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CENTAURO

Deliverable D2.2 Prototype of Upper Body of CENTAURO Robot

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0.2	2016-08-14	Nikos Tsagarakis, Lorenzo Baccielere	Added actuation system description
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Executive Summary

Within WP2 the main design activities during the first period of the project was related to the development of the upper body of the Centauro robot. The first main result from this effort is the demonstrator prototype of the CENTAURO upper body. This report provides the details of the design and development of the upper body demonstrator. In particular, the report presents an overview of the upper body features, including its general dimensions and weights and a description of its kinematics. The mechatronics of the entire upper body prototype are introduced. This includes the working principles and implementation of the series elastic, torque-controlled actuators developed. We present CAD documentation details and real assembly images of the actuation modules and the perception subsystems including the custom joint torque sensing and the 6 DOF force torque sensors installed at the wrists of the upper body. Further, the design approach of the upper body structures and the whole upper body assemblies are presented. Finally, some preliminary validation results of the joint torque sensing element and at the individual joint level are included.

Contents

1 Introduction

The overall goal of workpackage WP2 is development and test of the CENTAURO robotic platform. To achieve this, one of the main objectives of the workpackage is to design and fabricate all the necessary mechatronic components and finally assemble them to realize a functional CENTAURO robot prototype in two design iterations.

In particular within WP2, Task T2.1 focuses on the design and realization of the CENTAURO robot. Starting from the project objectives and desired functionalities, including locomotion and manipulation in unstructured workspaces, payload capacity, and interaction with the environment, the robot specifications were drawn and the specific design requirements were derived. Following this, the design activity started and during the first period was devoted on the development of CENTAURO upper body. This encompasses the development of the soft actuation system to be used in the arm joints, the design and realization of the torso module and the two manipulator arms. The first outcome of task T2.1 is therefore the release of CENTAURO upper body.

This report describes the construction and the interfaces of the prototype of the upper body of the CENTAURO robot. The document provides details on the solution adopted for the realization of the compliant torque controlled actuation system, the design and implementation of the arm kinematics and finally the integration of the two arms with the torso module.

Please also refer to the CENTAURO Grant Agreement [3].

2 Overview of CENTAURO Upper Body

Starting from the robot design specifications presented in deliverable D2.1 [1], the realization of the upper body design was executed to satisfy these design requirements. In particular concerning the manipulation requirements, two objectives that strongly influenced the robot and actuation sizing were

- the ability to perform powerful and robust manipulation with payloads up to 10Kg on a single arm and
- the capability of reaching objects on a shelf of 180cm height.

To meet the workspace and payload requirements of these foreseen manipulation tasks, the size of CENTAURO upper body approximates the dimensions of an adult human. The height of CENTAURO upper body from the pelvis to the shoulder centre is 250mm. The width between the two shoulders centres is 590mm and the depth (front/back) is 240mm. The approximate size template is shown in Fig. 1. As it can be seen, given the expected size of the lower body, the arm length was defined in the range of 60 to 70cm. The precise major dimensions of the upper body and arm segments are depicted in Fig. 2. More details on the arm size and kinematics are provided in the following section.

The total weight of CENTAURO upper body is 21Kg, distributed to 17Kg for the two arms and 4Kg for the torso structure. The CENTAURO upper body prototype has 15 DOF. Each arm has 7 DOF. For the trunk there is an additional 1 DOF that permits the yaw motion of the entire upper body and extends the manipulation workspace of the robot.

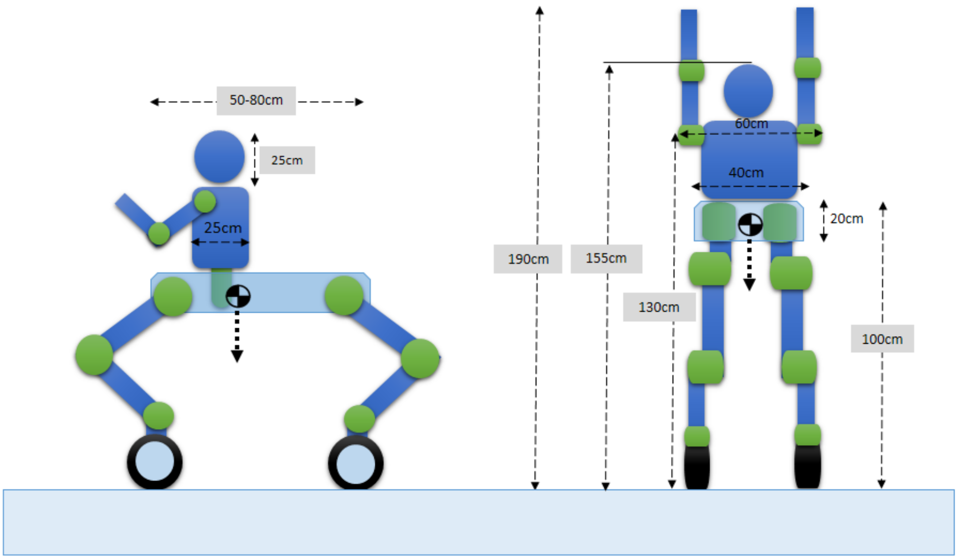

Figure 1: CENTAURO arm kinematic features.

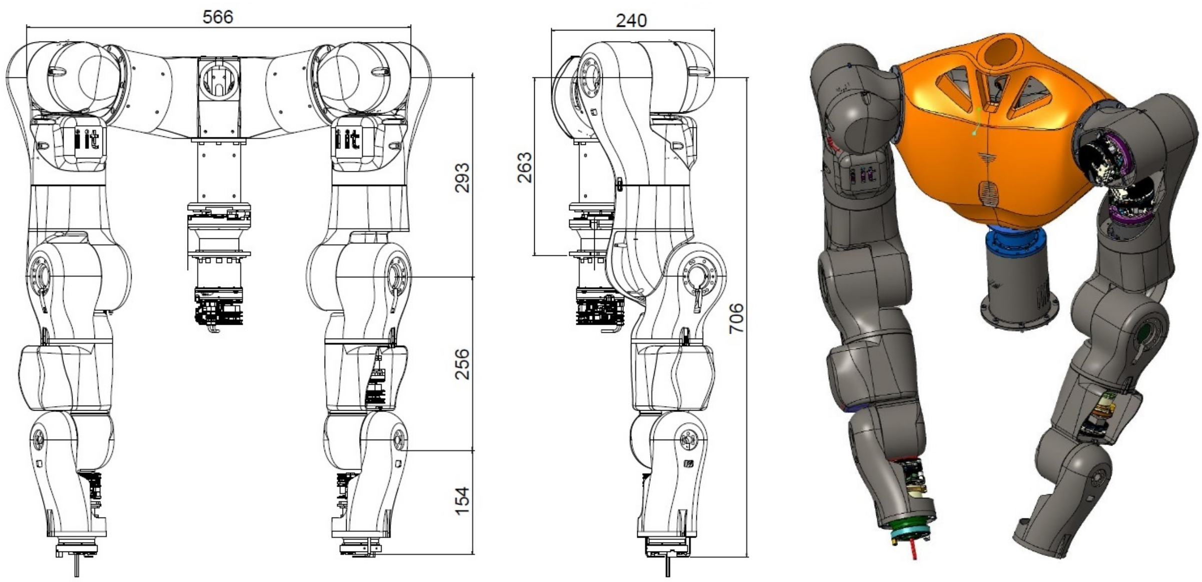

Figure 2: CENTAURO upper body size specifications, all dimensions are in (mm).

3 Arm Kinematics

CENTAURO arm kinematics closely resembles an anthropomorphic arrangement with 3 DOF at the shoulder, 1 DOF at the elbow and 3 DOF at the wrist, illustrated in Fig. 3. This is a typical arm configuration that will provide the humanoid upper body of CENTAURO the ability to manipulate the environment with adequate dexterity as well as using the one additional degree of redundancy in the arms to cope with constraints that may be introduced in the task space by the surrounding environment. Even though this is kind of a traditional design that aims at replicating the anthropomorphic structure of the human arm with 7-DOF, it is only approximately equivalent for the human arm kinematic structure. Indeed, humans have the ability to elevate (upward/downward) and to incline (forward/backward) the shoulder joint, utilizing supplementary kinematic redundancy of the arm to achieve certain goals in task coordinates. In the CENTAURO robot, this will be achieved by an additional DOF between the base and the upper body, and by using the DOFs in the legs. Fig. 4 shows the images of the manufactured CENTAURO arm prototype.

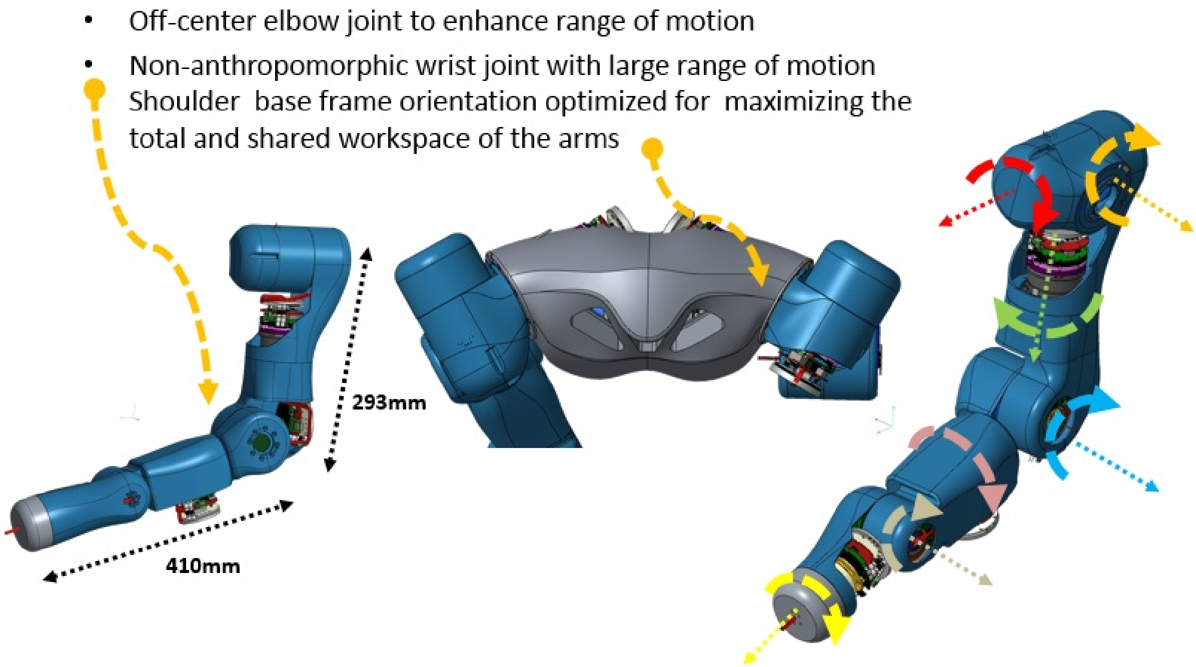

Figure 3: CENTAURO arm kinematic features.

Figure 4: CENTAURO arm prototype.

4 Shoulder Frame Orientation Optimization

To derive the values of the upward angle and forward angle of CENTAURO shoulder frame, Fig. 5, we perform an optimization in which important manipulation indices were considered and evaluated in a prioritized order, taking into account representative target tasks.

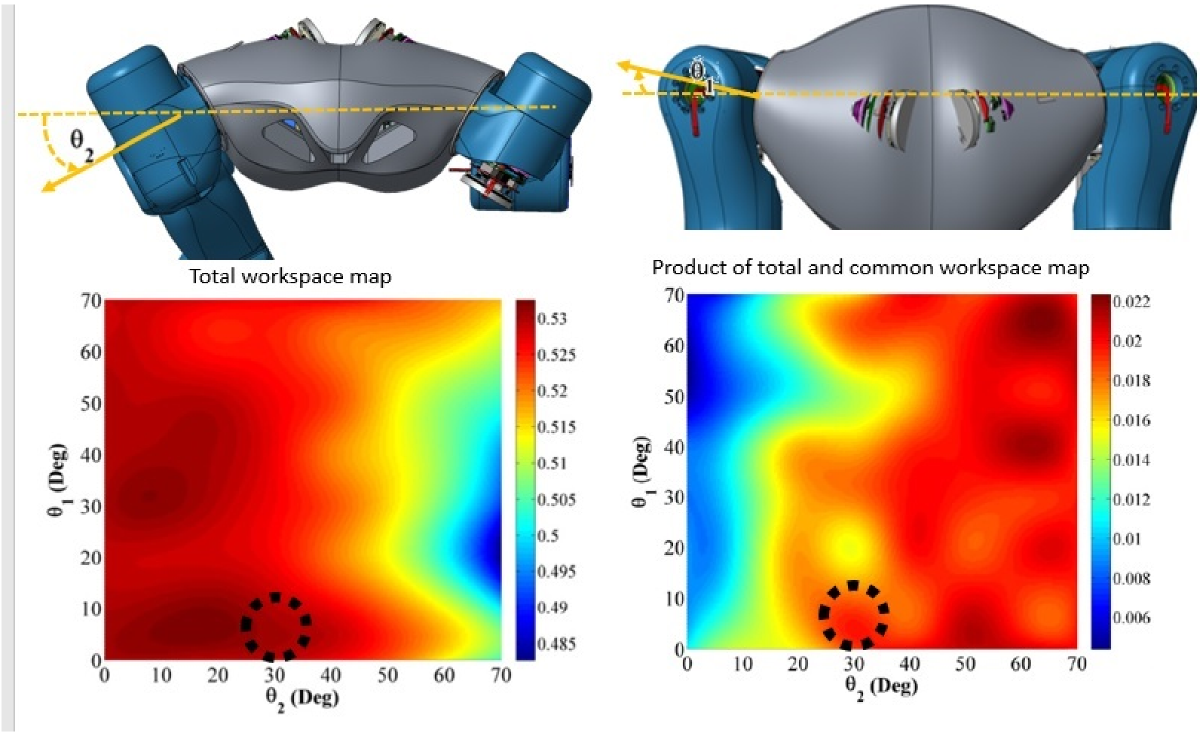

Figure 5: CENTAURO arm shoulder frame upward and forward angle selection.

The range of motion for the joints of CENTAURO arm was defined considering human ergonomic data, data from other successful humanoid bi-manual systems and simulation studies of a number of manipulation tasks. It is reported in Table. 1. The range of motion of the standard human arm was used as a starting point. Wherever it was possible, a greater range of motion with respect to human arm range was considered to enhance the motion and manipulation capability of the arm. In particular, the range of upper and lower arm rotations were extended. Similarly, the range of the elbow joint was increased by considering an off-centre elbow joint arrangement that results in a wide elbow flexion with respect to human elbow flexion. Finally, the wrist flexion joint range was also extended to provide a larger range than that of the human wrist flexion. Fig. 3 illustrates the arm kinematic arrangement.

5 Upper Body Actuation System

The realization of the arm was based on the integration of seven series elastic actuator (SEA) units along the kinematic chain of the arm. The arm actuators, shown in Fig. 6, are based on a design principle which incorporates a series elastic element. The SEA technology is used to protect the reduction gear against impacts while at the same time it is used for measuring the actuator torque through the monitoring of the elastic element deflection using high resolution (19-bit) absolute encoders. For the interconnection of the actuator units, the arm design followed an exoskeleton structure approach in which the body of the actuators are floating

Table 1: Specifications for the joint range of motion.

	Human	CENTAURO
ARM	Range of motion (°)	
Shoulder Flexion/Extension	+180, -80	+210,-110
Shoulder Abduction/Adduction	+180, -50	+200,0
Shoulder Rotation	+90, -90	+150,-150
Elbow	+145, 0	+145,-20
Forearm Rotation	+90, -90	+150,-150
Wrist Flexion/Extension	+90, -70	+90,-90
Wrist Rotation		+150,-150
WAIST		
Waist rotation	+80, -80	+150,-150

inside this exoskeleton structure while the actuator is fixed to the link structures. Fig. 7 shows the manufactured actuation units of the forearm and upper arm/elbow joints.

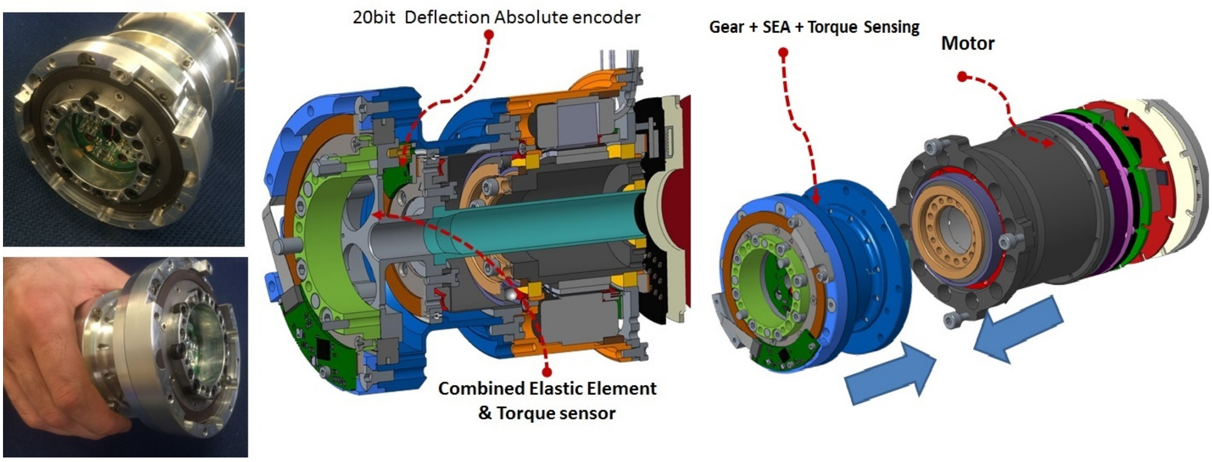

Figure 6: CENTAURO series elastic actuation module.

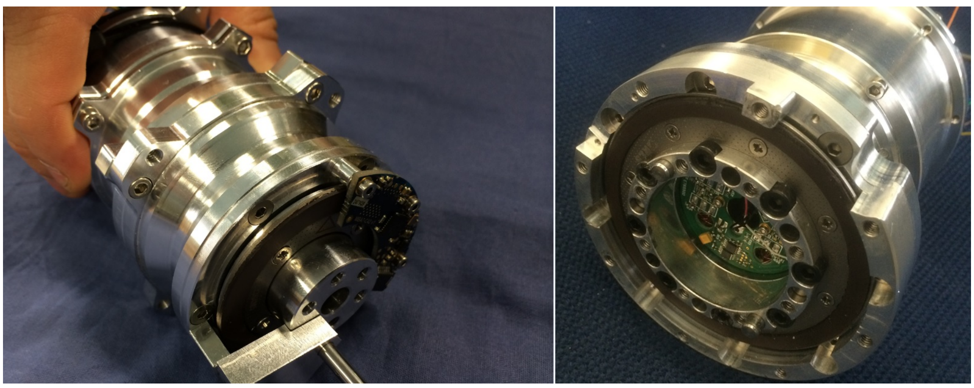

Figure 7: CENTAURO actuation units, on the left the forearm actuator and the on the right the unit used on the shoulder and elbow joints.

6 Upper Body Perception System

6.1 Joint Torque Sensing

Joint torque measurement in CENTAURO upper body is achieved by measuring the deflection of the series elastic element that has a known stiffness. The stiffness of the series elastic element of the arms, shown in Fig. 8, in the first release of the CENTAURO upper body, was defined on the basis of required torque measurement resolution along the different joints that was set to 10 times lower than the cogging torque of the motor drive of the joint.

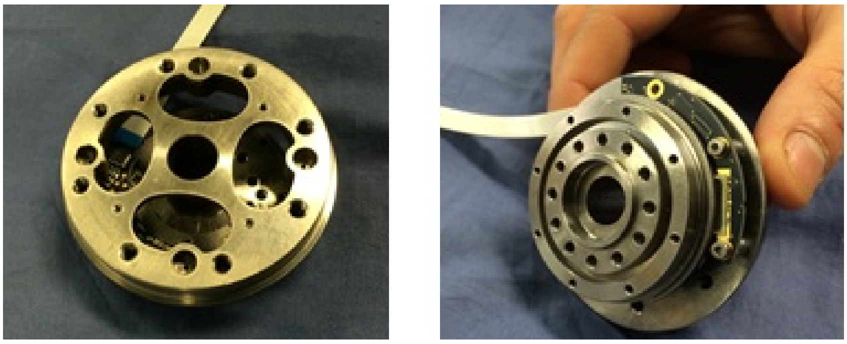

Figure 8: CENTAURO series elastic element and joint torque sensor.

Following the assembly of the actuator unit, an identification process was carried out to verify the deflection response of the elastic element subject to external loading and derive the precise stiffness level of each series elastic element. Fig. 9 shows a typical response of one of the shoulder actuators demonstrating a liner behaviour and a stiffness level of $4502\ Nm/rad$. The theoretical tuned response of the element through Finite Element studies is also plotted as a comparison. The FEM estimated stiffness is $4096\ Nm/rad$ which is 9% lower than the experimentally obtained.

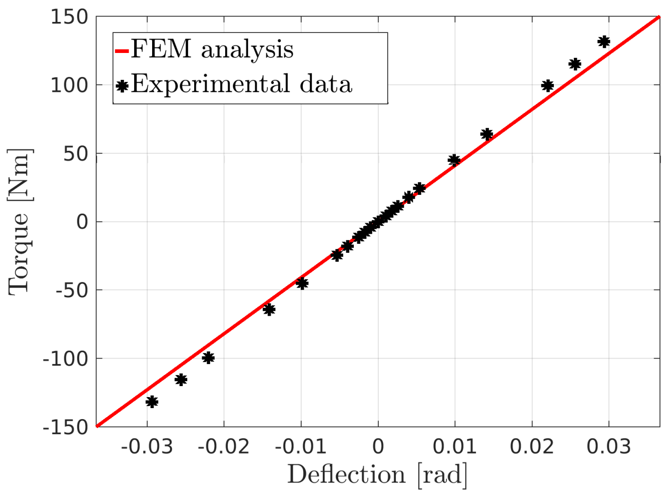

Figure 9: Series elastic element response to applied load.

6.2 Force and Torque Sensing at the End-effectors

In addition to the joint torque sensing and for the purpose of monitoring the integration forces at the end-effectors of the robot, we designed and developed customized 6-DOF Force/torque (FT) sensors, shown in Fig. 10, to tightly integrate this perception feature at the wrists of CENTAURO robot. It is based on a 3 spoke structure where 6 pairs of semiconductors strain gauges are mounted to measure the strain generated on the load cell as a response to the load applied. The sensor is made by stainless steel (17-4H) and has a torque measurement range operation of 40Nm around the three axes and a force range of 1500N along the three directions. The sensor has integrated data acquisition and signal conditioning electronics and communicates with the rest of the system using the same EtherCAT bus accommodating the interfacing and the low level communication.

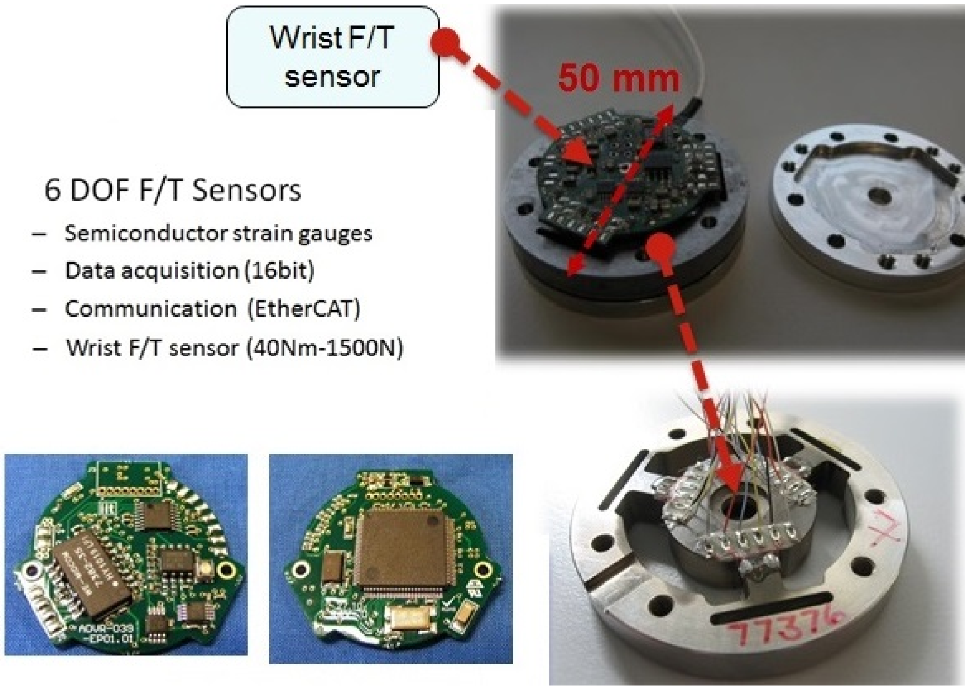

Figure 10: CENTAURO custom 6-DOF FT load cells.

6.3 Inertial Measurement Unit (IMU)

The CENTAURO upper body also incorporates an inertial measurement unit installed at the centre of the torso module to monitor the torso state in terms of acceleration and orientation. We selected a VectorNav IMU:Model VN-310 Dual GNSS/INS unit that incorporates 3-axis accelerometers, gyros, magnetometers, a barometric pressure sensor, two GNSS receivers, and a low-power micro-processor into a rugged aluminium enclosure, Fig. 11. The IMU offers an RS422 interface. To facilitate the integration in CENTAURO without additional communication wires, we developed a customized EtherCAT to RS422 device that converts the IMU device to an EtherCAT slave and permits the incorporation of the IMU in the EtherCAT network of the robot.

6.4 Vision-Perception Subsystem

The vision-perception system of CENTAURO is a module that combines three main sensors:

- An RGB-D sensor,
- A set of three color cameras, and
- A LiDAR sensor.

The integration of the three sensors on the vision-perception subsystem is shown in Fig. 12. As it can be seen the vision-perception subsystem incorporates a Kinect 2 sensor at the lower layer mounted on a 2-DOF mobility platform that permits the yaw and the pitch motions of this RGB-D sensor. Above the Kinect 2 sensor on the second level, an array of three colour cameras (PointGrey BlackFly BFLY-U3-23S6C wide angle cameras) are installed. They cover a combined panoramic filed of view of approximately $100 \times 200°$. Finally, in the top layer a 3D LiDAR sensor (Velodyne PUCK sensor) is installed and continuously rotates to provide spherical coverage of the environment around the robot.

The design of the vision-perception subsystem has been finalized and its production will start soon. It will be finally integrated on the top side of the torso module to form the overall assembly of the upper body system.

Figure 11: The VectorNav IMU unit.

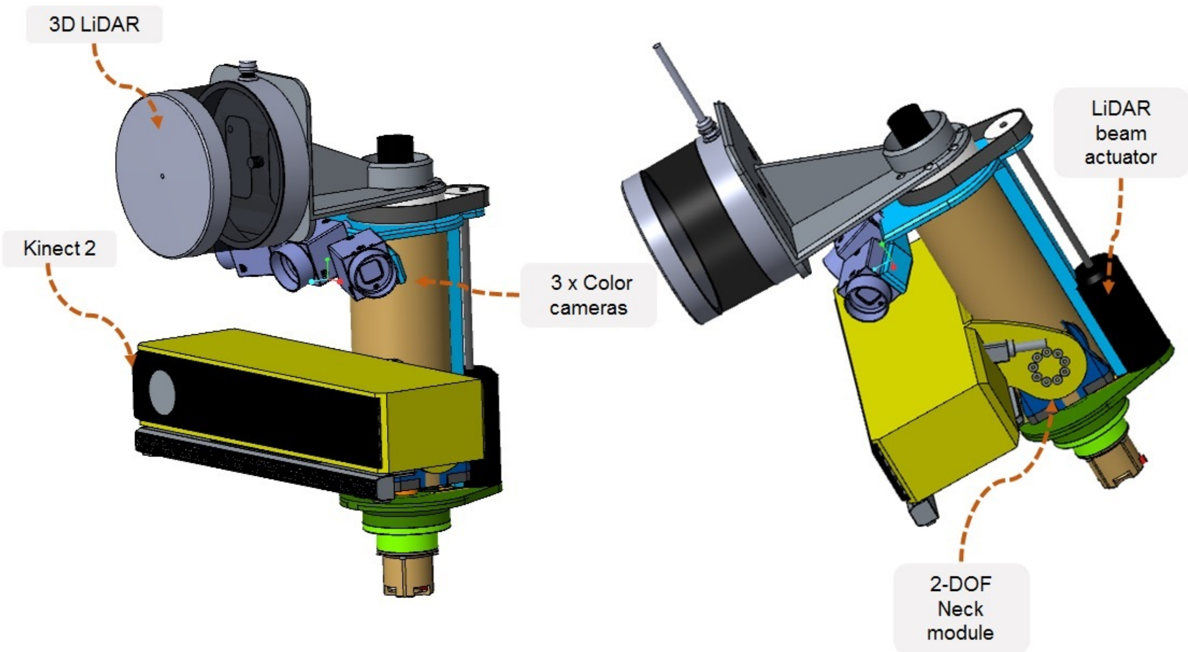

Figure 12: 3D CAD implementation of the vision-perception subsystem.

7 Actuation and Body Structure Interconnection

As mentioned in the previous section, the CENTAURO upper body employs an exoskeleton based structure approach to realize the interconnection between link bodies and actuation modules. Exoskeleton cells have higher structural stiffness and minimize the effect of unmeasured elasticities.

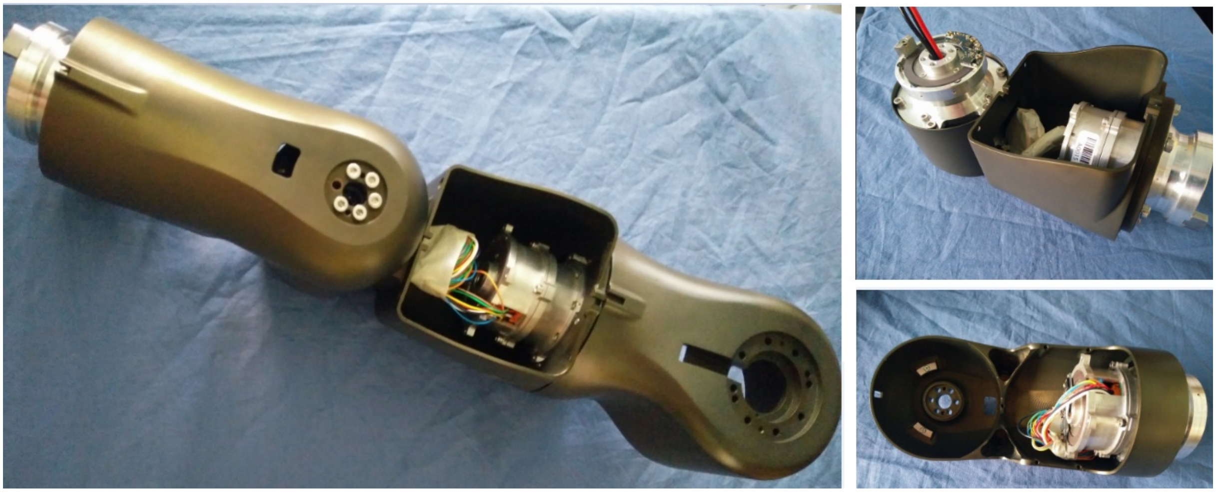

Figure 13: CENTAURO exoskeleton cell structure design principle and floating body actuator integration.

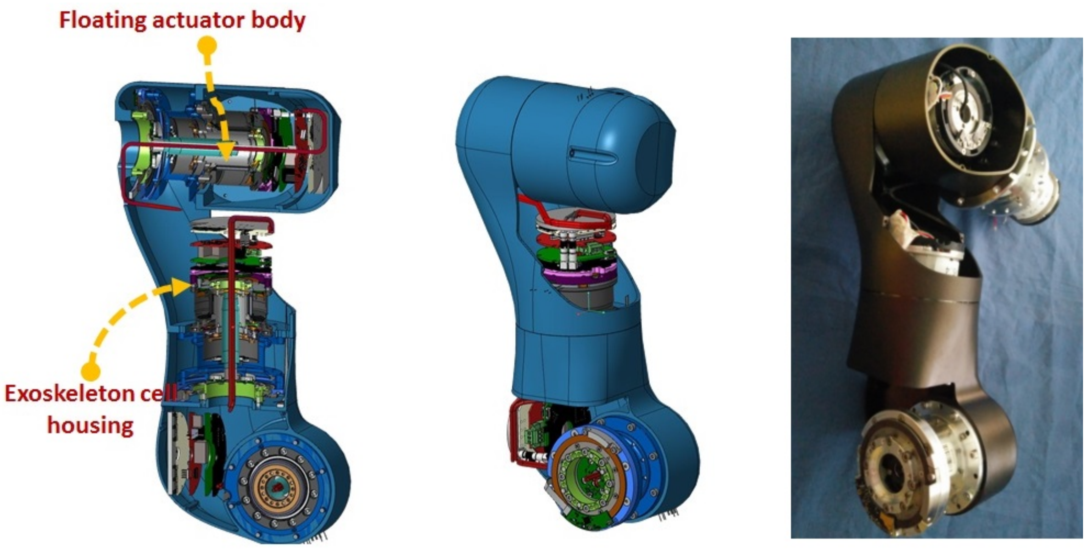

Figure 14: CENTAURO exoskeleton cell structure design principle and floating body actuator integration.

Figs. 13 and 14 introduce this principle of the structure and actuation integration. It shows the integration of the upper arm rotation and shoulder abduction actuators inside the cell type structure of the corresponding sections. As it can be seen, the actuation modules are mechanically interfaced to the exoskeleton cell links using two standard flange interfaces, one fixed to the previous link and the other to the subsequent link.

This exoskeleton structure and floating actuation integration approach offers several advantages with respect to the more traditional endoskeleton interconnection between the actuators and the robot links. Actuator bodies are not subject to loading as torques and forces generated from the joint loading or due to interactions are transmitted only through the two output flanges used to fix the actuator to the structure cell. It therefore allows for optimal and low-weight design of the actuation housing components that are not subject to the joint loading. It is an explicit design concept that the link cells form a wind tunnel around the actuation body that can be used for forced air cooling.

8 Upper Body Control Architecture and Interfacing

8.1 Interconnection of Control Components

A high level schematic of the interconnections of the CENTAURO upper body prototype control, actuation and perception components is shown in Fig. 15. The communication of the higher-level controllers with onboard PCs including Motion PC and Perception/Vision PC is through a GigaBit Ethernet interface. The Motion PC manages the data-broadcasting and centralized actuator control via real-time EtherCAT communication with both high and low power actuator controllers, the Inertial Measurement Unit (IMU) and the FT sensors. The Perception/Vision PC is dedicated to the perception sensors acquisition, including the cameras, R-GBD sensors and the laser scanner, through USB and Ethernet connections.

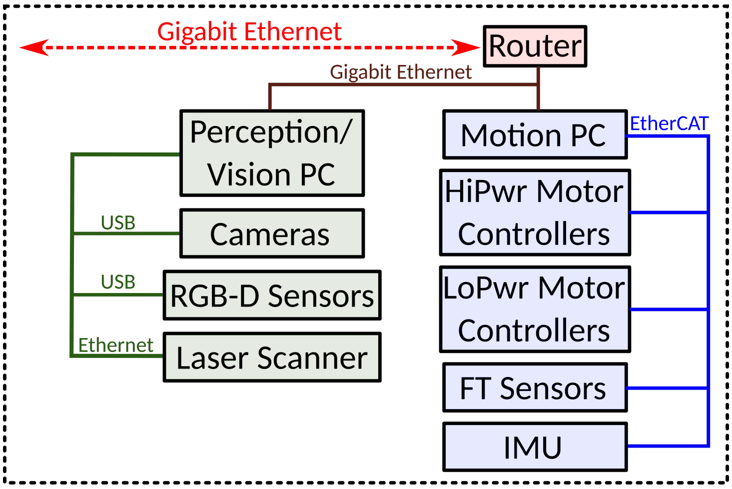

Figure 15: High level schematic of the interconnections of the CENTAURO upper body prototype control, actuation and perception components.

8.2 XBoTCore Control Architecture

For the control of CENTAURO, we have adapted XBotCore (*Cross-Bot-Core*), a light-weight, Real-Time (RT) software platform for EtherCAT based robots developed recently at IIT partially inside Centauro project. XBotCore is open-source and is designed to be both a RT robot control framework and a software middleware. It satisfies hard Real-Time requirements, ensuring 1 KHz hard real time control loop even in complex Multi-Degree-Of-Freedom systems. Moreover, it provides a simple and easy-to-use middleware Application Programming Interface (API), for both RT and non-RT control frameworks. The XBotCore API is completely flexible with respect to the external control framework the user wants to utilize. As shown in Figure 16,

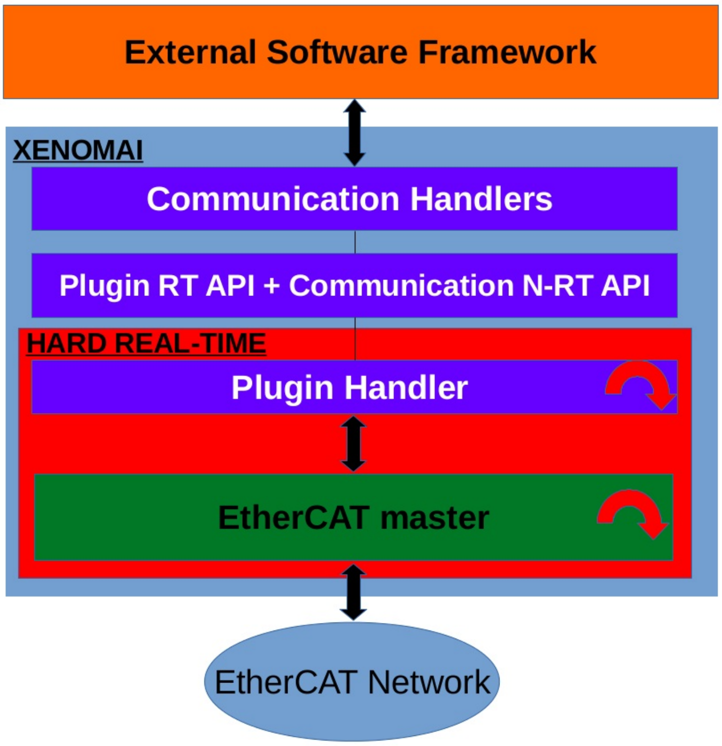

Figure 16. XBotCore components and relationships: EtherCAT slaves network, EtherCAT master implementation with one RT thread, Plugin handler for the RT plugin in the system with one RT thread, RT and non RT middleware API, Communication handlers for the external software frameworks integration and external Software Framework modules.

the following XBotCore components are used: EtherCAT master, Plugin Handler, RT and non-RT middleware API, and Communication Handlers.

8.2.1 EtherCAT Master

The XBotCore EtherCAT master implementation is developed starting from the SOEM (Simple Open EtherCAT Master) library— an open source EtherCAT master implementation, meant to be highly portable on variety of embedded platforms (HW and RTOSes) [2]. The structure of the data flowing in the EtherCAT network is called PDO (Process Data Object) and it has two different sub-structures:

- *PDO RX*: master input, slave output e.g. link position, motor position, motor velocity, torque, temperature etc.
- *PDO TX*: master output, slave input e.g. position reference, torque reference, gains etc.

Furthermore, the XBotCore EtherCAT master provides an asynchronous API to the higher-level components in order to read/write the PDO data.

8.2.2 Plugin Handler

The Plugin Handler is a RT thread that execute sequentially a set of plugins. A Plugin is just an instance of the abstract class *XBotPlugin*. From the user prospective, writing a Plugin is straightforward. He/She needs to implement three functions:

- an `init()` function that will be called only once by the Plugin Handler in order to initialize the varibles of the Plugin,
- a `run()` function which will be executed in the control loop of the Plugin Handler, and
- a `close()` function, called when the Plugin Handler wants to remove the plugin.

8.3 RT and non RT middleware API

XBotCore is a middleware that provides to the user both a RT and a non-RT flexible and easy-to-use API. The RT API is suitable for the RT plugins that will run in the Plugin Handler. It works using a shared memory communication mechanism with the low level RT EtherCAT thread. Examples of interfaces implemented by the RT API include:

- `IXBotJoint` : the abstraction of the robot joints with getters and setters related to the single joint element, e.g. `get_motor_pos()` or `set_torque_ref()`,
- `IXBotChain` : the abstraction of the robot kinematic chain with getters and setters related to a collection of joints e.g. `get_chain_motor_pos()` or `set_chain_torque_ref()`,
- `IXBotRobot` : the abstraction of the robot with getters and setters related to a collection of chains, e.g. `get_robot_motor_pos()` or `set_robot_torque_ref()`, and
- `IXBotFT` : the abstraction of the robot Force-Torque (FT) sensors with the getters related to the single FT sensor, e.g. `get_ft()` or `get_ft_fault()`.

The non-RT API has similar interfaces (i.e. `IXBotJoint` and `IXBotFT`) but the implementation of the functions uses the XDDP (Cross Domain Datagram Protocol) Xenomai pipes to have asynchronous communication between RT and N-RT threads.

The interface of the robot will evolve in the next months of the project in close interactions with the other CENTAURO partners and the requirements of the work plan in workpackages WP3, WP5, WP6 and WP7 adding gradually more functionality. Its documentation will be regularly updated and provided in the repository of the robot control software.

9 Upper Body Demonstrator Prototype

9.1 Fabrication and Assembly

Based on the design principles described above, the mechanical components of the upper body prototype were fabricated. The cell parts of the link structures were made from Aluminium T6-7075 (Ergal). The same material was used for the housing components of the harmonic gearbox and the interface flanges used to connect the actuation module to the link structures.

The mechanical components belonging to the floating part of the actuation body that are not subject to loading were machined using Magnesium Alloy AZ91. The series elastic modules of the actuation system were made using Titanium Alloy that combines high strength with increased elasticity. Finally, a number of no structural maintenance cover parts were made from ABS plastic using rapid prototyping fabrication. The following Fig. 18 demonstrates the first release of the upper body prototype that includes the two arms and the waist joint. Fig. 17 provides a comparison against the arm of an an adult subject of a height of 1.78m. As it can

Figure 17: CENTAURO arm size comparison against an average human arm.

Figure 18: D2.2 demonstrator showing CENTAURO upper body prototype in different arm poses.

be seen, the end effectors of the upper body are not yet integrated. They will be based on commercial robotic hands (Schunk hand and SoftHand modules) which are currently under procurement. The distal flange of the arms provides an easy to adapt mechanical interface that can be tuned to match the mounting interface of these commercial systems. Communication and power cabling has been already taken into account in the arm design to permit the internal routing of the end effector wires through the arm joints and links. In particular, two main cable routes are provided. One through the hollow shafts of the actuators that primarily serve for the routing of default power and communication (EtherCAT) wires while additional cables such as those expected from the hand end-effectors or camera sensors at the forearms are planned to be coiled and routed around the actuator body neck at the level of the gearbox to enable passing through the joints. Mechanical interfaces on the arm cells have been incorporated to allow the fixation of wire strain relief supports prior and after passing through the joints.

9.2 Single Joint Control and Validation

Initial tests has been performed to validate the first release of joint control and its response on individual joints. The schematic representation of the impedance/torque controller implemented in the firmware of the motor drivers is shown in Fig. 19. It is based on a cascade architecture with the inner most loop dedicated to motor current control running at 20KHz. The next outer loop regulates the motor torque. The torque loop runs at 4KHz. It accepts a torque reference commend from the most outer impedance loop and generates a current reference for the current loop. The outer impedance loop runs at 2KHz rate. Currently, the functionality of all actuators of the upper body have been verified including the calibration of the torque sensing and the execution of simple motion trajectories, a typical response of which is shown in Fig. 20.

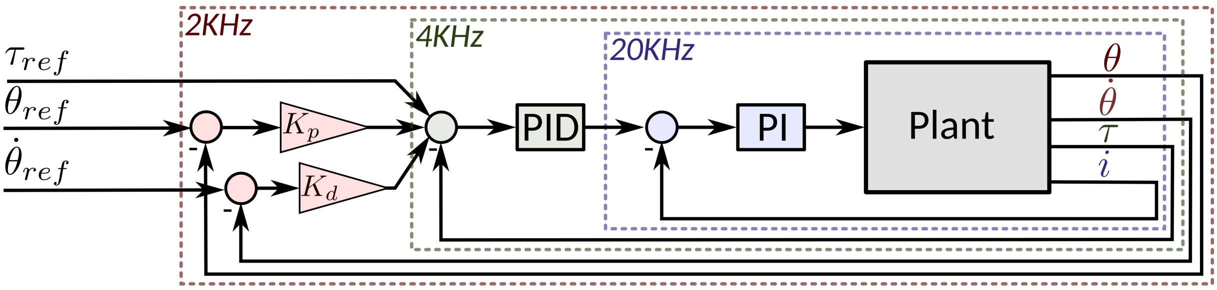

Figure 19: Schematic of the first release of the joint controller.

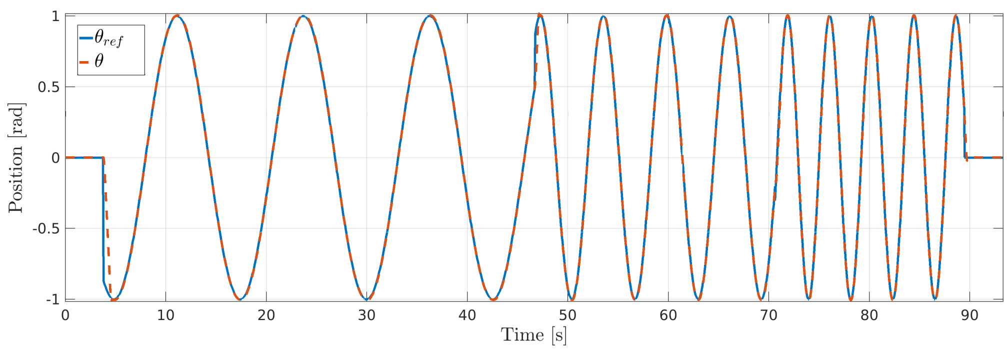

Figure 20: Typical response of the joint controller to a position reference.

10 Future Work

The design and development of the CENTAURO upper body has been mostly progressed as expected with two small deviations of the original plan. These are described below:

- The vision/perception module is being finalized and is currently under construction. The vision/perception module is expected to be ready within the following two months.
- The preliminary evaluation of the upper body has been performed mostly on the actuator level and with passive motions of the arms. The execution of active arm motions will be reported as part of Deliverable D8.2 Evaluation of Core Components.

11 Conclusions

This deliverable presented the first major outcome of WP2 with the realization of the CENTAURO upper body. This first iteration of the upper body was designed to satisfy the requirements of the system as originally described in the technical annex of the project and detailed in deliverable D2.1 [1]. The upper body components were fabricated and the prototype has been successfully assembled. Following efforts will concentrate on the debugging and initial evaluation of the system while executing a set of manipulation tasks under different control modes of operation. The integration of the hands will also occur as soon as the end-effectors will be available. The vision/perception module that is currently under design will be mounted on the top side of the upper body torso.

References

[1] Navvab. Kashiri, Houman. Dallali, and Nikos Tsagarakis. D2.1: Design concept of CENTAURO robot. 2015.

[2] D Orfanus, R Indergaard, G Prytz, and T Wien. EtherCAT-based platform for distributed control in high-performance industrial applications. In *2013 IEEE 18th Conference on Emerging Technologies Factory Automation (ETFA)*, pages 1–8. ieeexplore.ieee.org, 2013.

[3] European Commission Directorate General for Communications Networks, Content and Technology Components and Systems: Robotics. Grant Agreement 644839: CENTAURO—Robust Mobility and Dexterous Manipulation in Disaster Response by Fullbody Telepresence in a Centaur-like Robot, 2014.