The EU Framework Programme for Research and Innovation H2020
Research and Innovation Action

Deliverable D8.3 First CENTAURO System Evaluation

Dissemination Level: Public

Project acronym:	CENTAURO
Project full title:	Robust Mobility and Dexterous Manipulation in Disaster Response by Fullbody Telepresence in a Centaur-like Robot
Grant agreement no.:	644839
Lead beneficiary:	LiU – Linköpings Universitet
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Work package:	WP8 Requirement Specification and Evaluation
Date of preparation:	November 30, 2017
Type:	Report
Version number:	1.0

Document History

Version	Date	Author	Description
0.1	2017-11-24	KN	First empty draft
0.2	2017-12-05	US, KN	LaTeX version of KHG's report
0.3	2017-12-08	KN	Fixed some errors
0.4	2018-02-13	KN	Added some text from KHG
0.5	2018-04-26	KN	Updated after comments from Tobias Klamt
0.6	2018-07-16	NK, LM, NT	Added lower-body evaluation core component
0.7	2018-08-07	TK	Add further evaluation material
1.0			Submitted version

Executive Summary

This deliverable reports on the first evaluation of the integrated CENTAURO system, which took place in November 2017 at KHG. Several disaster-scenario relevant locomotion and manipulation tasks were specified together with performance metrics. The Centauro robot was controlled by remote operators using multiple operator interfaces, including an immersive exoskeleton teleoperation suit for the main operator and third-person interfaces for support operators. One of the tasks was executed autonomously. Almost all tasks were performed successfully or with partial success. The deliverable also contains the evaluation of the core component robot lower body. We report detailed evaluation results and analyze them throughly.

Contents

1 Introduction

Following the time-line of the project, the first CENTAURO system with partial functionality was evaluated in simplified scenarios. These scenarios were based on disaster-response benchmark scenarios and inspired by robot competitions and challenges, such as RoboCupRescue, the DARPA Robotics Challenge (DRC), and the DLR SpaceBot Cup. Input from professional rescue workers like KHG has also been used to ensure the relevance of the test scenarios.

KHG has extensive experience with remote mobile manipulation for disaster response, and is operating a large variety of tele-operated vehicles. Based on this knowhow, KHG has contributed to the development of evaluation criteria and test methods for the CENTAURO system. The KHG site outside Karlsruhe was chosen as the location for the evaluation tasks, given that its existing infrastructure provides an optimal base for these tests. All available data was captured and analyzed to assess task performance, operator work load, sensitivity to communication problems, and for finding the root causes of failures.

This report contains a documentation of the first CENTAURO system evaluation. Section 2 gives a brief background of the evaluation, while Section 3 contains a detailed description of the different tasks that were carried out. The lower body of the robot, which was not available in Deliverable D8.2 Core Component Evaluation [3], is evaluated in Section 4. Section 5 presents a summary of the results while the appendix contains the full set of protocols from the execution of the different tasks.

2 Evaluation Camp Planning

Before the evaluation could be carried out, it was necessary to first choose test methodologies, and customize them for CENTAURO system, as well as define test scenarios and tasks for evaluating the CENTAURO system.

2.1 Definition of Test Methodologies

To analyze the evaluation results after execution, test protocols have been conceived. They contain arrays to identify the task, e.g., the number of trials, the starting parameters, the task description, the target of the test and the achieved results. In addition, the start and end times of the evaluation task and the duration of each trial are recorded. These protocols have the same form for each evaluation task.

2.2 Definition of Test Scenarios

Testing arenas developed by NIST and RoboCupRescue offer a valuable testbed to quantitatively evaluate components of the CENTAURO system. Based on these testing areas, and with additional input from professional rescue workers, the following tasks for evaluating the locomotion and manipulation capabilities of the CENTAURO system were defined:

Locomotion

L1a Small Door: Opening a small door.

L1b Regular Door: Opening a regular door, and moving the robot through it.

L2 Step Field: Moving the robot over an uneven field.

L3 Stair: Moving the robot up and down a flight of stairs.

L4 Ramp: Moving the robot up and down a ramp.

L5 Gap: Moving the robot across a gap.

Manipulation

M1a Valve (gate type): Opening and closing a gate type valve.

M1b Valve (lever type): Opening and closing a lever type valve.

M2 Fire Hose: Connecting and disconnecting a fire hose to a nozzle.

M3 230V Connector: Connecting and disconnecting a standard 230 Volt electrical plug to a socket.

M4 Follow a Surface: Make the robot hand follow a surface at a specified distance.

M5 Snap-hook: Snap a hook to a metal ring.

M6 Screw Driver: Drive a screw into a wall using an electrical screw driver.

M7 Driller: Drill a hole through a wood wall.

M8 Cutting Tool: Cut an electrical wire with an electrical cutting tool.

A1 Autonomous Grasping: Automatic grasping of electrical tool by the robot's hand.

These test cases were first specified in CENTAURO Deliverable D8.1 [2], then further developed at the CENTAURO consortium meeting at KTH, in June 2016. They have been used to specify the development of the first CENTAURO system that was the subject of this evaluation.

2.3 Detailed Descriptions of Tasks

A detailed description of the locomotion tasks is presented in Table 1. The corresponding description for the manipulation tasks is presented in Table 2. The autonomous task, and its level of autonomy, is described more detailed in Section 3.2.14 on page 16.

In these tables, the column labeled *Difficulty* gives an initial estimate in the range 1–10 of how difficult the task is to perform, where 1 means easy and 10 indicates very difficult. This estimate was used during the execution, which started with the easier ones and progressed to the more difficult ones at the end. After the evaluation, the robot operators mentioned that they would give other difficulty measures for some of the tasks.

Task	Task Object	Description	Difficulty	Initial Condition	End Criteria
L1a	**Small door** with handle - Width 90 cm - Height 90 cm - Unlocked - Opens toward the robot - Hinges on the right side	Opening the door - Use handle - Keep door open	3	Robot in front of the door	Door is open
L1b	**Regular door** with handle - Width 90 cm - Height 200 cm - Unlocked - Opens toward the robot - Hinges on the right side	Opening the door - Use handle - Keep door open Going through the door	6	Robot in front of the door	Door is open and robot has moved through the door
L2	**Step-field** - Width 120 cm - Length 200 cm - Max. diff. of height 10 cm	Walking over the step-field	7	Robot in front of the step-field	Robot on opposite side of the step-field
L3	**Stairs** - 4 steps - Step height 20 cm - Angle 30°	Walking up and down the stairs	7	Robot in front of the stair	Robot returned to original position after walking up and down the stairs
L4	**Ramp** - Two loading ramps, - With support structure Angle: 20°	Driving up the ramp	7	Robot in front of the ramp	Robot returned to original position after moving up and down the ramp
L5	**Gap** - Width 120 cm - Length 250 cm - Gap of 30 cm	Walking over the gap	4	Robot in front of the gap	Robot on the other side of the gap

Table 1: Detailed description of the locomotion tasks.

Task	Task Object	Description	Difficulty	Initial Condition	End Criteria
M1a	**Valve** (Gate type) - Valve wheel 8 cm - Valve in middle position - Valve vertical - Fixed 100 cm above floor - Wheel in middle position	Open and close the valve (multiple turns of hand wheel)	5	Robot in front of the valve	Open and close the valve
M1b	**Valve** (lever type) - Valve lever length 10 cm - Valve in middle position - Valve vertical - Fixed 1 m above floor	Open and close the valve (90° turn of lever)	4	Robot in front of the valve	Open and close the valve
M2	**Fire hose** - Bajonet type - Fixed part of hose mounted at height 100 cm - Loose part in the gripper	Connect and disconnect the fire hose (push and turn 45°)	9	Robot in front of the workbench	Connect and disconnect the fire hose (30°)
M3	**230V Connector** - Standard household (Schuko) connector - Outlet mounted 100 cm above the floor - Loose part in the gripper	Connect and disconnect the 230V connector	10	Robot in front of the workbench	Connect and disconnect the 230V connector
M4	**Follow Surface** - Done on a standard cask lid section	Sensor follows the surface at a defined distance (10 mm)	3	Robot in front of the workbench Sensor in the gripper	Sensor follows the surface at defined distance
M5	**Snap-hook** - Metal ring mounted 100 cm above the floor - Open in vertical direction	Hook the snap-hook in the ring	6	Robot in front of the workbench; Snap-hook in the gripper	Snap-hook hooked in the metal ring
M6	**Screw Driver** - Wood-block mounted 100 cm above the floor, with screws horizontal pre-mounted some turns - Diameter of screw 5 mm - Torx 25 screw driver	Turn screw completely into the wood-block	10	Robot in front of the workbench; Screw driver in the gripper	Screw completely turned in the wood-block
M7	**Driller** - Wood-block mounted 100 cm above the floor - Horizontal drill - Diameter of drill 6 mm	Drill a hole (complete length of driller)	8	Robot in front of the workbench	Driller in the gripper Hole with length of the driller in the wood-block
M8	**Cutting tool** - Wire fixed at two points 100 cm above the floor	Cutting a 5×1,5 NYM electric cable	8	Robot in front of the workbench; Cutting tool in the gripper	Cable cut
A1	**Autonomous grasping** - Ref. to task M6 Electric screw driver	Autonomous grasping of the screw driver	8	Robot in front of the workbench; Screw driver in a fixed pose relative to the robot	Robot hand has grasped the tool

Table 2: Detailed description of the manipulation tasks.

Order Number	Task	Task Object	Date
1	L4	Ramp	22.11.17
2	L5	Gap	
3	M4	Follow surface	
4	L1a	Small door	
5	M1a	Valve (Gate type)	
6	M1b	Valve (lever type)	
7	M8	Cutting tool	23.11.17
8	M5	Snap-hook	
9	M7	Driller	
10	M6	Screw driver	
11	M3	230V-Connector	
12	M2	Fire hose	
13	L1b	Regular door	
14	A1	Autonomous grasping	24.11.17
15	L3	Stair	
16	L2	Step-field	

Table 3: Chronological order of the tasks.

3 Evaluation Camp Execution

After two setup days, all evaluations were carried out during 2.5 evaluation days at the premises of KHG, near Karlsruhe Germany.

Important Remarks

1. During most of the tests, the robot was controlled by a human operator though an interface consisting of several different subsystems, such as a joystick, an exoskeleton, a keyframe editor, a semi-autonomous stepping controller, and a 6D mouse. The only exception was task A1 *Autonomous grasping*. The interfaces are described in detail in [1].

2. The operator had no direct visual contact or feedback from the robot's workspace, only via previously mentioned interfaces. As reported in Section 5.1, however, the operator was supported by a *person at location* who provided feedback for some of the tasks.

3. Communication between the operator station and the robot was made over cables only.

4. With respect to the cost of some robot components, during most of the tests the robot was secured by a support structure composed by a mobile suspension and a chain block. The only exception was task L1b *Regular door*.

3.1 Chronological Order of Tasks

The tests were executed with regard to the complexity of the task and a good test flow, given that the tasks were performed at different sites within the KHG facilities. Table 3 lists the performed tests in chronological order.

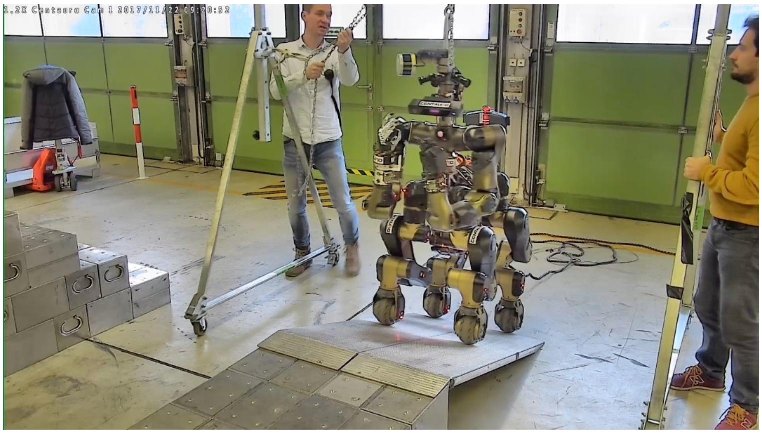


Figure 1: Centauro robot driving up a ramp.

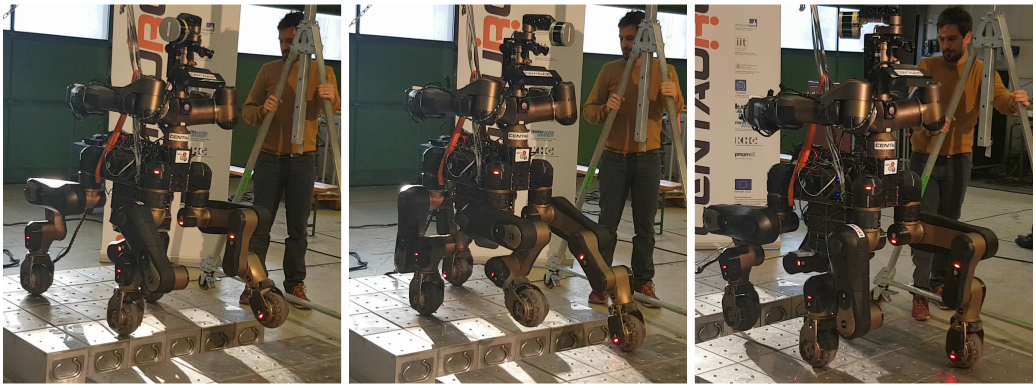


Figure 2: Overcoming a gap.

3.2 Detailed Description of the Execution of Tasks

All evaluation tasks are described in detail in the following sections, in the chronological order they were executed. More details, together with execution times can be found in the protocols in the appendix (Section A). Summary of results and success rates are presented in Section 5.

3.2.1 Task L4: Ramp

The ramp was constructed out of two loading ramps and a support structure. It had a slope of 20°. The robot started directly in front of the ramp and used its wheels to drive up the ramp, see Figure 1. The robot was controlled using joystick teleoperation. The base pitch was adjusted by predefined motion primitives.

3.2.2 Task L5: Gap

The gap was constructed out of two platforms, with a gap of 0.3 m between. The robot started directly in front of the first platform and used his legs to walk over the gap, see Figure 2. The operators used predesigned motion primitives interleaved with joystick driving commands to accomplished the task.

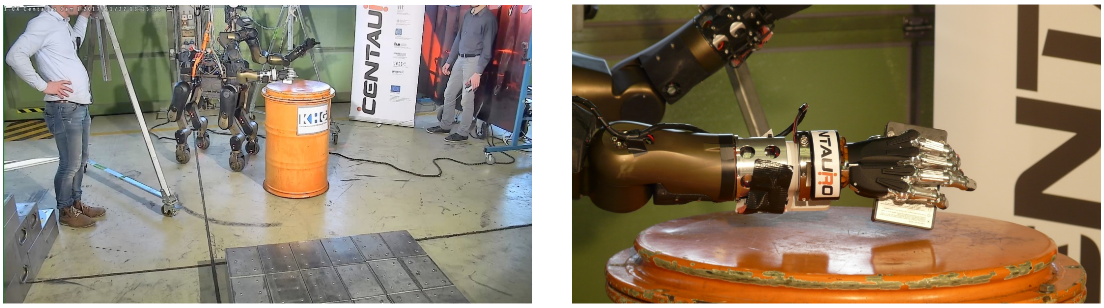


Figure 3: Following the surface of a casket, at some distance above.

Figure 4: Opening a small door.

3.2.3 Task M4: Follow Surface

This task required the robot to sweep a planar surface with a (dummy) radiation sensor without touching the surface. The robot started in front of a cask with a radiation sensor in its hand. It used either one of its arms to move the sensor over the lid of the cask, or it moves with the entire robot, see Figure 3. This task was successfully performed both using exoskeleton and the 6D mouse for wrist control and locomotion via joystick. Especially useful was the ability of the 6D mouse control to constrain hand movement to the horizontal plane, parallel to the surface.

3.2.4 Task L1a: Small Door

To open the small door the robot started directly in front of the door. The robot used one of its arms to open the door towards its body, see Figure 4.

3.2.5 Task M1a: Valve (gate type)

The valve was mounted in a height of 1 m above the floor. The wheel had a diameter of 8 cm and was mounted vertically. It was positioned in the middle of the work range. The robot started directly in front of the valve, see Figure 5. This task was solved successfully by using the telepresence suit.

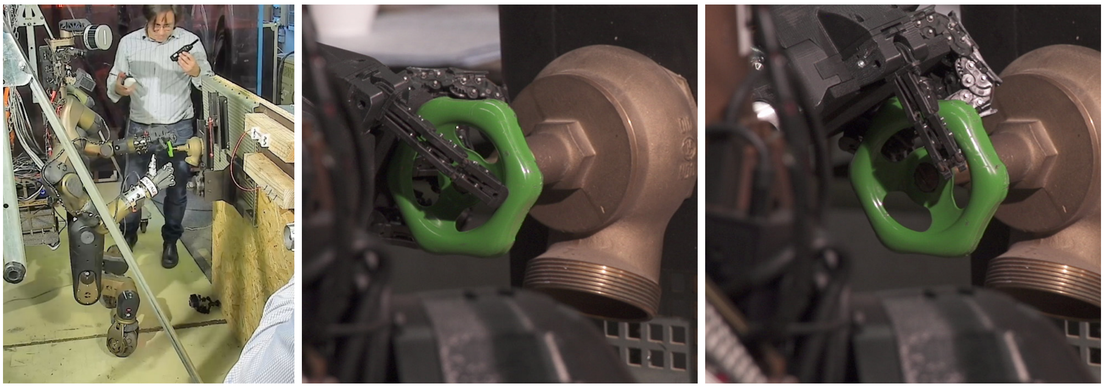


Figure 5: Manipulation of gate type valve.

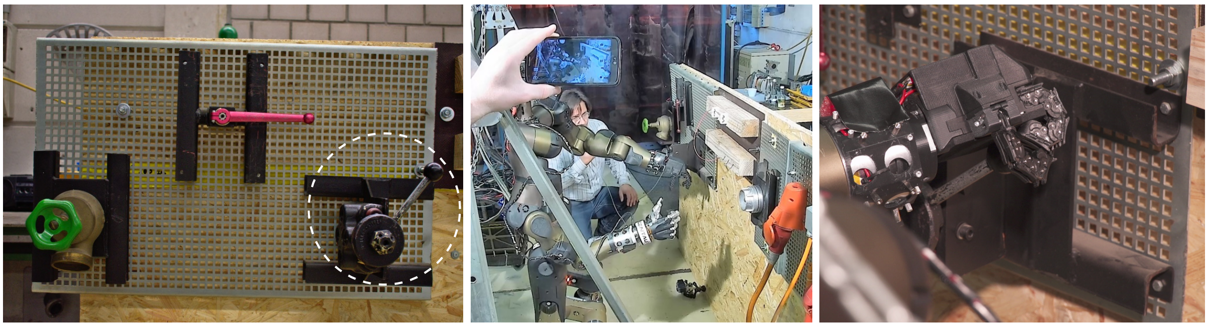


Figure 6: Manipulation of lever type valve.

3.2.6 Task M1b: Valve (lever type)

The valve was mounted in a height of 1 m above the floor. The lever had a length of 10 cm and was mounted vertically. It was positioned on one end of the work range. The robot started directly in front of the valve, see Figure 6. As for the gate type valve, this task was solved with the exoskeleton.

3.2.7 Task M8: Cutting Tool

A flexible wire, to be cut, was mounted at a height of 1 m above the floor. The wire had a diameter of 1 mm and was fixed between two clamps horizontally. The powered cutting tool was in the hand of the robot. The robot starts directly in front of wire, see Figure 8 and details in Figure 7. The test was performed under exoskeleton control. The tool was not easy to trigger, which accounts for the large number of failed attempts. A modification on the tool to enlarge the trigger would increase the success rate.

3.2.8 Task M5: Snap-hook

A snap-hook should be fixed in a metal ring. The robot started directly in front of the ring, with the snap-hook in the hand, see Figure 9. The telepresence suit was used to solve this task.

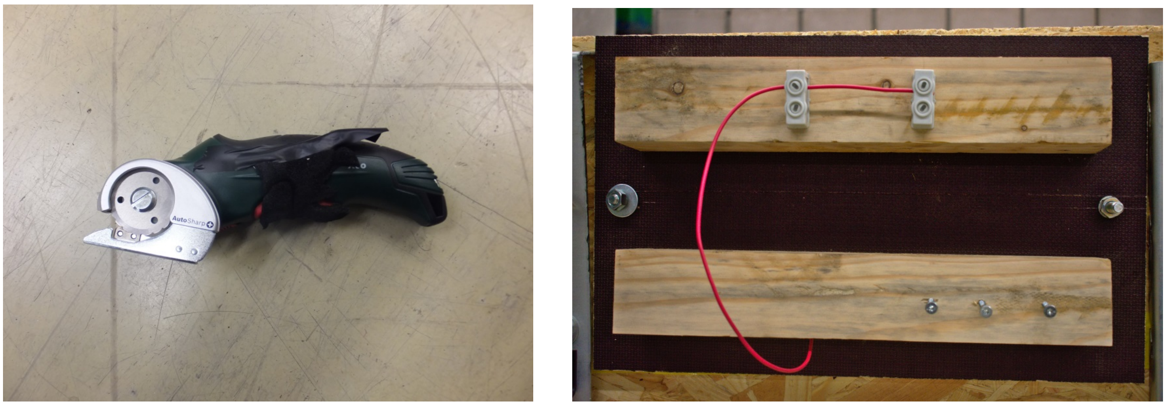


Figure 7: Left: the cutting tool. Right: the wire before being cut.

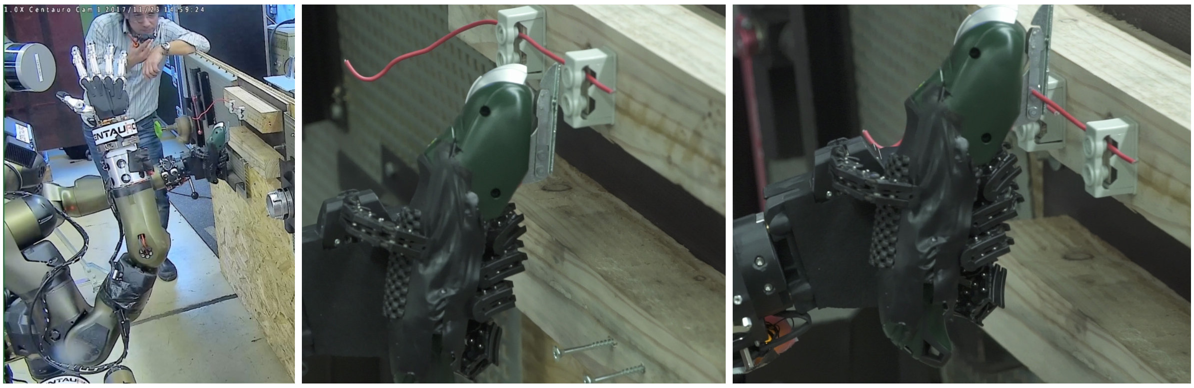


Figure 8: Cutting a wire.

Figure 9: The snap-hook is hooked to a metal ring.

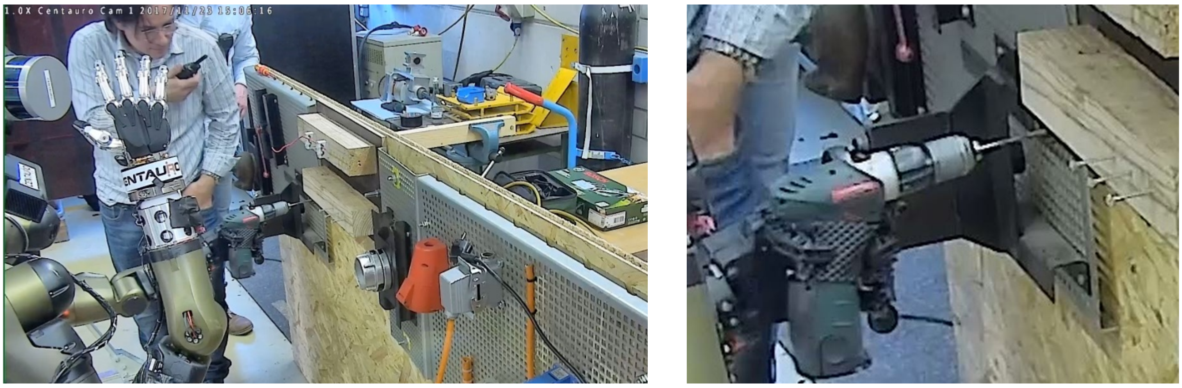


Figure 10: Drilling holes in a block of wood.

Figure 11: Driving screws into a block a wood.

3.2.9 Task M7: Driller

Three holes of 6 mm diameter had to be drilled in a piece of wood mounted at a height of 1 m above the floor. The holes should be drilled to the complete length of the driller. The robot started directly in front of the piece of wood with the driller in the hand, see Figure 10. This task was performed without problems using exoskeleton control.

3.2.10 Task M6: Screw Driver

Three screws (diameter 5 mm, TORX) had to be fastened completely in a piece of wood mounted in a height of 1 m above the floor. The screws were pre-mounted in a sense that the screws had three pre-turns in the wood. The robot started in some distance to the workspace with the cordless powered screw driver in the hand, see Figure 11. The wooden block was approached using joystick locomotion, mainly guided by camera images and the 3D laser scanner point cloud. After approaching the wooden block, the tip of the screw driver was aligned with the screw using 6D mouse control, guided by camera images. For gaining an additional perspective, a small webcam was mounted on the other hand, providing a controllable-viewpoint perspective to the operators. After alignment was visually confirmed, the cordless screwdriver was activated using the index finger of the robot. During the screwing process, the operators had to ensure that the tool tip was in constant contact with the screw head, which was facilitated using the single-axis mode of the 6D mouse interface. Overall, three out of three attempts were successful.

Figure 12: Connecting a 230 Volt plug to a socket.

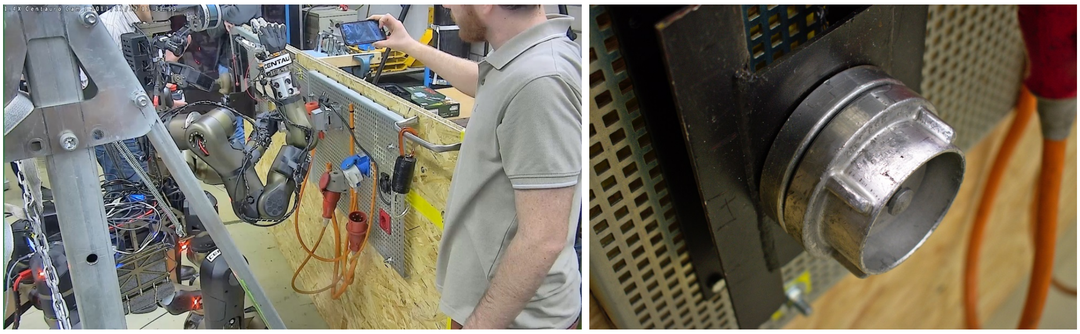


Figure 13: Connecting a fire hose to nozzle.

3.2.11 Task M3: 230 Volt Connector

A household 230V connector had to be pulled out and pushed in a wall socket mounted in a height of 1 m above the floor. The robot started directly in front of the socket with the connector in the hand, see Figure 12. We attempted both exoskeleton and 6D mouse control. Here, the exoskeleton test suffered from inconvenient wrist poses and insufficient precision for inserting the plug. The 6D mouse control was more suited for this task, since very small adjustments could be made easily. After successful completion of the third attempt, a plastic part in the robot wrist broke due to excessive force—the operators had misjudged the situation slightly.

3.2.12 Task M2: Fire Hose

A fire hose had to be connected and disconnected. The connector was secured by a lock which required a 90 degrees rotation to connect and disconnect. The robot started directly in front of the fixed part of the fire hose in a height of 1 m above the floor, see Figure 13. The robot managed to grasp and disconnect the connector; however it failed to reconnect it during the three trials which were made due to insufficient precision under exoskeleton control.

3.2.13 Task L1b: Regular Door

To open the regular door, the robot started directly in front of the door. The robot used one of its arms to open the door, away from its body. It had to keep open the door and then to drive through it, see Figure 14.

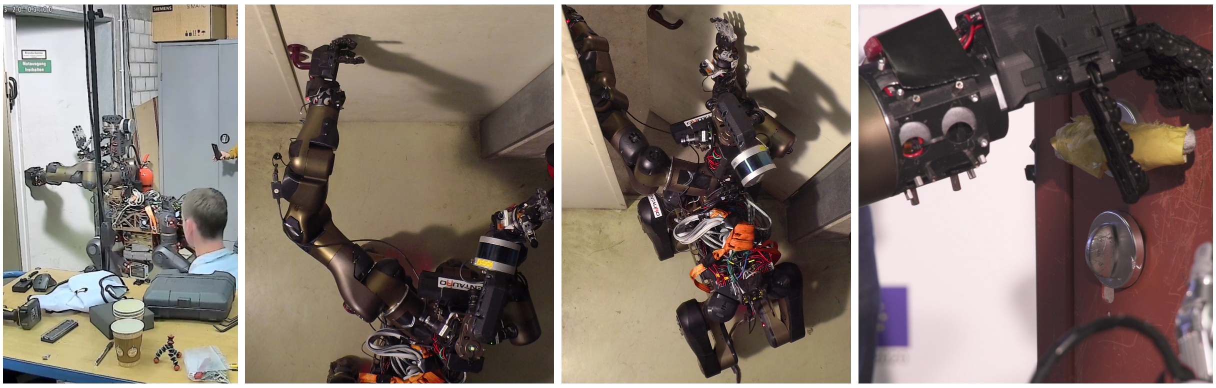


Figure 14: Going through a regular door.

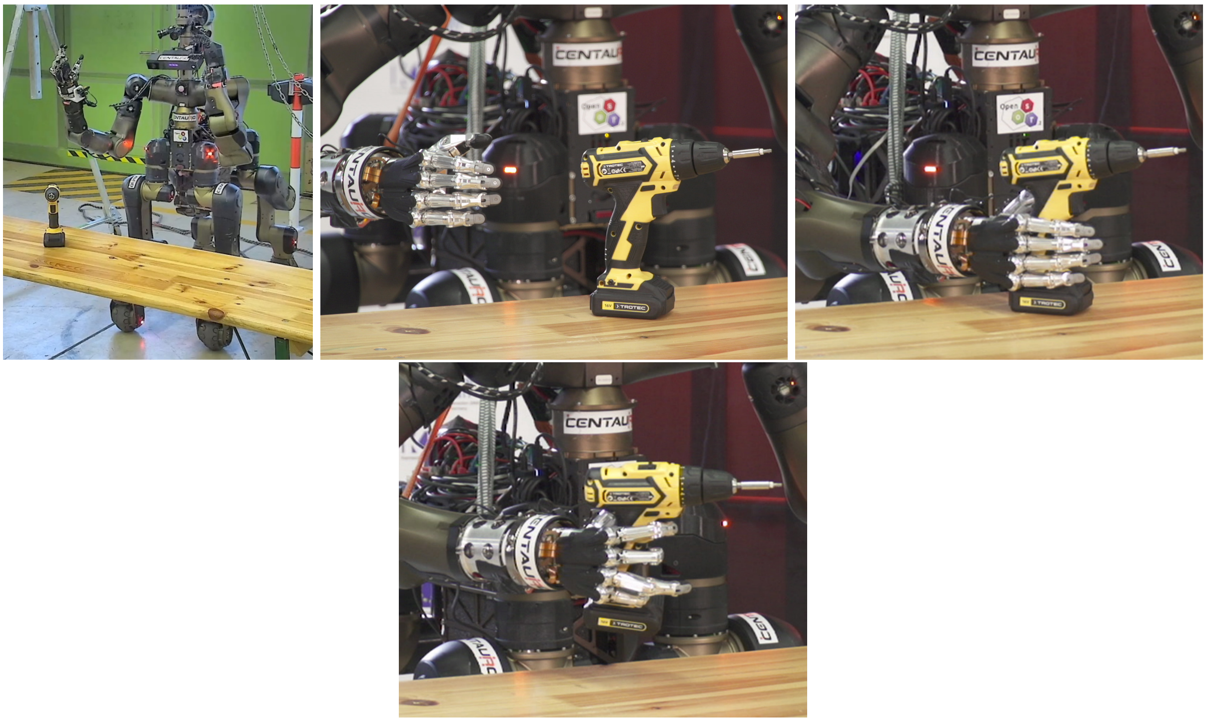


Figure 15: Autonomous grasping of the drilling tool.

3.2.14 Task A1: Autonomous Grasping

To grasp the driller autonomously, the robot started directly in front of the table which was used to position a previously unknown driller. In contrast to all other tasks, where a human operator was “in the loop”, in this task the robot worked autonomously. Using sensor data and information about the tool which should be grasped, the position and orientation of the tool was estimated and the best strategy to grasp the object was calculated and performed by the robot. The objective was to detect, segment, and estimate the pose of the driller, plan feasible trajectory and grasping motions and execute them.

We performed this experiment multiple times, since it had a higher failure rate due to the complexity and the number of involved components. Failure cases included imprecise segmentation or misregistration, both resulting in missed grasps, and hardware failures. Overall, the success rate improved during testing.

Figure 16: Climbing a 4-steps stair.

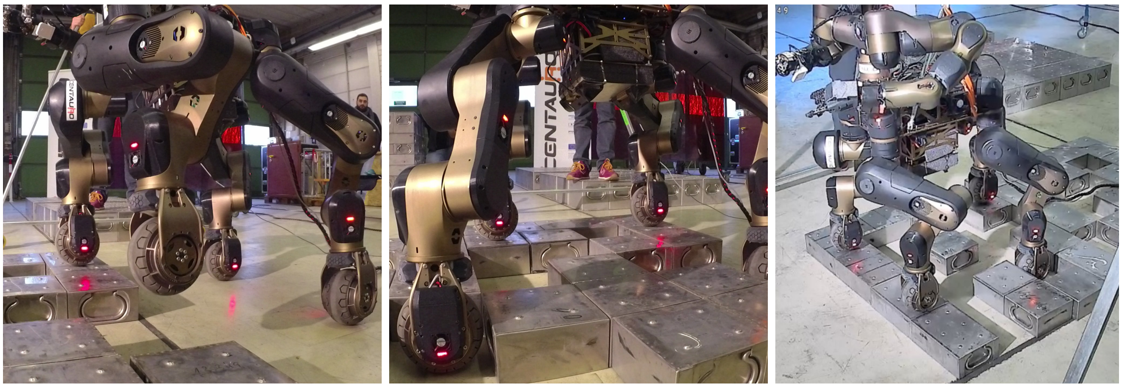


Figure 17: Moving across a step field.

3.2.15 Task L3: Stairs

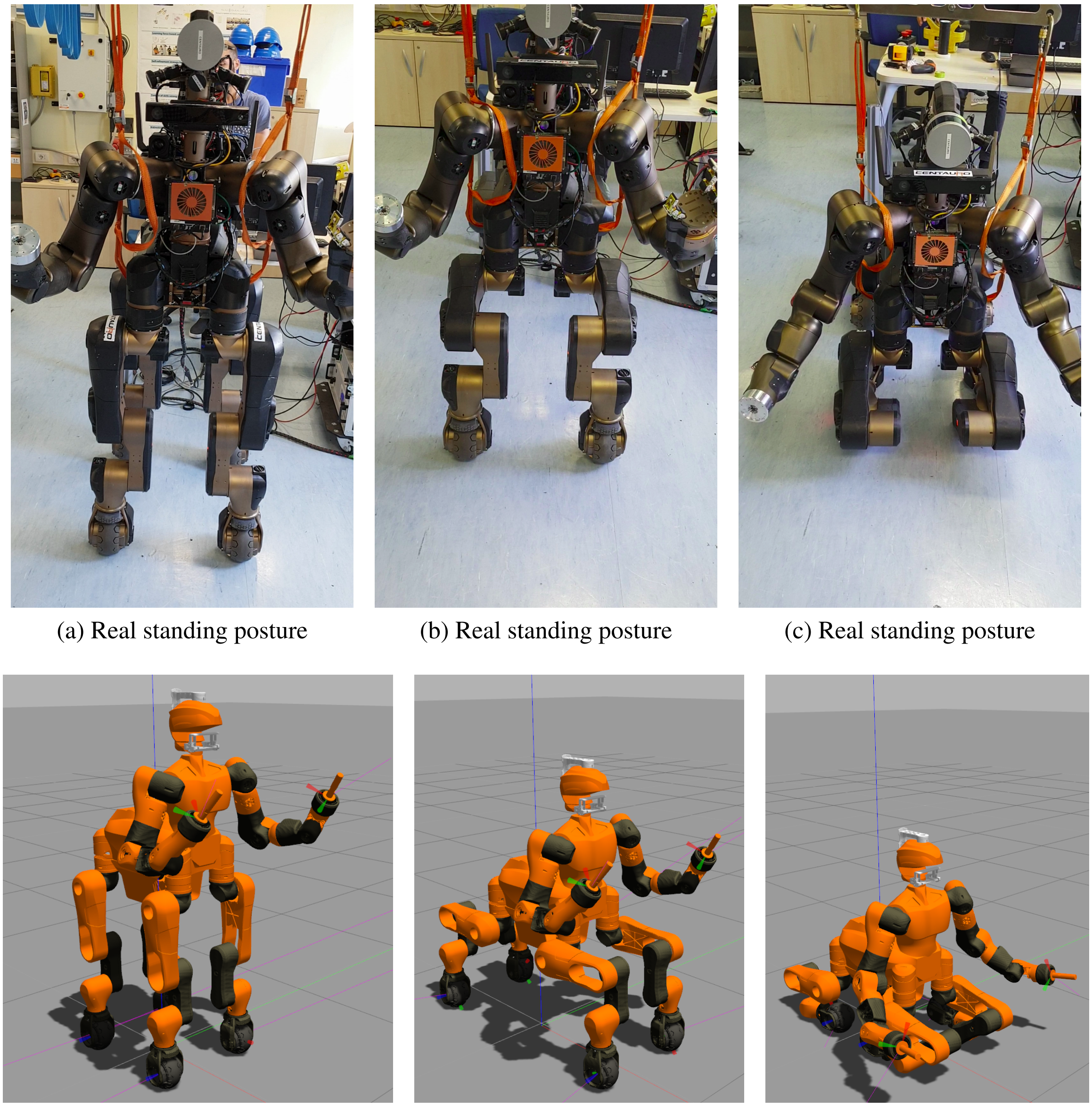
The most stressful task for the robot hardware was performed by climbing a set of stairs. The robot started directly in front of the stair. The stair had 4 steps with a height of 20 cm and a slope of 20°, see Figure 16. For this purpose, motion primitives were designed offline before the test, and executed under supervision of the operators, which could take corrective action using the joystick. Due to hardware problems caused by the high load, it was only possible to make one serious attempt at climbing the stairs, which had to be stopped after an actuator shutdown halfway up—with the robot being completely on the stairs.

3.2.16 Task L2: Step Field

The step field consisted of $20\times20\times10$ cm blocks which were placed on the ground. The maximum height difference was 10 cm. The robot started directly in front of the step field. The operators issued stepping commands via the semi-autonomous stepping GUI. The step field was traversed reliably two out of two attempts.

4 Evaluation of Core Component Robot Lower Body

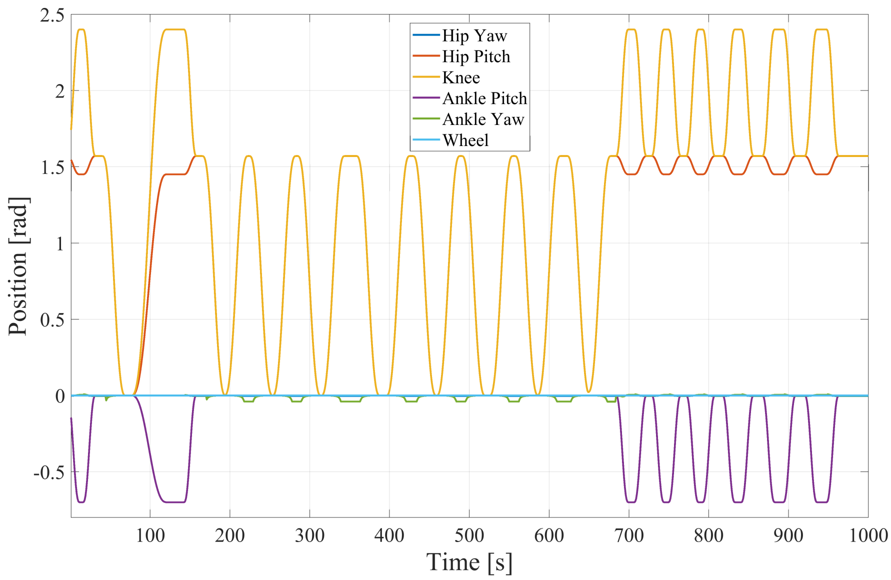
The performance validation of the lower body in terms of torque capacity for executing demanding motions is presented in this section since the tests at the Evaluation camp provided valuable insight on system level but the individual performance and robustness of the lower body is key to a successfully execution of most tasks and has not been evaluated before. The robot is therefore commanded to perform a set of postures demanding large efforts. Simulation snapshots of the robot, as well as the robot snapshots during the experiment, are presented in Fig. 18. The postures are experimentally executed on the robot for about 16 minutes. The evolution (in the last one minute of motion) of joint positions associated with one of legs is shown in Fig 19, and that of joint torques corresponding to one of the rear legs and one of the front legs is presented in Fig. 20.



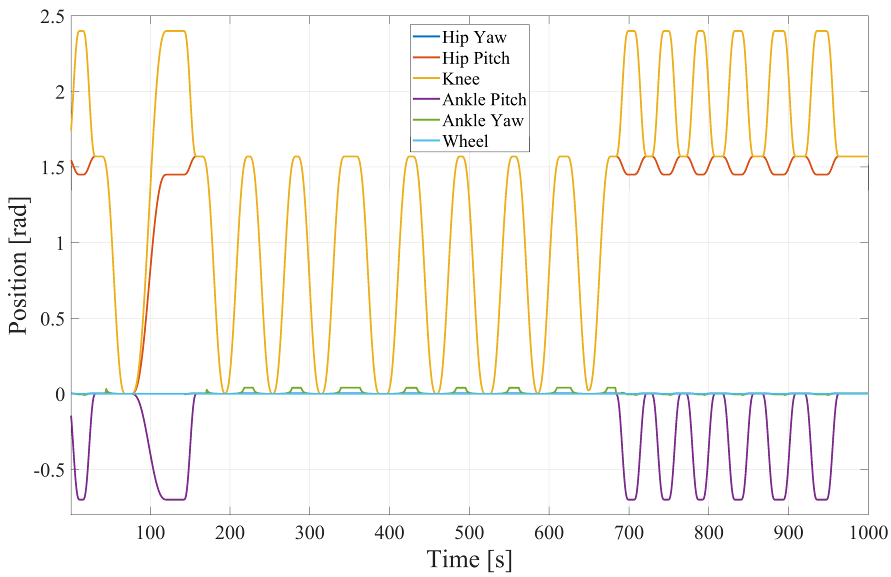
(a) Real standing posture (b) Real standing posture (c) Real standing posture

(d) Simulated standing posture (e) Simulated sitting posture (f) Simulated parking posture

Figure 18: Simulation snapshots of the robot in squat motion.



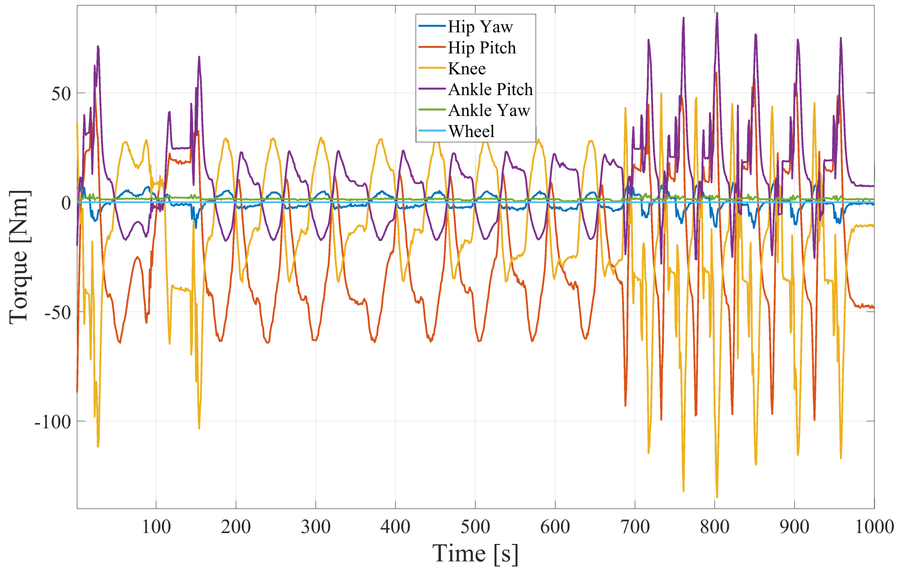
(a) Rear leg joints



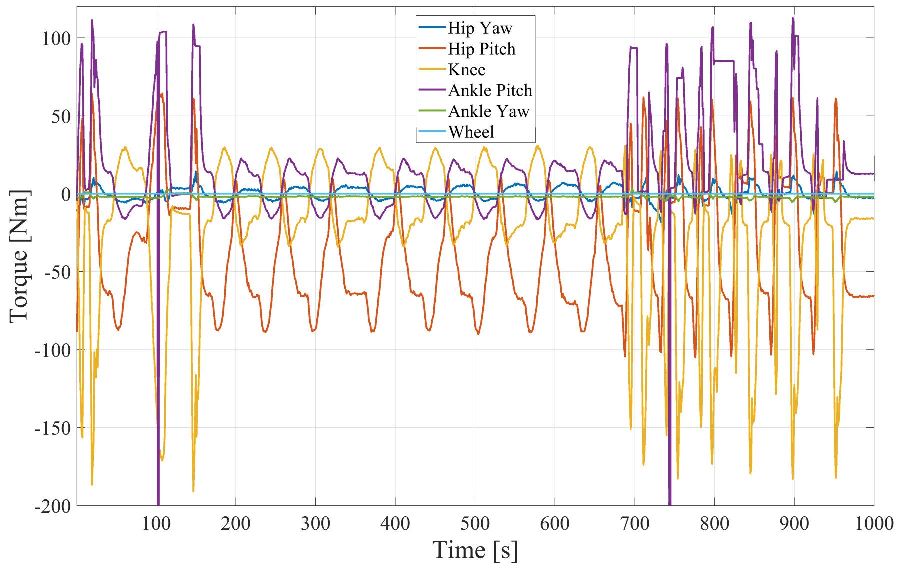
(b) Front leg joints

Figure 19: Time history of leg joint positions.

The temperature data of these joint were acquired in 2 Hz, and are shown in Fig 21. One can see the temperatures of most joints start decreasing when reaching 50^{o}C. This behavior is due to the limit set on the operation of fans to ensure they will function only when it is necessary i.e. the temperature is greater or equal to 50^{o}C, while fans stop working when the temperature goes below 45^{o}C.

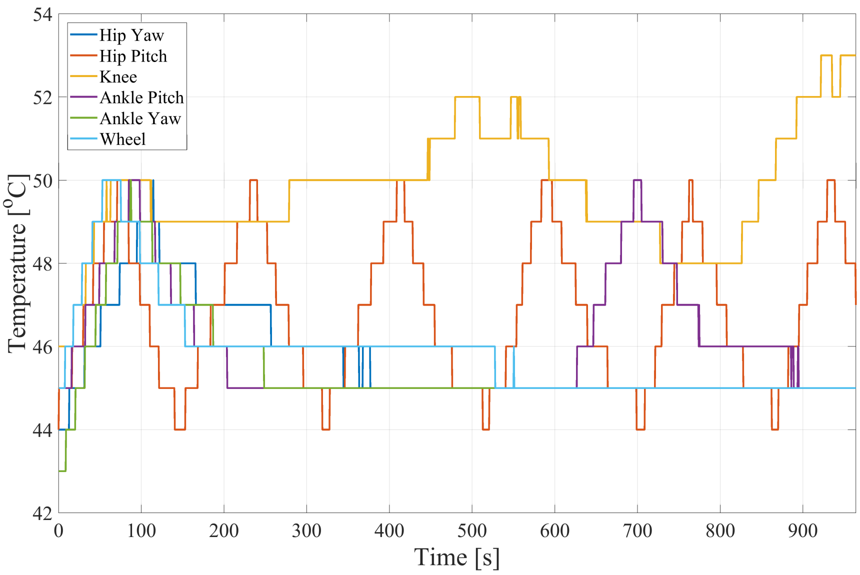


(a) Rear leg joints

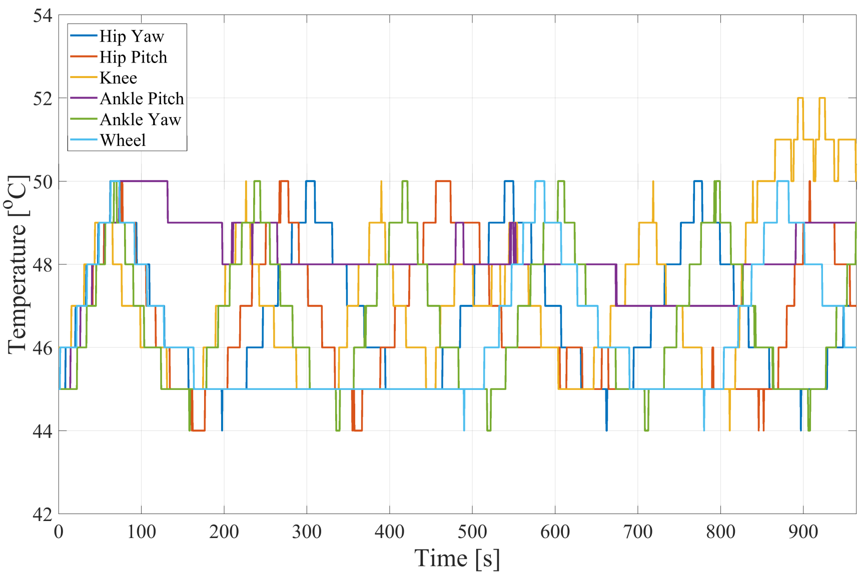


(b) Front leg joints

Figure 20: Time history of leg joint torques.



(a) Rear leg joints



(b) Front leg joints

Figure 21: Time history of leg joint temperature.

5 Summary and Conclusion

A detailed description of the results from the evaluation is found in the protocols, provided in Appendix A. These results are summarized in Table 4.

In summary, during the first evaluation tests, 16 tasks were performed. Most of the tasks have been carried out with success (9 tasks), or with partial success (6 tasks). Only one of the evaluated tasks (L3 Stairs) failed.

Overall, the locomotion capabilities were demonstrated successfully. The more complex tasks would have been impossible to finish in acceptable time without autonomy functions. We are confident that remaining hardware issues can be addressed to improve robustness in high-load situations. The manipulation tests successfully showcased a wide variety of manipulation capabilities. The exoskeleton allowed for intuitive and robust manipulation, while the 6D mouse control facilitated the precise incremental adjustments required for intricate manipulation.

	Task	Task Name	Number of Trials				PAL	Remarks
			Total	With success	Partial success	Without success		
1	L4	Ramp	3	3				
2	L5	Gap	4	3		1		
3	M4	Follow Surface	2	2				
4	L1a	Small Door	3	3			x	
5	M1a	Valve (gate type)	3	3			x	
6	M1b	Valve (lever type)	2	2				
7	M8	Cutting Tool	9	3		6		
8	M5	Snap-hook	2	2				
9	M7	Driller	4		4		x	Driller manually switched on
10	M6	Screw Driver	5	3	1	1	x	PAL only when using LEFT HAND
11	M3	230V Connector	8	3	1	4	x	PAL only when using LEFT HAND
12	M2	Fire Hose	3		1	2		Hose opened only in one direction
13	L1b	Regular Door	3		3			Only in one direction (door opened in the direction of motion)
14	A1	Autonomous Grasping	14	2	5	7		
15	L3	Stair	4			4		
16	L2	Step Field	2		2			Nudging two steps during walking

Total number of trials	71	29	17	25
Total number of tasks	16	9	6	1

Table 4: Evaluation statistics.

In addition, we presented multiple experiments to evaluate several modules on component level.

5.1 Levels of Autonomy

At the current level of the CENTAURO performance, nearly all tasks are done with the "man in the loop". That means that a human operator is performing the task using a suitable selection of input devices and sensor data generated by the CENTAURO system. The successful finishing of the task is then deeply influenced by the skills of the operator and the boundary limitations, like sight to the scene. To respect these factors, and to "equalize" the influences to the results of the performance tests in this first evaluation step, it was allowed that the operator was supported by an additional *person at the location*: PAL. The PAL could then support the operator with optical or acoustic feedback and thereby helping to complete the task.

Of the 16 tasks, all but one were done using the "man-in-the-loop" concept. Of these, five tasks have been done with the PAL. Task A1 was carried out in autonomous mode.

5.2 Analysis

The main reason for the number of tasks with partly success was the late integration of the components in the human-machine-interface. The time for training with the complete system was too short to get a reliable access to the functionality of the complex CENTAURO robot. The "man-in-the-loop" factor played an important role during the execution of a task. A valuable insight is that operators still prefer 2D camera images over 3D visualizations. While the latter are certainly helpful in addition to 2D images, in general, operators tended to rely on camera images. Since we still believe that immersive 3D visualization is a fundamentally better solution, this can mean that the available 3D sensing, aggregation, and fusion with 2D camera images is not good enough yet. Also, more operator training with the 3D visualization could help.

Another insight is that the most appropriate interface for a task is very dependent on the specific task. Our telepresence suit provides a high degree of immersion and thus a very intuitive teleoperation, but for some tasks, other interfaces showed better performance. e.g. operating an electrical screw driver for driving a screw was easier with the 6D mouse interface.

The root cause for failure in task L3 (Stair) was a weakness in the design of the lower body of the Centauro robot. In the evaluation it seemed that the rear legs of the robot did not have enough power to lift the robot completely to the stair. The lower body evaluation in Section 4 demonstrates that this issue has been addressed.

Overall, we demonstrated a highly versatile, intuitive, and robust robotic system capable of solving a wide range of complex disaster-response tasks under the guidance of remote human operators. The evaluation gave us valuable insights for the developments in the final phase of the CENTAURO project, towards the final demonstration of integrated realistic disaster-response missions.

5.3 Conclusions

In summary, the first evaluation tests have shown that the CENTAURO system mainly complies with the specified functionality. The remaining analyzed issues will be addressed until the final CENTAURO system evaluation.

A Appendices

CENTAURO Test protocol "Complete system"							
Functionality		**Locomotion**		**Date** **22.11.17**			
Task Nr.	**L1a**	**Taskname**	**Small Door**	**Modus**	**Manual** ☒ **Auto** ☐		
Subtask		**Opening a door**		**Number of trial**	**3**		
Starting parameters							
Robot 1m in front of the door. Door: 90cm x 90cm right flanged unlocked							

Task description	**Target**	**Actual**	**Time**	**Duration**
Using a handle the door should be opened towards the robot	Door is open and kept open	Door open and kept open Robot directly in front of the door Opening with left hand Operator guided by PAL???	Start 13:45 End 13:52	50 sec 35 sec 40 sec
		If not possible record on backside or separate paper		
Photo or video takes refer to:				

CENTAURO Test protocol "Complete system"						
Functionality	**Locomotion**		**Date** **23.11.17**			
Task Nr.	**L1b**	**Taskname**	**Regular Door**	**Modus**	**Manual** ☒ **Auto** ☐	
Subtask	**Opening a door**		**Number of trial**	**3**		
Starting parameters						
Robot 1m in front of the door. Door: 200cm x 90cm right flanged unlocked						

Task description	**Target**	**Actual**	**Time**	**Duration**
Using a handle the door should be opened from both sides and the robot should go through the door	Door is open and robot has moved through the door	Door was open and robot moved through the door in one direction (opening the door in driving direction)	Start 19:15	13 min 10 min 11 min
			End 20:15	
		If not possible record on backside or separate paper		
Photo or video takes refer to:				

CENTAURO Test protocol “Complete system”			
Functionality	**Locomotion**	**Date** **22.11.17**	
Task Nr. **L2**	**Taskname** **Step field**	**Modus**	**Manual** ☒ **Auto** ☐
Subtask	**Walking over the stepfield**	**Number of trial**	**2**
Starting parameters			
Robot 0.,5m in front of the stepfileld. Stepfield LxW: 250 cm x 150 cm max. Diff. Heigth : 10cm			

Task description	**Target**	**Actual**	**Time**	**Duration**
Walking over the stepfield	Walk over the stepfield without falling	Walked over the stepfield, turned and walk back without falling While walking nudging 2 steps	Start 14:10	15 min 14.5 min
			End 14:55	
		If not possible record on backside or separate paper		
Photo or video takes refer to:				

Evaluation protocol “Stair”: Annex

Trial Nr.	**Description**	**Duration**	**Result**	**Remark**
1	FLL, FLR on step 1 FLL on step 2 while lifting FLR to step 2 robot falls	5 min	Robot falls	FLL: FRONT LEG LEFT
2	FLL, FLR on step 2 Communication lost	5 min	Total shutdown	Before the trial, relocation of the robot and reboot
3	FLL, FLR on step 2 BLL, BLR on step 1	4 min	One leg failed	
4	FLL, FLR on step 1	4 min	One leg failed	

CENTAURO Test protocol “Complete system”							
Functionality		**Locomotion**		**Date** **22.11.17**			
Task Nr.	**L4**	**Taskname**	**Ramp**	**Modus**	**Manual** ☒ **Auto** ☐		
Subtask		**Driving up and down a ramp**		**Number of trial**	**3**		

Starting parameters

Robot 1m in front of the ramp
Ramp; 2 loading ramps with support structure
Angle: 20°

Task description	Target	Actual	Time	Duration
Driving up and down a ramp	Drive up and down a ramp without falling	Drived up and down a ramp without falling	Start 9:15	1 min 30 sec 1 min 29 sec 1 min 10 sec
			End 9:30	
		If not possible record on backside or separate paper		
Photo or video takes refer to:				

CENTAURO Test protocol “Complete system”							
Functionality		**Locomotion**		**Date** **22.11.17**			
Task Nr.	**L5**	**Taskname**	**Gap**	**Modus**	**Manual** ☒ **Auto** ☐		
Subtask		**Walking over a gap**		**Number of trial**	**4**		
Starting parameters							
Robot 1m in front of the gap field Gap of 30cm							

Task description	**Target**	**Actual**	**Time**	**Duratiion**
Walking over a gap	Walk over the gap without falling	Walked over the gap without falling One time: Fall down to left front leg : Center of gravitiy too far forward	Start 9:35	3 min 2 min 45 sec 2 min 25 sec 2 min 50 sec
			End	
		If not possible record on backside or separate paper		
Photo or video takes refer to:				

CENTAURO Test protocol "Complete system"					
Functionality		**Manipulation**		**Date** **22.11.17**	
Task Nr.	**M1a**	**Taskname**	**Valve (Gate type)**	**Modus**	**Manual** ☒ **Auto** ☐
Subtask		**Handling a valve**		**Number of trial**	**3**

Starting parameters

Robot in front the valve
Valve in middle position between open and close
Valve wheel vertical
valve wheel diameter 8cm

Task description	**Target**	**Actual**	**Time**	**Duration**
Handling a valve	Open and close a gate typed valve	Opened and closed a gate typed valve Using left hand Operator guided by PAL	Start 15:24 End 15:36	1 min 30 sec 1 min 10 sec 1 min 20 sec
		If not possible record on backside or separate paper		
Photo or video takes refer to:				

CENTAURO Test protocol "Complete system"						
Functionality		**Manipulation**		**Date** **22.11.17**		
Task Nr.	**M1b**	**Taskname**	**Valve (lever type)**	**Modus**	**Manual** ☒ **Auto** ☐	
Subtask		**Handling a valve**		**Number of trial**	**2**	
Starting parameters						
Robot in front the valve Valve in middle position between open and close Valve lever vertical valve lever length 10 cm						

Task description	**Target**	**Actual**	**Time**	**Duration**
Handling a valve	Open and close a lever typed valve	Open and close a lever typed valve Using left hand	Start 15:17	51 sec 37 sec
			End 15:22	
		If not possible record on backside or separate paper		
Photo or video takes refer to:				

CENTAURO Test protocol “Complete system”					
Functionality		**Manipulation**		**Date** **22.11.17**	
Task Nr.	**M2**	**Taskname**	**Fire hose**	**Modus**	**Manual** ☒ **Auto** ☐
Subtask		**Handling a fire hose**		**Number of trial**	**3**

Starting parameters
Robot in front of the hose (bajonett type) Fixed part of the hose 100 cm above ground level Loose part of the hose in the gripper

Task description	**Target**	**Actual**	**Time**	**Duration**
Connect and disconnect the fire hose by pushing and turning it about 45°)	Open and close a fire hose connection	Only opened a fire hose connection Using left hand Improper grip Fire hose drops to floor	Start 17:28 End 17:46	2 min 30 sec 1 min 55 sec 1 min 58 sec
		If not possible record on backside or separate paper		
Photo or video takes refer to:				

CENTAURO Test protocol “Complete system”					
Functionality		**Manipulation**		**Date** **23.11.17**	
Task Nr.	**M3**	**Taskname**	**230V-Connector**	**Modus**	**Manual** ☒ **Auto** ☐
Subtask		**Handling a 230V-connector**		**Number of trial**	**8**
Starting parameters					
Robot in front of the connector (standard household type) Fixed part of the connector 100 cm above ground level Loose part of the connector in the gripper					

Task description	**Target**	**Actual**	**Time**	**Duration**
Connect and disconnect a 230V-connector by pulling and pushing the loose part in the fixed part	Connect and disconnect a 230V-connector	Exosceleton (5 trials) • Left hand • Disconnect 1 time • Disconnect/Connect passed 1 time • Operator guided by PAL 6D mouse (3 trials) • Schunk hand • Disconnect/Connect passed 2 time • Hand lost after 3 trial	Start 16:45 End	Exo 3 min 5 min UBO 5 min 1 min
		If not possible record on backside or separate paper	18:00	
Photo or video takes refer to:				

CENTAURO Test protocol "Complete system"						
Functionality		**Manipulation**		**Date** **22.11.17**		
Task Nr.	**M4**	**Taskname**	**Detection of a surface**	**Modus**	**Manual** ☒ **Auto** ☐	
Subtask		**Detection of a cask lid section**		**Number of trial**	**2**	
Starting parameters						
Robot in front of the Cask						

Task description	**Target**	**Actual**	**Time**	**Duration**
Gripper follows the surface of a standard cask in a defined distance (10cm; visual inspection of distance)	Gripper follows the surface	Gripper followed the surface Using Exosceleton + robot arm: • Distance 5…10 cm • Operator guided by PAL Using 6D-mouse + fixed robot arm: • Distance 10 cm Using 6D-mouse + moving robot arm: • Distance +/- 3 cm	Start 13:15 End 13:25	30 sec 32 sec
		If not possible record on backside or separate paper		
Photo or video takes refer to:				

CENTAURO Test protocol "Complete system"						
Functionality		**Manipulation**		**Date**		
Task Nr.	**M5**	**Taskname**	**Snap-hook**	**Modus**	**Manual** ☐ **Auto** ☐	
Subtask		**Hook snap-hook in a ring**		**Number of trial**	**3**	
Starting parameters						
Robot in front of the ring Ring fixed 100 cm above ground level Snap-hook in the gripper						

Task description	**Target**	**Actual**	**Time**	**Duration**
Hook the snap-hook in the ring	Snap-hook hooked in the ring	Snap-hook hooked in the ring	Start 15:57	17 sec 23 sec 19 sec
			End	
		If not possible record on backside or separate paper	16:05	
Photo or video takes refer to:				

CENTAURO Test protocol "Complete system"							
Functionality		**Manipulation**		**Date** **23.11.17**			
Task Nr.	**M6**	**Taskname**	**Screw driver**	**Modus**	**Manual** ☒ **Auto** ☐		
Subtask		**Turn a screw**		**Number of trial**	**5**		
Starting parameters							
Robot in front of a woodblock Woodblock fixed 100 cm above ground level Screw pre-mounted in the woodblock Electric screw driver in the gripper							

Task description	**Target**	**Actual**	**Time**	**Duration**
Use a electric screw driver and turn screw completely in the woodblock	Screw completely in the woodblock	a,b: Exosceleton • Left hand • Screw turned about 5 times • Operator guided by PAL c, d,e: 6D mouse • Schunk hand • Screw turned completely in	Start 15:20 End	a:1min20sec b: 1min 40sec c: 23min d: 4min 30sec e: 3,im10sec
		If not possible record on backside or separate paper	16:05	
Photo or video takes refer to:				

CENTAURO Test protocol "Complete system"							
Functionality		**Manipulation**		**Date** **23.11.17**			
Task Nr.	**M7**	**Taskname**	**Driller**	**Modus**	**Manual** ☒ **Auto** ☐		
Subtask		**Drill a hole**		**Number of trial**	**4**		
Starting parameters							
Robot in front of a woodblock Woodblock fixed 100 cm above ground level Electric driller (6mm) in the gripper							

Task description	Target	Actual	Time	Duration
Use a electric driller and drill a hole of 6mm diameter	Hole (6mm; complete length of the driller)	Exosceleton • Left hand • Driller manually switched on • Hole (6 mm; 1 cm deep) • Operator guided by PAL	Start 15:05	2 min 15 sec 40 sec 1 min 20 sec 3 min 31
			End	
		If not possible record on backside or separate paper	15:15	
Photo or video takes refer to:				

CENTAURO Test protocol "Complete system"					
Functionality	**Manipulation**		**Date**		
Task Nr.	**M8**	**Taskname**	**Cutting tool**	**Modus**	**Manual** ☒ **Auto** ☐
Subtask	**Cut a cable**		**Number of trial**	**9**	

Starting parameters

Robot in front of a cable
Flexible wire (1,5mm) fixed at two points 100 cm above ground level
Electric cutter in the gripper

Task description	**Target**	**Actual**	**Time**	**Duration**
Use a electric cutter and cut a wire (1,5mm)	Cable completely cut	Exosceleton • Left hand Several times lost contact with tool trigger	Start 14:45	20 sec 45 sec 34 sec
			End	
		If not possible record on backside or separate paper	15:00	
Photo or video takes refer to:				

Evaluation protocol “Autonomous grasping”: Annex

Tests performed with Schunk hand				
Trial Nr.	**Description**	**Duration**	**Result**	**Remark**
1	Screw driver grasped	6 min	not in a good posture	
2	Screw driver upsetted	4 min		
3	Screw driver grasped	1 min	not in a good posture	
4	Screw driver shifted	4 min		Before the trial, relocation of the robot
5	Screw driver shifted	3 min		
6	Screw driver grasped and lifted	3 min	not possible to trigger	
7	Screw driver upsetted	8 min		
8	Screw driver upsetted	4 min		Before the trial, relocation of the screw driver
9	Screw driver grasped and lifted. Driver sunk down	2 min		Before the trial, relocation of the screw driver Maintenance necessary
10	Screw driver shifted	10 min	Fingers stradded	
11	Screw driver upsetted	5 min		Before the trial pre-gripping pose redefinend
12	Screw driver grasped, lifted and triggered	7 min		Before the trial new initialisation
13	Screw driver grasped, lifted and triggered	4 min		
14	Screw driver grasped	3 min		Before the trial optimization of the trajectory with Laser

References

[1] Tobias Klamt et al. Solving Disaster-response Tasks through the Centaur-like Robot Centauro: Full-body Telepresence and Autonomous Operator Assistance. *Journal of Field Robotics*. Submitted Jan 2018.

[2] Giulia Meneghetti, Michael Felsberg, and Klas Nordberg. Deliverable D8.1 CENTAURO Evaluation Concept. Technical report, 2015.

[3] K. Nordberg, M. Felsberg, K. Holmquist, F. Järemo-Lawin, A. Robinson, A. Frisoli, N. Kashiri, N. Tsagarakis, L. Muratore, M. Solazzi, D. Buongiorno, D. Chiaradia, M. Sarac, X. Chen, F. Schilling, M. Schwarz, T. Klamt, D. Pavlichenko, T. Cichon, C. Schlette, and S. Behnke. Deliverable D8.2 CENTAURO Core Component Evaluation. Technical report, 2016.