THE CAPIO ACTIVE UPPER BODY EXOSKELETON AND ITS APPLICATION FOR TELEOPERATION

Martin Mallwitz[1], **Niels Will**[1], **Johannes Teiwes**[1], **and Elsa Andrea Kirchner**[1,2]

[1]*Robotics Innovation Center, German Research Center for Artificial Intelligence, Bremen, Germany*
[2]*Robotics Lab, University of Bremen, Bremen, Germany*

ABSTRACT

In this paper the active dual-arm upper body exoskeleton *Capio*, its application for the teleoperation of a complex humanoid robot, as well as its use in a virtual environment are presented. The *Capio* exoskeleton is a human-machine interface that tracks the operator's movements and transfers them to a target system. Multiple contact points at back and arms to the user enable a precise motion measurement and allow a specific force feedback. The combination of the kinematic configuration with 20 active serial elastic joints controlled by a rigid body dynamics algorithm provides mechanical transparency. The possibility to move the torso enhances the exoskeleton workspace. The *Capio* system is designed portable and lightweight with an easy dressing procedure.

Key words: space robotics, teleoperation, robot design, system engineering, virtual environment, exoskeleton, human-machine interface.

1. INTRODUCTION

The overall goal of a teleoperation application is to achieve telepresence of a human operator in the remote working site of the robot. The user should not only have the ability to manipulate the remote environment, but also to perceive it as if encountered directly [1]. A central element of every teleoperation system is the haptic device which realizes the interface between human and machine. The *Capio* exoskeleton is a prime example of a haptic device.

In general, an exoskeleton is a human-machine interface (HMI) facilitating interaction between an operator and a robotic system. The exoskeleton captures the movement of the human body and transfers it to the remote system to command it. Beyond that, force feedback generated by the remote system, gives the operator the illusion of being on-site. This allows the operator to control the robot in an intuitive way.

Remote controlled robots are indispensable tools for exploration and operation in environments that are highly risky or unsuitable for human beings. For applications in space or hazardous environments it is often not suitable to have humans on-site but a robot. Many tasks and decisions cannot be made by the robots themselves yet. Therefore, the human must be in the loop to supervise and teleoperate robotic systems. The machines, their action spaces and their tasks have reached a level of complexity that makes it increasingly difficult for operators to control them. In many current teleoperation applications a joystick is still used as a control device. In case exoskeletons are used as haptic interfaces, they are usually mounted to a supporting structure and are therefore unable to support control of a robot by the human upper body like hip and shoulder [2], [3]. However, mobile systems are usually confined to one limb according to the weight and user optimization. Examples for these systems are described in [4] and [5]. Due to these restrictions the full potential of a haptic teleoperation cannot be used.

In general, teleoperation does not only involve navigation but also the control of parts of a system like a robotic arm for manipulation tasks. An input device that can do both, i.e., can control the robot's body and can initiate certain other behaviours of the robot with respect to mission control, is required. Therefore, new approaches for controlling such a system and handling kinematics and dynamics efficiently in real-time are indispensable for the *Capio* exoskeleton.

In the first part of the paper the design, control and software features are described. The second part presents the teleoperation scenarios and gives an overview about the remote systems. The section conclusion and outlook summarizes the achieved results and gives an outlook on further development.

2. EXOSKELETON

As main requirements for teleoperation it was identified that the exoskeleton should cover a large human workspace, be mechanical transparent, precisely measure the operators movement, be easy to dress and safe in usage. The fulfilment of the requirements are explained in the following sections. A short overview about the *Capio* exoskeleton, shown in Figure 1, and its specifications is given in Table 1.

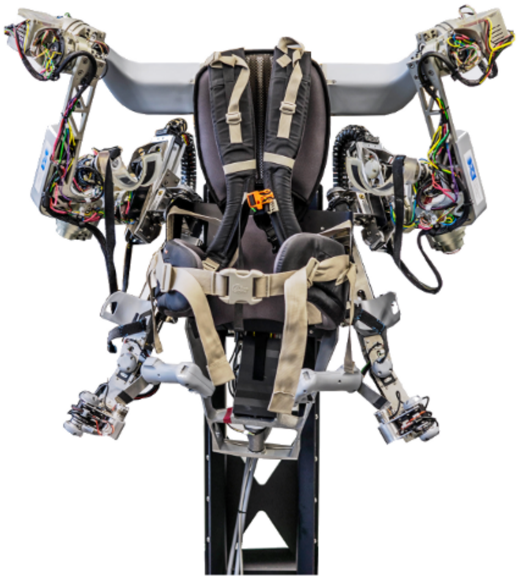

Figure 1. Capio active exoskeleton.

Table 1. Capio exoskeleton system overview.

Feature	Value
Active degree of freedom at the back	4 [1]
Active degree of freedom of one arm	8 [1]
Contact Points	8 [1]
Current consumption	48 [A]
Voltage	12 and 48 [V]
Total Weight	24 [kg]

2.1. Kinematics

Regarding to [6] and based on the experience of the precursor exoskeleton project VI-Bot, described in [7] and [8], several serial and parallel kinematic setups for the subsystems back and arm were developed. The key point in the development was the human dual arm manipulation workspace. The combined result of several iterations is shown in Figure 2.

To specify the kinematics, the Sheth-Uicker two-frame convention [9] is used. This means, beginning from root, child links need to have an increasing index. The joint enumeration represent this by including the start and end link number: link 2 is framed by joint 001-002 and joint 002-003.

To test the functionality a passive exoskeleton was build up as displacement study as depicted in Figure 3. With the passive exoskeleton the joint angles can be measured and the corresponding velocities and accelerations can be calculated.

The kinematic structure includes two contact points at the back and three contact points at each arm. Advantage arises from the close arrangement between exoskeleton and user which enables a precise measurement and force feedback but enhances the required performance of the control algorithms and the kinematic.

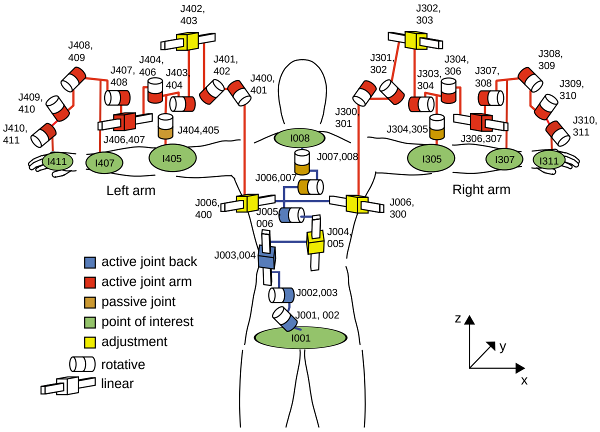

Figure 2. Capio Exoskeleton kinematic structure.

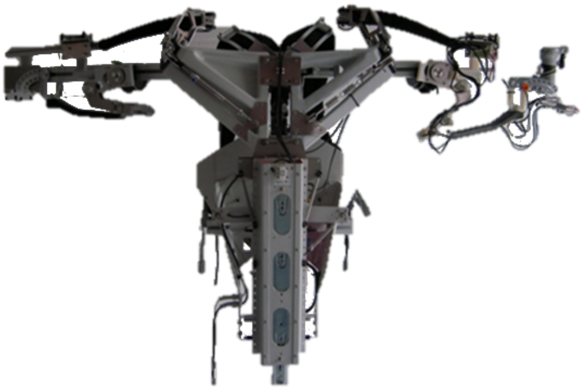

Figure 3. Capio passive Exoskeleton as kinematic displacement study.

Four active degrees of freedom (DOF) realise the back movement with two adjustment possibilities, see Figure 4. The first joint allows the rotation of the back relative to the hip. The torso flexion and extension is achieved by the second joint in combination with a linear joint. The linear joint provides an extension of the structure, to compensate the larger movement radius of the structure.

Eight active DOF are applied at each arm. Three drives represent the shoulder joint with a common intersection point. The elbow is simplified to a rotative joint in combination with a linear compensation joint. A passive joint connects the exoskeleton to the users upper arm.

To achieve an easy dressing procedure and improve the system's handling, an "OpenJoint" concept is developed [10], shown in Figure 5. The forearm pronation and supination is simplified to the longitudinal forearm axis. In this case a standard solution for an exoskeleton design is coaxial to this axis, often leading to a circular closed bearing design. In the "OpenJoint" set-up, the joint actu-

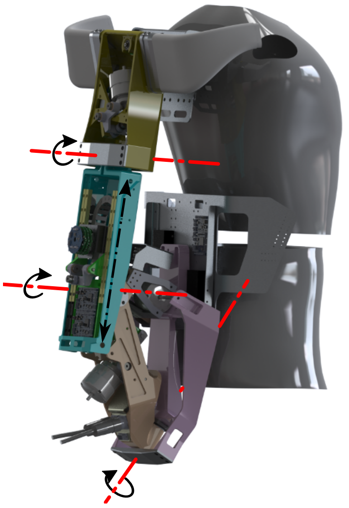

Figure 4. Capio exoskeleton CAD kinematic back structure.

ation and measuring axis is not coaxial to the pronation and supination axis but intersects with this axis in one center of rotation. This center of rotation is at the same time the intersection point of the wrist exoskeleton joints. Thereby, the misalignment of the pronation and supination of the exoskeleton is compensated. At the forearm section of the exoskeleton the second contact is mounted.

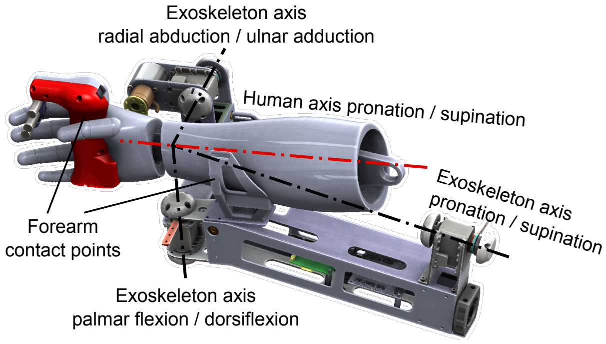

Figure 5. Capio "open joint" concept.

The end-effector is held by the operator and is the third contact point. The end-effector includes a force controlled trigger driven by a servo motor to provides a force feedback, see Figure 6.

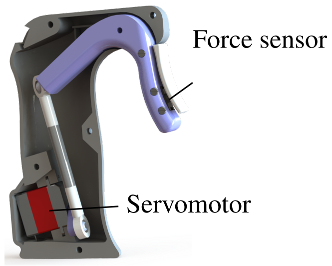

Figure 6. Capio active handinterface.

To transfer the originary CAD data to a concise kinematic and dynamic model an automated software tool chain CAD2SIM is developed [11]. The CAD data is classified to the main links, including the fixed part from each drive. In respect to the Shet-Uicker convention, at each main link two frames at start and endpoint in the CAD software are integrated. As result of the CAD2SIM tool chain mechanism specifications for the software platforms *Openrave* and *MARS*, the *Orocos KDL* library and the *Rigid Body Dynamics Library* (RBDL) are generated. They include information about the system zero-posture, link-joint configurations, dynamical properties and graphical representation.

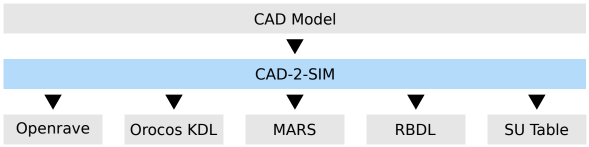

Figure 7. CAD2SIM simplified schematic sketch.

2.2. Capio Drives

For an inherent safe design and a natural smooth system movement of all active joints are realized as serial elastic actuator (SEA). In the development of the SEA the usage as sensor by measuring the deflection of a spring set is in the focus. This principle provides a SEA joint with an integrated torque sensor. An overview of the Capio drives characteristics is shown in Table 2.

Table 2. Capio drives characteristics.

Feature	Linear BLDC	Rotative BLDC	Servo
Force/Torque	790 [N]	28 [Nm]	2.7 [Nm]
Calc. accuracy	0.02 [N]	0.002 [Nm]	0.16 [Nm]
Compliance	4 [°]	8 [°]	5 [°]
Weight	300 [g]	620 [g]	168 [g]
Current	3.5 [A]	3.5 [A]	2 [A]
Voltage	48 [V]	48 [V]	12 [V]

Linear Spindle Drive The linear spindle drive is developed to deliver all the required forces at the back structure. Figure 8 gives an overview of the assembly. The rotor of a brushless direct current drive (BLDC) *robodrive ILM50x8* is fixed to a spindle nut, allowing the actuator to move on a fixed spindle. A off axis absolute position encoder provides information for motor commutation and multi-turn position calculation. A tooth wheel gear transfers the rotational movement of rotor and spindle nut to a second encoder. Due to the gear ratio the second encoder rotates one time at the linear workspace of 70 mm. This enables a accurate position information at the start up.

The compliance is implemented by a base mounted leverarm. Variable springs set can be applied.

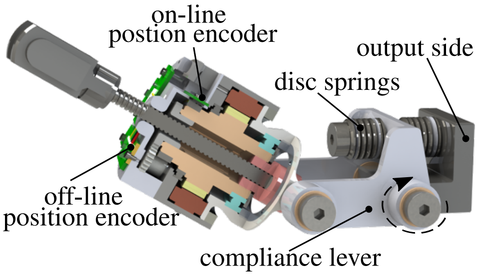

Figure 8. Capio linear spindle drive.

Rotative BLDC Drive The developed rotative BLDC drives are a combination of a *robodrive* with a *Harmonic Drive* gear: a 28 Nm version with an *ILM 50x8* and a 60 Nm version with an *ILM 70x10*. Both are working by the same principle, the rotor moves the wave generator of the *Harmonic Drive*, the flexspline serves as output and is coupled to the housing via a set of disc springs, see Figure 9. Various stiffness of the disc spring set is available. Three-off axis absolute position encoders provide the required information: the first is responsible for the motor commutation, the second gives the absolute joint position and the third measures the spring set deflection for the torque calculation.

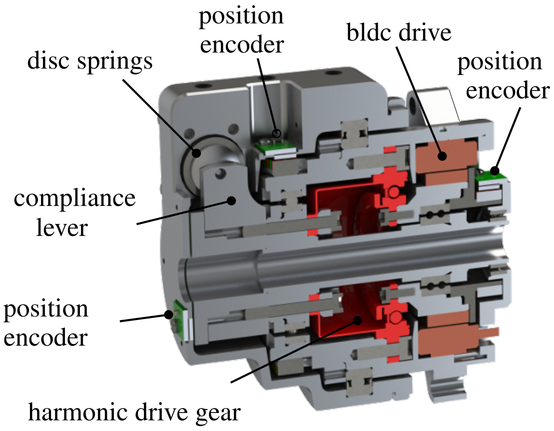

Figure 9. Capio rotative BLDC drive.

Rotative Servo Drive For smaller torques at the forearm a modular drive concept is developed. The output of a *Dynamixel* servo motor is linked via a spring to the exoskeleton's structure, see Figure 10. Various types of *Dynamixel* servo motors and springs can be applied. The deflection of the spring is calculated by the difference of two position encoder arranged on the *Dynamixel* axis.

2.3. Control

The control architecture is designed in three layers. The active joints are controlled on the low-level, spatial dynamics are computed on the mid-level layer and the high-level layer gives the user the possibility to choose different control modes or postures.

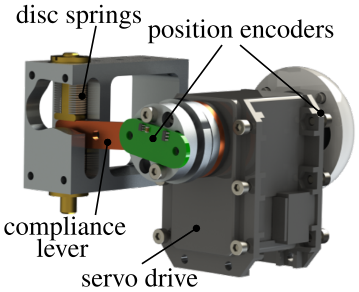

Figure 10. Capio rotative servo drive.

Low level control The control algorithm of each joint is implemented on a *STM32 F4* micro-controller and is distributed to the exoskeleton. Figure 11 shows the control scheme, a cascade torque speed control with a flatness based feed-forward control.

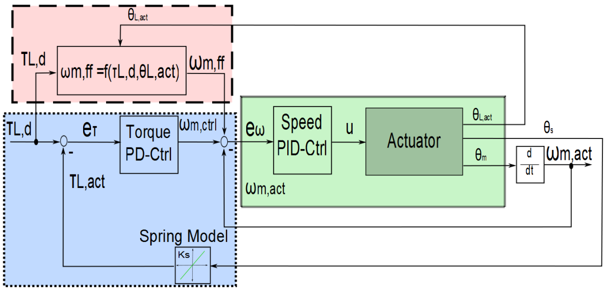

Figure 11. Low level control scheme of Capio exoskeleton rotative BLDC joints. Red (- - -): white-box feed-forward model. Blue (· · ·): cascade feed-back control structure for set point tracking. Green (—): speed PID-controller.

Mid level control On the mid-level the coordinated function of all joint is realised by solving the inverse dynamic model with the recursive Newton-Euler method. On this layer, the following equation of motion has to be solved:

$$\boldsymbol{\tau} = \underbrace{H(\mathbf{q}) \cdot \ddot{\mathbf{q}} + C(\mathbf{q}, \dot{\mathbf{q}}) \cdot \dot{\mathbf{q}} + \boldsymbol{\tau}_g}_{(1.1)} + \underbrace{J(\mathbf{q})^T \cdot \mathbf{f}_{ext}}_{(1.2)} \qquad (1)$$

where:

- $\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}$: joint positions, velocities, and accelerations,
- $\boldsymbol{\tau}$: joint forces and torques,
- H: the inertia tensor,
- C: Coriolis and centrifugal forces,
- $\boldsymbol{\tau}_g$: gravity terms,
- J: Jacobian,
- $\mathbf{f}_{ext}$: external forces acting on the robot.

For this purpose, the open source *Rigid Body Dynamics Library* [12] is used.

The dynamic model of the exoskeleton is employed to compensate the gravitational forces of the exoskeleton's structure. The resulting force is only applied at the back of the human operator when wearing the system. Furthermore, it is used to simulate any contact forces in space to generate force-feedback.

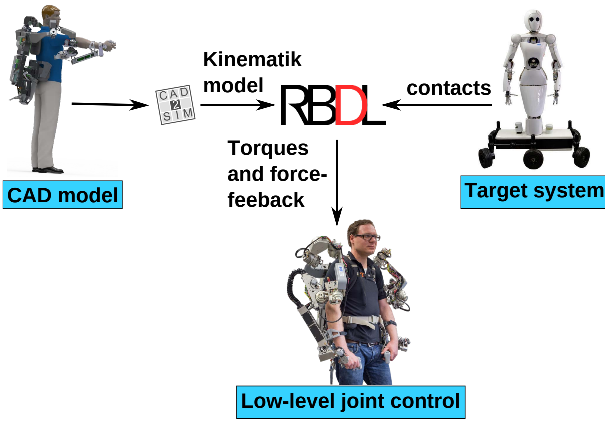

Figure 12. Capio mid-level control.

High level control At the high-level control the system's behavior can be influenced by the user. A graphical user interface gives information about the system's state and enables to choose different modes like "zero force", "inverse dynamic", "force feedback" and "determinate force" modes.

Safety features The direct interaction with human requires a reliable and safe system. Figure 13 shows the different layers of the system security. On the hardware side an emergency switch and mechanical limits are implemented. The low-level control includes joint and torque limits on the micro-controller level. Thereby, false joint positions or extreme torques of the mid-level control are intercepted. A communication check verifies sensor signals, correct joint directions and the connection to the mid-level control. Torque limits are also implemented at the inverse dynamic controller on the mid-level layer. System tuning implies the update of the dynamic model if the exoskeleton structure is modified. Each joint is monitored (positions limits, torques, sensor states) in the graphical user interface. Misarrangements of exoskeleton model can be detected in the visualisation of the exoskeleton in *MARS* software. On the user side a documentation and a two person rule complete the safety features.

3. TELEOPERATION

The *Capio* exoskeleton is developed for the teleoperation of complex robotic systems. An important feature of the exoskeleton is that it enables dual arm manipulation of humanoid robots including the control of the torso of the robot to significantly extend the workspace.

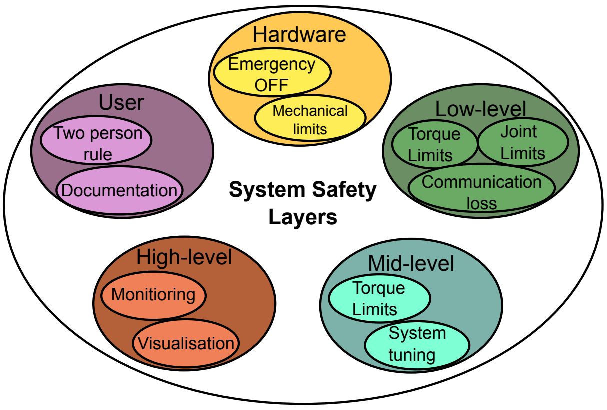

Figure 13. Capio system safety features.

3.1. Teleoperating a dual arm humanoid robot

The dual arm humanoid robot AILA is a research platform to study the multidisciplinary topic of mobile manipulation, [13]. The system has the possibility to perform complex manipulation tasks. AILA is mounted on a mobile platform equipped with six two DOF wheels. A short overview of the system is shown in Table 3.

Table 3. AILA mobile dual arm manipulation robot system overview.

Feature	Value
Active DOF at each arm	7 [1]
Arm payload/weight ratio	1.45 [1]
Active DOF at torso	4 [1]
Mobile platform DOF	12 [1]
Current consumption	40 [A]
Voltage	12 and 24 [V]

Scenario setup The control of humanoid robots does not only involve the control of their arms but also the other parts of their body. For dual arm manipulation the torso is of high relevance. The *Capio* exoskeleton allows to control the torso by tracking the operators back movements.

To evaluate the teleoperation performance of the exoskeleton a test scenario in two different buildings was set up. The robot AILA shall perform a manipulation task in an ISS mockup. The communication link is established with Ethernet. Two web-cams give the exoskeleton operator a view of the robot's hands from two different angles, see Figure 14 (left).

A second test scenario is shown in Figure 15. The robot AILA handles a bulky object by remote control. The

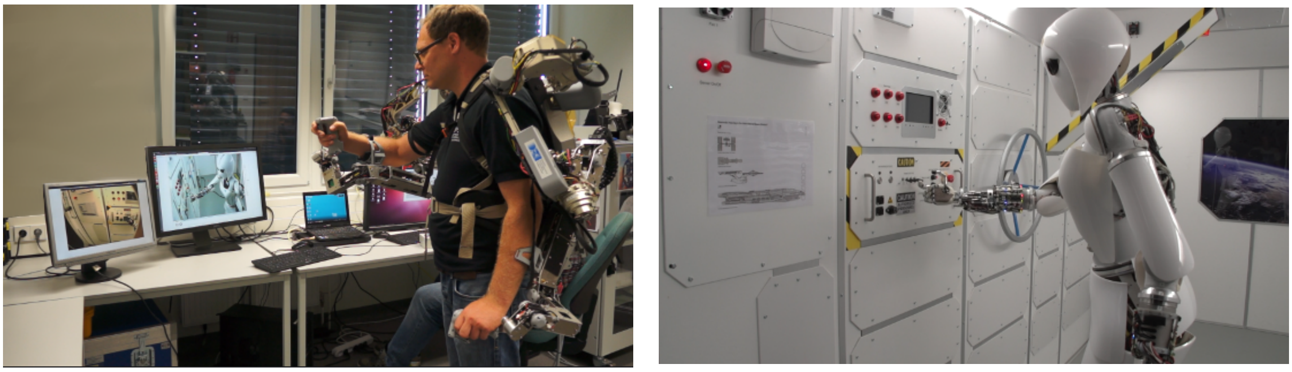

Figure 14. Capio Exoskeleton teleoperating humanoid robot AILA in ISS mockup.

needed force to hold the object is transferred to the operator by the force feedback. This enables a sensitive and safe dual arm manipulation.

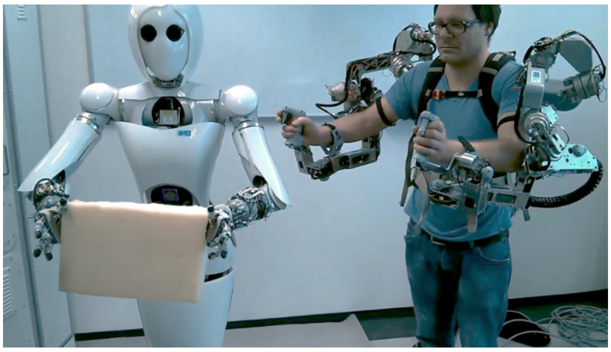

Figure 15. Capio exoskeleton dual arm manipulation

Results Experiments have shown that the exoskeleton is a suitable input device for teleoperation. It gives the user an appropriate workspace to fulfil filigree manipulation tasks in an intuitive way. The torso movements enhances the action radius.

The robotic system AILA could be remote controlled to perform fine manipulations, e.g., turn switches and to manipulate objects with two arms. A 6 DOF force torque sensor at AILA's wrist measures external forces and calculates above a specified threshold AILA's joint torques which are mapped back to the exoskeleton. Figure 16 shows the transferred torques of the upper arm rotation. The reference signal for the *Capio* joint is a superposition of the *RBDL* inverse dynamics reference, see Equation (1.1), and the external torque, see Equation (1.2).

In Figure 16 the resulting influence of the external torque from AILA (lower plot) can be seen in the exoskeleton joint torque (middle plot) as well as in the joint position (upper plot). At the beginning of the measurement a torque of -2.1 Nm is applied to the exoskeleton joint by the *RBDL* reference, determined by the states of all exoskeleton joints. At the marked period T_1 the first external torque is taking effect. This rises the superposition reference torque and causes a position changing. In this period the human inside the exoskeleton is responsible for the control error between the superposition reference signal and the measured exoskeleton joint torque.

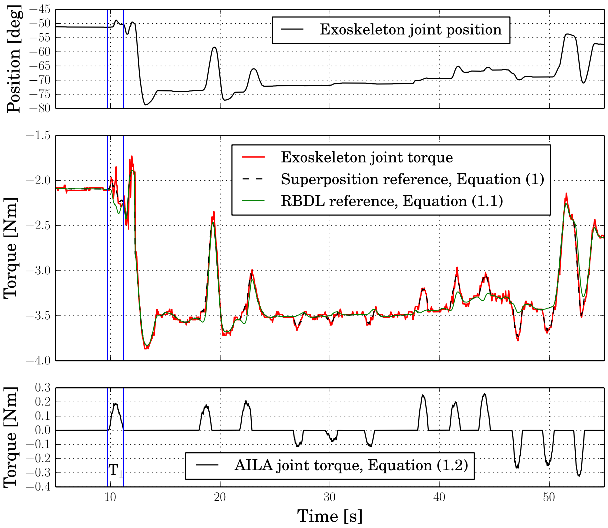

Figure 16. External torques on the Capio exoskeleton transferred from AILA upper arm rotation.

The changes of the exoskeleton torque and position during the next seven seconds are the only result of the entire system dynamics including the human operator. Then the next external torque is applied. In the following time period it can be seen that external torques below 0.1 Nm have no effect to the joint position.

3.2. Teleoperation in a simulated lunar mission

Performing teleoperation on remote robotic systems is considered to be a complex task. Virtual Immersion can help to simplify the control for the user. To immerse the operator into the current environment of the target system, a CAVE-like system is used. The system consists of seven screens, which are positioned on a semicircle around the user. The screens display a 3D representation of a virtual lunar mission scenario using the *MARS* simulation framework [14].

Simulated lunar mission The mission displays a simulated moon environment. Four robots (equipped with wheels), five labelled waypoint markers and a lander module are positioned inside the scene. The task for the user is to complete missions, which are assigned to him by the system. To fulfill the missions, the operator needs to perform several actions with the simulated robots, such as control and navigation. Possible missions are navigating to a waypoint, recharging the robots battery at the lander module and submitting the robots status to the ground control.

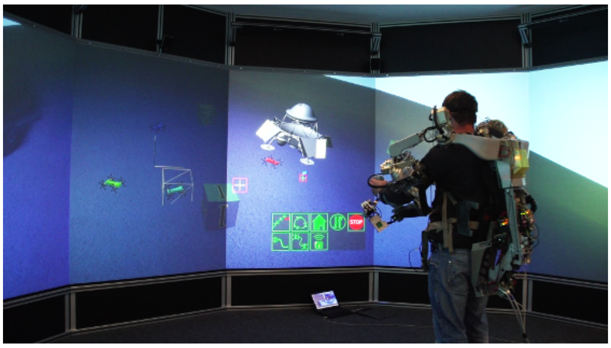

Figure 17. Capio Exoskeleton teleoperating in a virtual environment displayed on a CAVE like system.

Setup The user is located in a fixed position in front of the CAVE screens wearing the exoskeleton. The angular positions of the exoskeleton's joints are used to calculate the forward kinematics of the structure. The posture of the right hand's interface is used to display a virtual cursor on the CAVE screens. The cursor's position is calculated by projecting and mapping the position and orientation of the right end-effector of the exoskeleton onto the plane of the screens. By moving his arm and hand the operator can move the cursor across the virtual scene. The general data-flow diagram is shown in Figure 18.

By pressing the button on the right hand's interface the user can perform actions in the virtual scenario. The right hand's interface can be used to select a robot, trigger an action linked to a button on the user interface (UI) or to set waypoints for navigating the selected robot to a target destination. The button on the left hand's interface is used to deselect the current system in the simulated environment.

Results Preliminary results from first experiments have shown that the user is able to control the scenario using the exoskeleton. It is also possible to solve the missions assigned to him by the system in an adequate amount of time. For planned work in this setup see Section 4.

4. CONCLUSION AND FUTURE WORK

The active *Capio* upper body dual arm exoskeleton is a complex robotic system. With multiple contact points it covers a large workspace and provides a sensitive force feedback. A proper kinematic was developed, so that in combination with the inverse dynamics calculation the system acts mechanical transparent. An easy dressing procedure is achieved by the "OpenJoint" concept.

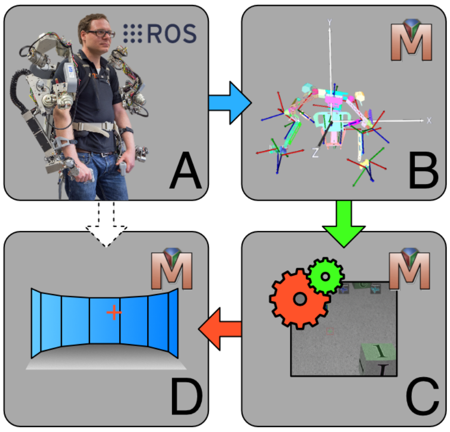

*Figure 18. Data flow from the exoskeleton to the cave's screens. **A:** The system publishes the joint angles via ROS. **B:** A simulated model of the exoskeleton in MARS is used to calculate the forward kinematics and to publish cartesian coordinates of the end-effectors. **C:** The cartesian values are transformed to screen coordinates in the simulated environment. **D:** The cursor is displayed on the CAVE screens.*

Controlling the robot AILA by the exoskeleton shows the intuitive usage as input device for teleoperation. The exact movement representation can be used to control a robotic arm with high precision, thereby it is possible to manipulate filigree structures. The possibility to move the torso expands the robot's workspace. The dual arm manipulation enables the operator to handle bulky objects in an intuitive way.

The Capio exoskeleton was successful integrated into the virtual environment CAVE. It was used to control the virtual lunar robot scenario. Commonly only a single cursor is used to control UI on computer systems. The exoskeleton can provide two pointers by the position of the left and right hand.

To incorporate this option into the control architecture of user interfaces is a future challenge and field of research for UI design and user experience testing.

Regarding teleoperation the exoskeleton can be used to a greater extend. The extraction of movement primitives can be used to teach certain behaviours to robotic systems, as it was shown in [15]. Force feedback from the real system can also be applied by the exoskeleton to a certain extend.

The further mechatronic development of the exoskeleton system will focus on the reduction of the exoskeleton weight. This will be achieved by customizing the arm joints and the forearm structure.

Furthermore, it is planed to transfer the exoskeleton technology into rehabilitation applications. Based on the experiences gained with the *Capio* exoskeleton the development will include the lower part of the body to design a full-body exoskeleton for upper body robotic assistance.

ACKNOWLEDGEMENTS

This work was supported by the German Federal Ministry of Education and Research (grant no. 01IW10001).

REFERENCES

[1] G. Niemeyer, Preusche C., and Hirzinger G. *Handbook of Robotics, Tele*. Springer, 2008.

[2] Joel C Perry and Jacob Rosen. Design of a 7 degree-of-freedom upper-limb powered exoskeleton. In *Biomedical Robotics and Biomechatronics, 2006. BioRob 2006. The First IEEE/RAS-EMBS International Conference on*, pages 805–810. IEEE, 2006.

[3] R.A.R.C. Gopura, Kazuo Kiguchi, and D.S.V. Bandara. A brief review on upper extremity robotic exoskeleton systems. In *Industrial and Information Systems (ICIIS), 2011 6th IEEE International Conference on*, pages 346–351. IEEE, 2011.

[4] A. Schiele, H.-P. Seiberth, P. Klär, and G. Hirzinger. Mechatronics characterization of a novel high-performance ergonomic exoskeleton for space robotics telepresence. In *International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS)*, pages 499–506, 2009.

[5] Antonio Frisoli, Fabrizio Rocchi, Simone Marcheschi, Andrea Dettori, Fabio Salsedo, and Massimo Bergamasco. A new force-feedback arm exoskeleton for haptic interaction in virtual environments. In *Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint*, pages 195–201. IEEE, 2005.

[6] Wolfgang Lange and JH Kirchner. *Kleine ergonomische Datensammlung*. Verlag TÜV Rheinland, 1978.

[7] Michele Folgheraiter, Bertold Bongardt, Jan Christian Albiez, and Frank Kirchner. Design of a bio-inspired wearable exoskeleton for applications in robotics. In *BIODEVICES*, pages 414–421, 2009.

[8] M Folgheraiter, B Bongardt, S Schmidt, J De Gea, J Albiez, and F Kirchner. Design of an arm exoskeleton using a hybrid model-and motion-capture-based technique. In *Workshop on Interfacing the Human and the Robot (IHR). Proceedings of the 2009 IEEE International Conference on Robotics and Automation (ICRA 2009)*, 2009.

[9] Bertold Bongardt. Sheth–Uicker convention revisited. *Mechanism and Machine Theory*, 69:200 – 229, 2013.

[10] Schmidt Steffen. Menschliche nicht redundante Parallelkinematik für eine Orthese oder eine Exoskelett mit seitlichen Kopplungsstellen. Petty Patent, DE202013009698U1, 2013.

[11] Bertold Bongardt. Cad-2-sim–kinematic modeling of mechanisms based on the sheth-uicker convention. In *Intelligent Robotics and Applications*, pages 465–477. Springer, 2011.

[12] Martin L. Felis. RBDL - the Rigid Body Dynamics Library. http://rbdl.bitbucket.org, 2013.

[13] Johannes Lemburg, José de Gea Fernández, Markus Eich, Dennis Mronga, Peter Kampmann, Andreas Vogt, Achint Aggarwal, Yuping Shi, and Frank Kirchner. Aila-design of an autonomous mobile dual-arm robot. In *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, pages 5147–5153. IEEE, 2011.

[14] DFKI-RIC. Mars - an open-source, flexible 3d physical simulation framework. http://rock-simulation.github.io/mars/, April 2015.

[15] Lisa Senger, Martin Schroer, Jan Hendrik Metzen, and Elsa Andrea Kirchner. Velocity-Based Multiple Change-Point Inference for Unsupervised Segmentation of Human Movement Behavior. In *2014 22nd International Conference on Pattern Recognition (ICPR)*, pages 4564–4569. IEEE, 2014.