 8b10b encoding by mapping the SpacewWire escape-characters to the 8b10b-K.Chars (see Table 1]). This implementation is flexible, since the link-layer implementation can be used for different character-layers. But the broken-link propagation with timeout is not efficient. A dedicated SpaceWire link-layer specification for 8b10b would be useful.

| ESC | KChar |
|---|---|
| IDLE | K28.5 |
| TC | K28.1 |
| FCT | K28.2 |
| EEP | K28.3 |
| EOP | K28.4 |
| NULL | K28.6 |

Table 1: ESC to KChar mapping

## 2.2 NETWORK LAYER

Table 2 shows the links and switches that are developed for the backbone of the DLRs Hand Arm System:

| Name | Platform | Comment |
|---|---|---|
| SW-Switch | QNX | SpaceWire Crossbar Switch for QNX with optional LUT for logical address resolution |
| HW-Switch | FPGA | SpaceWire Crossbar Switch for QNX with optional LUT for logical address resolution |
| HW/SW-Switch | FPGA and QNX | Runs on in-house PCIe interface card. Routes packets in dedicated DMA-buffers or HW-links. Allows high performance packet routing with minimum latency. |
| Copper Link | FPGA to FPGA | See 2.1 |
| HW-Link | FPGA | Connects HW-Switches and/or HW-Nodes within an FPGA. Optional FIFO allows to buffer characters or packets. If packet-buffering is switched on, EEP-packets can be deleted. |
| IPC-Link | QNX | connects SW-Switches and/or SW-Nodes |
| HW/SW-Link | FPGA and QNX | connects HW-Switches or HW-Nodes to SW-Switches or SW-Nodes |
| Copper2Fiber | | Transceiver for seamless connection of fiber and copper networks |

Table 2: Building blocks for SpaceWire backbone

## 2.3 TRANSPORT LAYER

The Datagram Protocol defines a simple non-reliable connection between Sink and Source. A Datagram is a single Spacewire Packet. The payload of the datagram is validated by crc (see Fig. 4).


Fig 4: Datagram Protocol

The RequestResponse Protocol is a transmission control protocol optimized for the implementation on FPGAs. The payload is validated by a crc. The process flow is validated by a configurable timeout (see Fig 5).

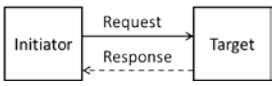


Fig 5: RequestResponse Protocol

The timeout control is located at the Initiator. Hence, the footprint on the target side is reduced. A detected timeout triggers an error-cycle, which is repeated until the Target acknowledges the error (see Fig. 6).

Datagram Sink and Source as well as Initiator and Target are SpaceWire Nodes. Source, Initiator, and Target store the address of their peer Node in a lookup table. A Node Configuration Protocol allows the configuration of this peer-address-LUT during runtime (see 2.4).

Fig. 7 shows the SpaceWire-packets of Datagram Protocol and RequestResponse Protocol.

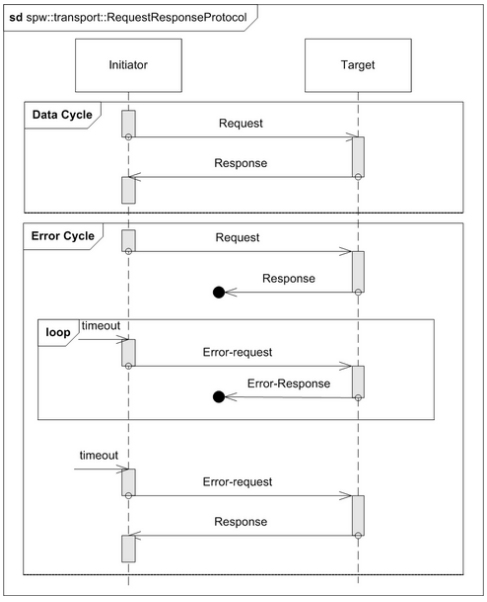


Fig 6: RequestResponse Protocol

### 2.4 APPLICATION LAYER

Switches with dynamic logical address mapping are configured by the Switch Configuration Protocol. The Configurator is an independent Node that configures the SpaceWire network. If the configuration has failed, the response packet is determined by EEP. Thus, configuration errors yield a Configurator timeout. Analogous, the Configurator configures the lookup tables of Nodes (see 2.3) by the Node Configuration Protocol (see Fig. 7).

Furthermore, a configurable Test Suite is available. A dedicated Test Node, which can act as Sink, Source, Initiator, or Target, generates periodical or random network traffic.

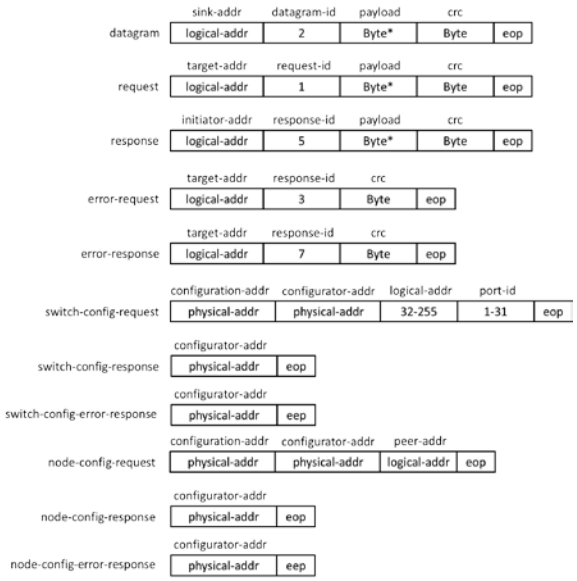


Fig 7: SpaceWire Packets for Datagram, RequestResponse, Switch Configuration, and Node Configuration Protocol

## 3 CONCLUSIONS

The concepts of FIFO channels and wormhole packet routing of the SpaceWire specification [3] combined with GigE physical-layer circuits results in a valuable communication platform for complex applications that require hard real-time. In [2] is shown that the Hand Arm System operates with control sample rates of 3 kHz and latencies below 333 us.

Especially the extended communication bandwidth of 1 Gbit/sec and the determinism (for known network topologies) make SpaceWire to be a good choice for high performance signal processing, since there is still no common alternative for deterministic communication beyond 1 GBit.

Beyond that, dynamic network configuration and the configuration of connections (i.e. peer-address) by an independent Configurator is a scalable solution with small footprint and a high degree of flexibility.

## 4 REFERENCES


1) M. Grebenstein et al., “The DLR hand arm system”, Proc. IEEE International Conf. on Robotics and Automation, April 2011.
2) Stefan Jörg, Mathias Nickl, Alexander Nothhelfer, Thomas Bahls, Gerd Hirzinger, “The Computing and Communication Architecture of the DLR Hand Arm System”, IEEE International Conf. on Intelligent Robots and Systems, 2011, tbp.
3) ECSS E-50-12A SpaceWire - Links, nodes, routers and networks, European Cooperation for Space Standardization (ECSS), http://spacewire.esa.int, 2003.
4) A. X. Widmer, P. A. Franaszek, “A DC-Balanced, Partitioned-Block, 8B/10B Transmission Code”, *IBM Journal of Research and Development, (1983) Volume 27, Number 5, Page 440*