Modularity in humanoid robot design for flexibility in system structure and application

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Abstract— **In this work we present the modularity aspect in the development of neoDavid, a robust humanoid robot with dexterous manipulation skills. We highlight the benefits of modularity in humanoid robot design for flexible service robotic applications. Our modular approach to system development begins with the system architecture and extends through the mechatronics, connectivity, and control components to the higher-level software and applications that match the growing system architecture. We show how the modularity scales and how it was used to gradually expand the system from an arm and hand to a full humanoid upper body on wheels. The modularity allowed us to adapt our system to changing needs as our focus shifted from technology basics to skills and finally to applications in the human environment with human tools.**

I. Introduction

In many applications, humanoid robots will be used as assistants to humans or in place of humans where the environment has been designed for humans. Consequently, human size, human-like performance, and human-like kinematics are relevant goals in humanoid robot design. Other soft goals include human acceptance, predictable behavior even for non-roboticists, and the ability to grasp and manipulate objects designed for human operation and manipulation. These goals result in robotic systems with many degrees of freedom (DoF) and complex hardware and software.

Humanoid robots commonly use at least some kind of modularization in order to reduce the number of different parts and handle the complexity of the many DoF. We want to focus and refer to compliant humanoid robots with a rigid link structure. This includes active compliance control, e.g. Rollin' Justin [1] and TORO [2], as well as robots with inherent elasticity, such as those with serial-elastic drives like LIMS2-AMBIDEX [3], COMAN [4], and WALK-MAN [5]. The humanoid ALTER-EGO [6] uses Variable Stiffness Actuators (VSAs), similar to our humanoid neoDavid, which is developed at DLR. All of these robots reuse a part of their electronics in several spots, use joint hardware modules and modular software. To the authors' knowledge, in contrast to neoDavid, these robots were developed all at once at a time when their final outlines and areas of application were clear.

Our robot neoDavid serves in this paper as the practical example of modularization of a complex and gradually evolving robot. neoDavid has 92 motors in 6 different actuator types. Three of the actuator types are VSAs with different principles, one actuator is a 2 DoF parallel tendon setup with overload couplings and mechanical gravity compensation, one type is a structurally elastic 3 DoF joint, and the last actuator type is common motor gear unit without intrinsic decoupling of the actuator output from the motor inertia. The complexity and number of motors is even higher in neoDavid than in the other humanoids mentioned above. The development of neoDavid started, when the technology of Variable Stiffness Actuators (VSAs) was relatively new and very basic questions on how to build good VSAs and how to properly control them in a multi-DoF robot had to be answered. Having our long term vision of a dexterous and robust humanoid robot in mind, our focus changed step by step from technological basics to skills and finally applications, see Fig. 1. Driven by the unclear concrete applications and the gradual change of research focus and complexity, a bottom-up development approach was chosen instead of the traditional top-down design. Nevertheless, we wanted to develop a system which can be adapted to new emerging humanoid robotic applications. Targeted applications are in the fields of service robotics and craftsmanship, where dynamic and powerful interaction and sophisticated manipulation of tools and objects are relevant. We wanted to build a research platform on which we have our individual research topics of mechatronics, control, perception, and planning working together in an application. This helps us to develop robust methods that are suitable for real life applications. Our derived requirements (R) and resulting challenges (C) where:

- (R) powerful, dexterous, but also compact (human silhouette)
- (R) be adaptable to unspecific applications and final manifestation
- (R) build the humanoid robot with restricted human resources
- (C) develop a scalable concept and system architecture
- (C) find modularization size and interfaces that fulfill our requirements
- (C) minimizing effort and system downtime for maintenance and troubleshooting

This paper is structured as follows. In Section II we present our modularization concept in mechatronics and system architecture giving an overview on the system design, our modularization choices, and how things work together. We discuss the approach and how it affected the development of David in Section III and give a short conclusion in Section IV.

II. Modularization

Managing sustainably the complexity of a humanoid robot like neoDavid requires a modular approach to hardware and control firmware combined with a flexible communications infrastructure. This approach involves breaking down the

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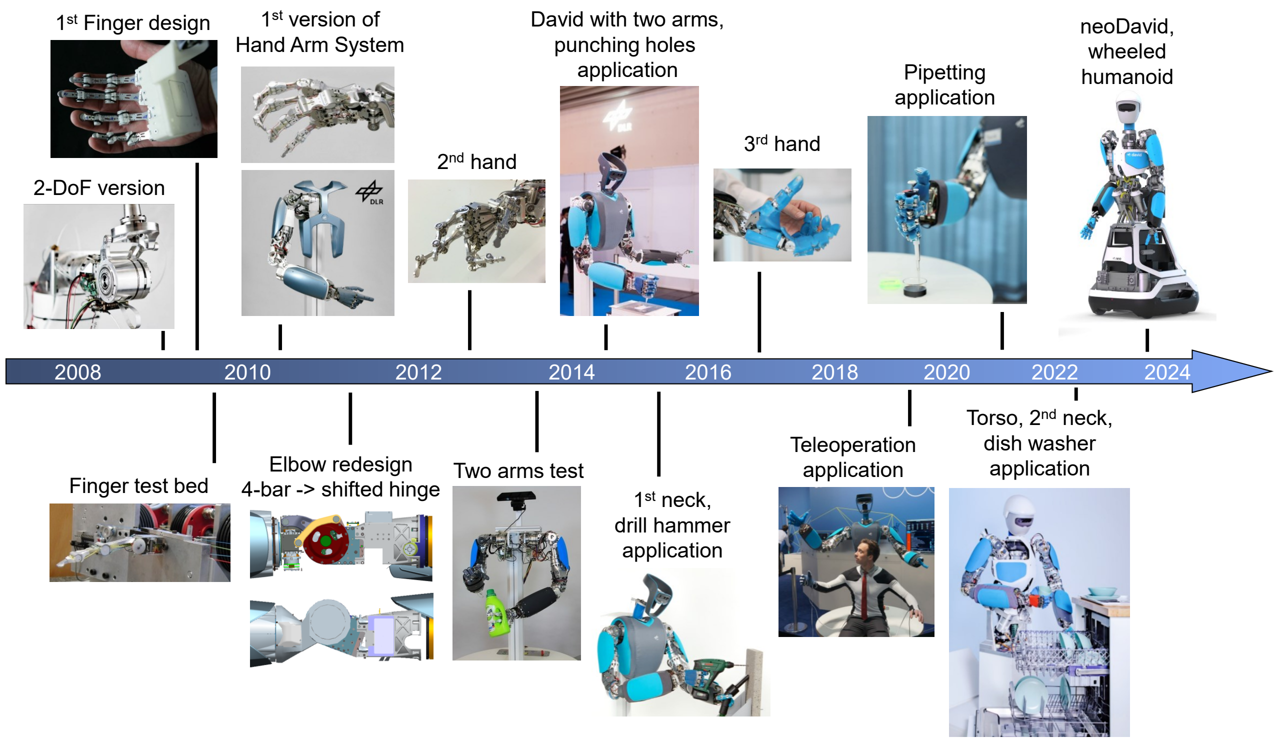

Fig. 1: Evolution steps of the wheeled humanoid robot neoDavid.

robot's hardware and control system into smaller, more manageable modules that can be designed, tested, and optimized independently before being combined into the complete system. Overall, modularity allows for greater flexibility and expandability in the design of the robot and makes it easy to build testbeds and transfer technology to other robots, e.g. DLR MIRO [7] and TINA [8].

A. System Architecture

The depth of development ranges from mechatronics, over skills to applications, and interaction with the human. In order to give an overview of the involved topics and communication structure, as can be seen in Fig. 2, we classified these in system architecture layers:

- The lowest level with mechatronics including the physical manifestation, firmware, and middleware.
- The behavioral control layer with skills that are needed to fulfill a task and low level data processing software.
- The executive layer in which we develop our applications or demos and coordinate the skills to achieve a task.
- The task planning layer with scheduling, high level task priority handling, and human robot interaction.

Our main research activities are on the mechatronic and skill level, as indicated in orange in Fig. 2. Though, during development of the individual research topics we always keep in mind the big picture of sufficient reliability and compatibility with each other to achieve an additional value in the application. Suitability for a higher level application helps the individual research topics to focus on practicability and naturally increases relevance in the related research field.

B. Mechatronics

Mechatronics was the main research focus at the beginning of development. Consequently, many innovative developments have been made in this area.

1) Kinematics: The first public presentation of the system in 2010 had one right arm with 7 DoF and one right hand with 19 DoF, called the DLR Hand Arm System, which is described in [9]. During development, the system was significantly expanded to include a 5 DoF left arm with an 8 DoF two-finger hand, a 3 DoF neck, and a 3 DoF torso. The arms are mounted with quick-lock couplings to the torso and also the forearms and neck can be separated from the system as fully functional units by a flange and two connectors. These extensions significantly increased the capabilities and motion range of the system, but also added many motors and sensors. Therefore, the complexity of the system increased dramatically.

The right hand received two updates with changes in the thumb and little finger kinematics as well as changes in the stiffness couplings in ring finger and little finger. These changes affected the tendon number and routing from the forearm, where the actuators for the fingers are located, to the hand. All these changes could be performed without a redesign of the forearm mechanics or the forearm PCBs.

The end result of these developments was an upper body that came as close as possible to human capabilities. The next logical step was to add a lower body to the existing robot to create a fully humanoid robot that could be operated in a human-like environment, significantly expanding the robot's workspace. The analysis of this environment was based on the mentioned targeted applications in the field of

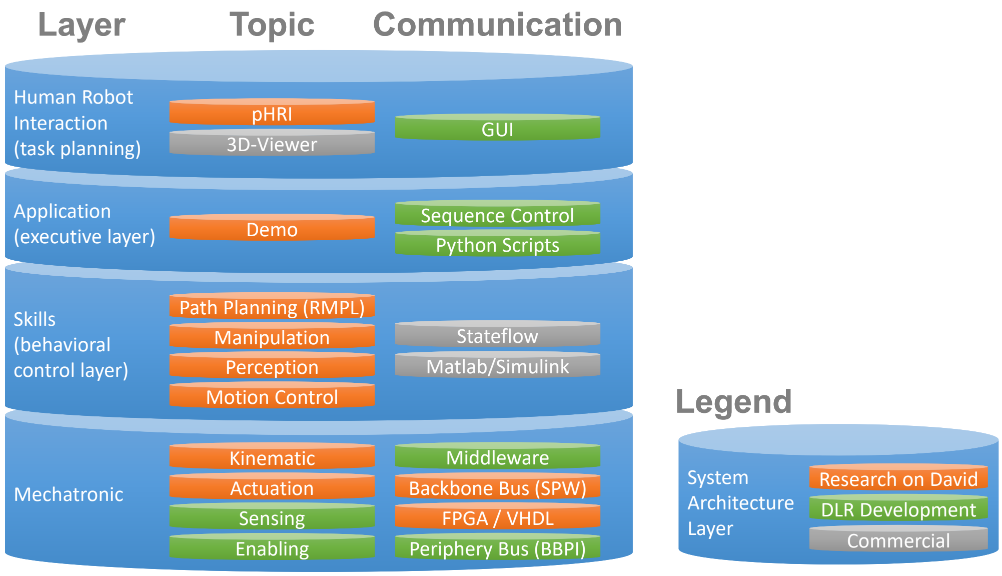

Fig. 2: David's system architecture and research focus.

service robotics and craftsmanship. The result of the analysis provided the requirement for the humanoid robot to be used in an unobstructed environment. An efficient solution to meet this requirement is to use a wheel-based lower body, which makes the robot mobile. An already existing mobile platform was chosen for economic reasons. We selected the third-party product MPO-700 from NEOBOTIX because it directly met the requirements of the intended humanoid robot:

- The size
- Omnidirectional driving
- Soft movements in all directions due to its conventional wheels
- Capability to carry the weight of the planned payload
- Possibility to either use the built-in ROS 2 platform pilot or directly control the wheels and steering with an own controller

As a result, neoDavid, the new wheeled humanoid was developed, see Fig. 1.

2) Actuation: We distinguish between electric nodes that control and supply the mechatronics, the motor and VSA modules, and the communication infrastructure.

a) Electronic modules: Our electronics are clustered into local nodes, which are located in several actuators, links, and body parts.

The David digital inverter electronic node is an integrated inverter module consisting of a base power supply module and up to three stacked smart inverter modules - one smart inverter module per actuator, see also Fig. 3. The power supply module contains the dc/dc converters, each smart inverter module contains a motor inverter as well as a FPGA based digital electronics part. The FPGA comprises the motor control firmware module as well as the sensor communication and SpaceWire backbone communication interface.

The forearm electronics node is also equipped with FPGAs and inherits the motor module and sensor communication as well as the SpaceWire backbone communication interface.

The Power Management (PM) base technology, developed in-house, is used to power the individual electronic components (local nodes). The PM is a modular power infrastructure consisting of three hierarchies of components.

Firstly, a modular high power infrastructure. This is a back-plane (BPL) with a motherboard-style structure. It combines a high-current rail with a communication and synchronization interface that is designed to be quickly and easily expandable. The BPL provides multiple slots for edge contact strips.

The second level is the Base Module (BAM). The BAMs handle the internal housekeeping, which includes the internal communication between all the base modules, such as the distribution of fault conditions. This includes the ability to safely shut down associated components in the event of a fault or to switch to redundant branches in critical infrastructures, as well as monitoring relevant parameters such as input voltage or temperature. Internal communication within a base module is used to communicate with a function module. Several function modules can be used on one base module. It is also possible to use different function modules on one base module. The base module can be rearranged as required within the BPL infrastructure and individually adapted to the task. The function boards on a base module can also be arranged in any order.

The third level consists of the function boards mentioned above. The required output power is generated, made available, and monitored according to the needs of a local node. Several different function boards are used in neoDavid. Three examples are described here:

- The Circuit Limiter (ICL) is a two channel soft start switch with an integrated electronic fuse that can safely start and operate up to 20 mF capacitors in less than 200 mS.
- For the Buck Control Units (BCU), a two-channel

- DC/DC converter, each channel is fully and individually parameterizable.
- The Input Conversion Unit (ICU) is a bi-directional buck-boost DC/DC converter for integrating different power sources. Due to its open configurability, it can be individually adapted to the respective input sources.

If the power available from one channel is not sufficient, performance can be increased by paralleling function modules. This can be done in one function module or across multiple function modules that do not need to be on the same BAM.

b) Motor modules: We used three different types of motor modules in the mechatronic design of neoDavid.

- neoDavid utilizes as main motors TQ-Robodrive ILM50x14 in the arms and the ILM70x18 in the torso, as it requires higher torque. Both motor modules feature a commutation sensor and rotor bearings.
- A miniservo motor module based on the TQ-Robodrive ILM25 series was developed, which includes a power electronics PCB with integrated commutation sensor and a FPGA-based digital electronics PCB, which are directly included in the module. The module is used as stiffness adjuster motor in the Floating Spring Joint (FSJ), and in addition as the main drive in the forearm and finger actuation.
- The neck of neoDavid is driven by Robotis' Dynamixel MX servo drives, because of the low demands on the torque density and control bandwidth in the neck. The servo drives are controlled by the real-time computer via an RS485 interface.

c) Actuators: The neoDavid actuator modules can be divided into the following groups:

- In neoDavid, the FSJ is implemented in the 3 shoulder joints of each arm and in a special hinge joint version in both elbows, see Fig. 3 and [10].
- Two different Bi-directional Antagonistic Variable Stiffness actuator (BAVS) implementations are developed for the wrist and forearm rotation of neoDavid. This concept is an extension to an antagonistic actuator, see [11].
- A variable stiffness spring element for tendon driven joints such as neoDavids (AWIWI) hand is the Flexible Antagonistic Spring (FAS), which are actuated by an antagonistic concept, see [12].
- The structure elastic neck unit with 4 internal tendons can be seen as a 3 DoF actuator and is driven by pulleys on the Dynamixel MX servo drives. Robustness is achieved not by the inelastic tendons, but the elasticity of the silicone structure, see [13].
- The tendon actuators of the torso have an overload coupling in series to the gear box to make it robust to external impacts, see [14].
- The motor is directly connected by a gear to the output. This setup is implemented in the 3rd axis of the torso and in the MPO-700. The MPO-700's wheel modules have 2 DoF with an off-centre vertical sear axis, driven by Elmo Motion Control's Whistle 10/60.

3) Communication: Discrete time systems such as neoDavid and its subsystems (torso, neck, right arm, left arm, right forearm with hand, and left forearm with two-finger hand, mobile platform) can be approximated by continuous time systems if a sufficient sample rate can be guaranteed [15]. This is beneficial to apply well known control approaches and stability considerations from continuous time domain. Therefore high main control loop frequencies are necessary. Hence, this leads to tough requirements to the communication system regarding low latency, time distribution and synchronization of all involved sensors and actuators.

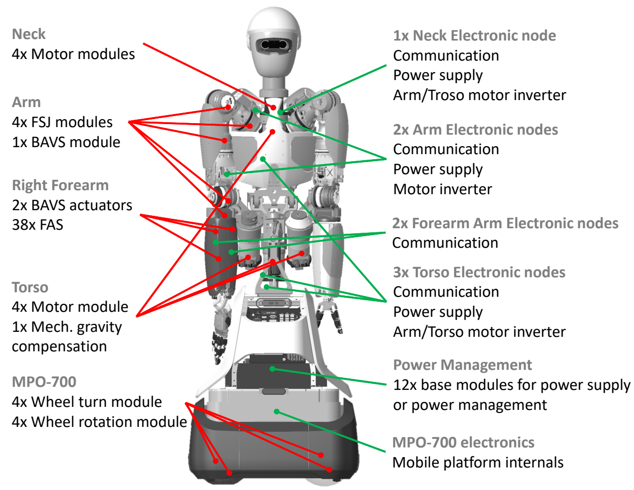

Fig. 3: The actuators (red) and electronic nodes (green) of neoDavid. For sake of simplicity neoDavid's left arm and hand components are not labeled.

The present version of the upper-body David consists of 170 position sensors, three force sensors, and 84 actuators as well as housekeeping sensors (temperature, current) of all installed printed circuit boards (PCB). The newly integrated mobile platform NEO has additional 8 motors and 8 position sensors in the four 2-DoF wheels. neoDavid is still under development. Therefore, customization and extensibility have been taken into account. In addition, computing trends such as Big Data and data mining etc. should also be considered. As a result the communication system has to be hierarchical, scalable, flexible, and modular.

To provide a high degree of flexibility, adjustability, and expandability field programmable gate arrays (FPGA) are used as the core component of each electronic module. As communication backbone SpaceWire is used since it fulfills according to [16] all above mentioned requirements:

- small footprint, little resources, easy to implement on FPGAs
- supports arbitrary network topologies
- infinite number of participants
- no restriction regarding packet length
- supports deterministic communication
- provides time distribution
- reconfiguration of network routes and runtime
- low latency and high bandwidth with an adapted physical layer [17]
- expandable for higher level protocols

For peripheral communication bidirectional bit pipeline interface (BBPI) is used. BBPI is a proprietary development based on FPGA especially designed for the resource saving communication with sensors and actuators. It is a single master multi slave communication, which is chainable inside the FPGAs as well as on connector level or variations of both. BBPI also supports position determination in the chain. Each channel (data exchange between a master and a slave) is secured by an eight bit CRC.

Each main control loop cycle is initiated via SpaceWire time distribution mechanism. Alternatively, to further reduce system jitter due to communication delays globally synchronized local clocks presented in [18] can be used. The interface to real-time host (standard PC with real-time Linux) is a PCI-Express card [19] which enables implementation of the SpaceWire approach also in software as a Robotkernel (our in house hardware abstraction layer approach) module. The overall communication approach can be described as asynchronous event-based hardware triggered. With this approach it is possible to run the upper body David with all involved subsystems and combinations of them in a main control loop frequency of up to 10 kHz. The flexibility and versatility of the communication approach was shown by introducing Big Data to the communication approach. We developed a real-time data miner that records all incoming and outgoing packets of the robot without affecting the determinism of the system.

David is not only mechanically an assembly of subsystems, i.e. torso, neck, right arm, left arm, right forearm with hand, and left forearm with two-finger hand, it has the same module borders in terms of real-time (RT) computation and control, see Fig. 4. Each of the subsystems can be seen as an individual robot of the whole David collective, which has its own RT computer connected via SpaceWire.

The communication between the RT computers is managed via Links & Nodes which is a middleware to create and manage flexible distributed real-time systems. It was created to develop and control embedded robotic systems. Links & Nodes provides deterministic and fast real-time communication between processes on a service or publisher/subscription basis.

The challenge in developing neoDavid was to integrate the additional communication with the MPO-700 platform into the David collective. Like the other subsystems of neoDavid, the mobile base is implemented as an individual robot with its own RT computer. We use the on-board computer of the MPO-700 as this RT computer. Communication with this RT computer is not via SpaceWire, but via ROS topics over a LAN connected to Links & Nodes.

III. Discussion

The hierarchical bus system with enough margin in terms of bandwidth, latency, and participant number was a key feature to the gradual extension of the system, as it would have been changed only at very high cost and effort. It is easily reconfigured, e.g. automatic detection or by a configuration file, which safes a lot of time during development.

Having individual RT computers and controllers for subsystems, e.g. arms and torso, makes debugging easier, development faster, and experimental setups for publications more efficient, as they can be modified and turned on/off without affecting the whole system.

We designed the system with electronic nodes that cluster the PCBs of multiple actuators, see Fig. 3. The power and communication cables run from one PCB cluster to the next over multiple joints and links. The advantage of this design is that there are only a few connections in series, which results in a very compact design, high power density and low losses in communication bandwidth and power transmission. However, this is at the detriment of modularity, because each actuator has individual cables running to these nodes, and it also makes maintenance more difficult. *Lesson learned:* The cabling should not be a single or just a few wiring looms, but if possible only connect as a bus from instance to instance (e.g. actuator to actuator to actuator, ...), not over multiple joints and links. More generally expressed, the physical borders of modularity in different domains should be at the same places.

We decided to have the forearm structural part with all the FAS and Miniservo motor modules, as well as the digital electronics for the forearm, as only two parts for the entire hand actuation. This allowed a very high power density and compact outline. However, this was at the cost of modularity and a rework would be very time consuming. As a consequence there were no iterations so far and small bugs of the first version still remain.

The use of a third-party product like the MPO-700, which appears as a black box with its own software in the overall system, does not fit well with the approach of breaking down the robot's hardware into small, manageable modules, nor with the concept of reusing mechanical and electronic parts in multiple locations and using common hardware modules and modular software. The big advantage of quickly integrating a reliable industry standard system, as opposed to the investment that would have been required to develop a new in-house platform based on existing mechanical and electronic parts, was the driving force behind this decision. Furthermore, rapid expansion of the robot's workspace is a great asset for research in the three fields of skills (layer 2), application (layer 3) and human robot interaction (layer 4), which exceeds the necessity for more research in the field of mechatronics (layer 1).

IV. Conclusion

We successfully planned, designed, and built the modular humanoid robot neoDavid. It was shown that our modular approach in mechatronics, communication, and control scales even over the firstly unplanned extension from a right hand and arm robot to a full humanoid upper body on a wheeled platform with modified kinematics. The modularization in terms of mechatronics, communication, and system architecture is presented and discussed.

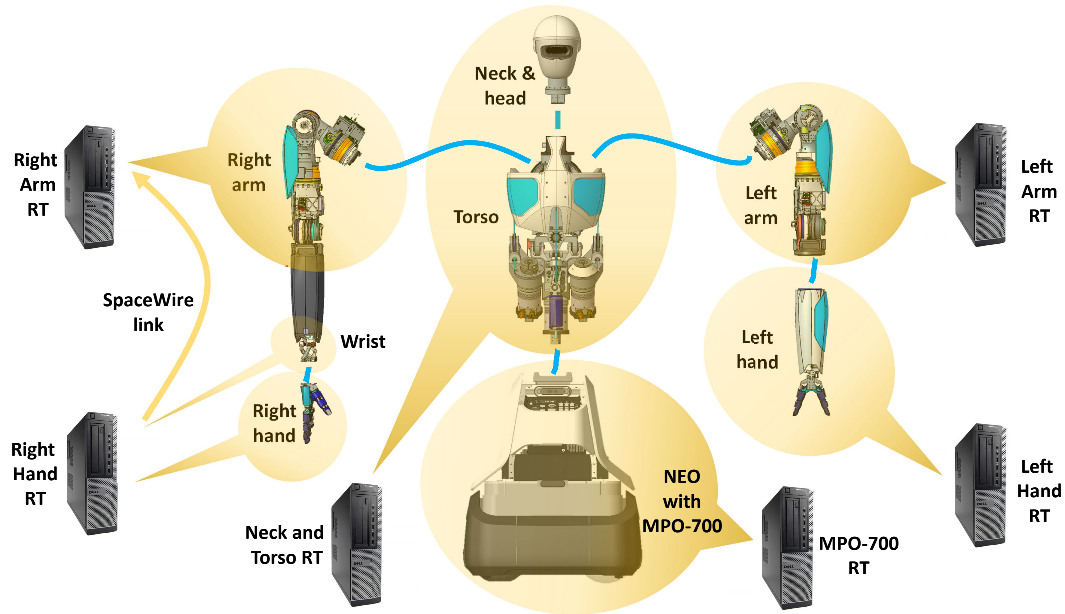

Fig. 4: Subsystems of neoDavid and their real-time computer nodes and distribution. Information from the right wrist is transmitted directly via SpaceWire to the right arm computer to provide 7 DoF arm control without time delay. In the NEO mobile platform, an additional non-real-time PC is used for localisation and path planning.

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