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Deliverable 8.4 Final CENTAURO System Evaluation

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Authors:	Uwe Süss, Michael Gustmann, Michael Felsberg, Tobias Klamt
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Executive Summary

This deliverable summarizes the results of the CENTAURO final system evaluation based on the system requirements formulated in Task T8.1. According to the Grant Agreement, the Final System Evaluation in Task T8.3 is the last stage of the evaluation campaign and part of milestone MS4.

During this evaluation, the CENTAURO system has performed a set of complex disaster-response tasks, benchmarking many of the system's capabilities. The tasks have been designed following special rules inspired by the ELROB 2018 (European Land Robot Trial). The results have been analysed and assessed with respect to predefined performance levels.

The overall result of this evaluation was very positive. The vast majority of the tasks could be solved completely. Almost all of the remaining tasks were partly solved. The final evaluation has shown that the CENTAURO system complies to a large extent with the specified functionality.

Contents

1 Introduction

Following the project plan, the integrated CENTAURO system with full functionality was evaluated in final test scenarios at the end of the project. These scenarios were defined in task T8.1 and are based on disaster-response benchmark scenarios and inspired by robot competitions and challenges, such as RoboCupRescue, the DARPA Robotics Challenge (DRC), the DLR SpaceBot Cup, and the European Land Robot Trial (ELROB). Input from professional rescue workers like our end user KHG has been used to ensure the relevance of the different tasks.

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 obtain a final evaluation of the system and give an assessment of its capabilities.

This deliverable contains a documentation of the final system evaluation.

2 Evaluation Planning

Before the evaluation was carried out, the rules, the test methodologies, the rating, and the different tasks for the CENTAURO system were defined.

2.1 Rules

The rules of the final evaluation test of the CENTAURO system were inspired by the ELROB 2018 (European Land Robot Trial).

2.1.1 Definition of Staff Roles

The staff involved in the evaluation was organized in:

- operating crew,
- operators,
- person at location (PAL), and
- referee.

The *operating crew* prepared the robot. During the starting procedure of the CENTAURO system, all crew members were allowed to work on it.

Two members of the operating crew acted as *operators* (main operator and support operator). As soon as the system was ready, they gave a "ready" signal this to the referee and as soon as they received the "starting" signal, they started with the task execution. During execution, the operators were not allowed to get in contact with other crew members.

The *PAL* was member of the operating crew and accompanied the robot during a task. In normal mode, no communication between the operators, the operating crew and the PAL was allowed. In the case of an operational problem and with the consent of the referee, the operators were allowed to contact the PAL who could potentially interact with the robot. In case of an emergency, the PAL could interrupt the operation (emergency stop).

The *referee* was not member of the operating crew. He was responsible to define the operation start and communicate this "start signal" to the operators. In addition, he rated and recorded the success on task fulfillment and supervised the compliance with the rules. In case of an emergency, he could also interrupt the operation (emergency stop).

2.1.2 Operation Modes

There were two operation modes defined:

- Tele-operated robot operation and
- Supervised autonomous robot operation.

In *tele-operated mode*, the operators were allowed to control the robot at any time during the trial.

In *supervised autonomous mode*, the robot operated autonomously while supervised by the operators. Direct control was only allowed to provide the robot with necessary input data before the robot starts operation and to receive result data from the robot after the trial finished. During the tests, the operators were allowed to monitor the system. However, for safety reasons, the operators were always able to stop autonomous execution and to take over control or the system.

2.1.3 Test Procedure

To start a test, the scenario and the robot had to be set up. As soon as the robot was in the defined starting configuration and all required hardware and software systems on the robot side

as well as on the operator side were started, the main operator gave the “ready signal” to the referee. As soon as the “start signal” was given by the referee, task execution was started. The operators had no direct visual contact to the robot or its workspace at any time during the procedure.

Data connection between the operator station and the robot was realized by either cable or wireless data link. Robot power supply was either given by cable or an internal battery. With respect to the high costs of some robot components, the robot was secured by a support structure composed of a mobile suspension and a chain block during some of the tests.

2.1.4 Evaluation Measurements

Test protocols were conceived to document the test and analyze the evaluation results after execution. They contain arrays to specify the task e.g., the number of trials, the starting parameters, the test target and the achieved results.

In addition, the start and end time of the test and the operation time were recorded for each trial. The operation time is defined to be the time from the start of the task until the task is finished with either “success”, “partial success” or “no success”.

The referee rated each task by assigning a performance level. The 100 %-criterion was defined in the task description. Every interaction between the PAL and the robot, the PAL and the operators, or the referee and the robot had a negative influence on the performance measure. In case of an emergency stop, the performance level was 0 %.

Protocols for all tasks are attached in Annex A.

2.2 Evaluation Tasks

Testing arenas developed by NIST and RoboCupRescue offer a valuable testbed to evaluate the CENTAURO system. Certain test cases (tasks) were first specified in CENTAURO Deliverable D8.1 and then further defined at the CENTAURO consortium meeting at IIT, Genoa in September 2018.

These tasks were classified in the categories

- Locomotion,
- Manipulation,
- Autonomy, and
- Combined.

As a final task an

- Integrated Mission

was specified after the evaluation of the single tasks.

2.2.1 Locomotion Tasks

L2 Step field: Move the robot over an uneven field with debris.

L3 Stair: Walk up a flight of stairs.

L4 Gap: Overcome a gap.

2.2.2 Manipulation Tasks

M2 Fire hose: Connect a fire hose to a nozzle using a tool.

M3 230V-connector: Connect a standard 230 Volt and a CEE-type connector.

M4 Shackle: Attach a shackle to a handle

M5 Screw driver: Screw a wooden board to a wooden block.

M6 Driller: Drill holes at defined positions into a wooden block with a two-handed driller.

2.2.3 Autonomous Tasks

A1 Autonomous locomotion: Hybrid driving-stepping navigation over challenging terrain.

A2 Autonomous manipulation: Autonomous dual arm grasping of a power tool.

2.2.4 Combined Tasks

L1 Regular door with handle and lock: Unlock and open the door away from the robot. Move the robot through it.

M1 Valve: Approach the workspace by climbing a platform, open, and close a gate type and a lever type valve.

M7 Pipe star: Grasp and view different parts of a pipe star.

2.2.5 Integrated Mission

IM1 Integrated Mission: Multiple locomotion and manipulations tasks queued to a mission which covers many aspects of a disaster-response mission.

3 Execution of the Evaluation

To perform the different tasks, either the Full-body telepresence stations (see Figure 1), the support operator control interfaces (see Figure 2), or a combination of both was used to control the robot. The support operators interface included several subsystems such as a joystick, a keyframe editor, a semi-autonomous stepping controller, or a 6D mouse. The two tasks "Autonomous manipulation" and "Autonomous locomotion" were performed in the autonomous mode without direct control but under supervision of the operators.

Figure 1: The Full-body Telepresence suit.

Figure 2: Control interfaces of the support operators.

3.1 Task L1: Regular door

The robot started 100 cm in front of the door (H x W: 200 cm x 90 cm) which it was approach and open (see Figure 3). An adaptor for standard keys special tool (which is often used by KHG in disaster response tasks) was to be used to unlock the door with two rotations of the key (see Figure 4). The robot was to push down the door handle and open the door away from its body with its second. Finally, the robot was to move through the door.

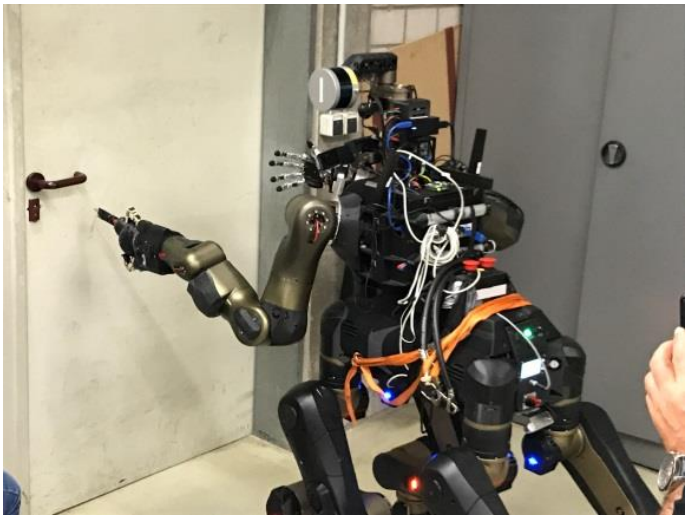


Figure 3: CENTAURO approaching the door with the key adapter in its left hand.

Figure 4: Detail view on the key adapter.

3.2 Task L2: Step field

A step field of size L×W = 240×140 cm with a maximal height difference of 20 cm was randomly generated out of concrete blocks. The step field itself followed a grid structure with 20 cm edge length. Five wooden beams were randomly placed on the field as debris. The robot started 100 cm in front of the step field and was to overcome it, as shown in Figure 5.

Figure 5: Centauro overcoming the step field.

3.3 Task L3: Stair

A stair case was built out of concrete blocks. It was 120 cm wide and was composed of three steps of 20 cm height and 30 cm depth. The topmost stair ended in a platform, as shown in Figure 6. The robot started 100 cm in front of this stair case and was to climb it to reach the goal pose on the platform.

Figure 6: Stair case.

3.4 Task L4: Gap

Two platforms of 140 cm width and 120 cm length with a 50 cm gap between them were composed out of concrete blocks. The robot started on the one platform and was to overcome the gap to reach the goal pose on the other platform. Figure 7 depicts the task.

Figure 7: Centauro in the start configuration of the gap task.

3.5 Task M1 Valves (gate type; lever type)

Two valves of gate type (8 cm diameter) and lever type were mounted on a wall at 120 cm height. A platform of size W×L×H = 140×60×20 cm was positioned in front of the valves on the ground. The robot was to start 100 cm in front of the platform. It was to climb the platform with its front feet to obtain a suitable manipulation pose, as shown in Figure 8. It was then to open and close both valves.

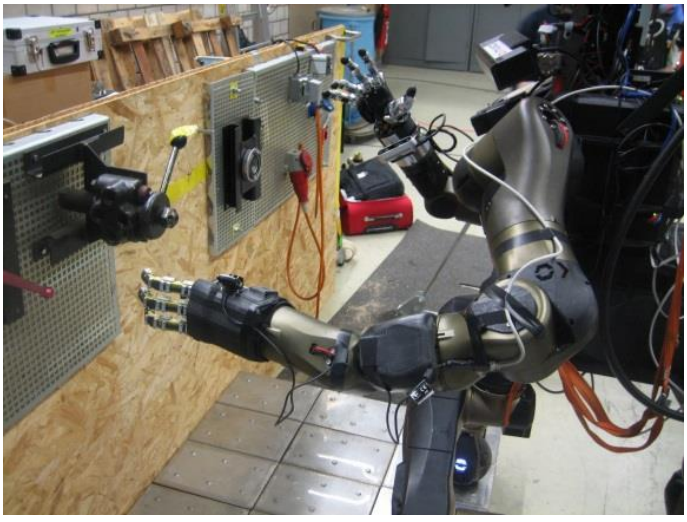


Figure 8: Centauro climbing the platform with its front feet to obtain a suitable manipulation pose for the valves.

3.6 Task M2: Fire hose

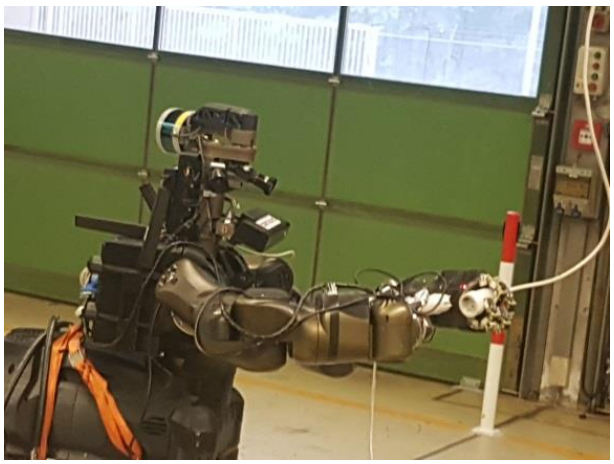
A nozzle was mounted in a height of 100 cm. The robot started 100 cm in front of the nozzle with a fire hose in his one hand and a corresponding tool in the other hand. The robot was to approach the nozzle, connect the fire hose to the nozzle, and use the tool to fasten it (Figure 9).

Figure 9: Centauro using a special tool to fasten the fire hose to the nozzle.

3.7 Task M3: 230 Volt Connector

In the first subtask, a standard household 230 V connector had to be plugged in a cable-outlet. The robot started with the plug in his right hand. The outlet was hanging from the ceiling, positioned in a reachable position in front of the robot. Figure 10 left shows Centauro performing this subtask.

In the second subtask, the robot had to plug a CEE-Type 230 V connector into an outlet, mounted at the wall in a height of 100 cm. The robot was to open the lid with his one hand before inserting the plug which was positioned in his other hand, as shown in Figure 10 right.



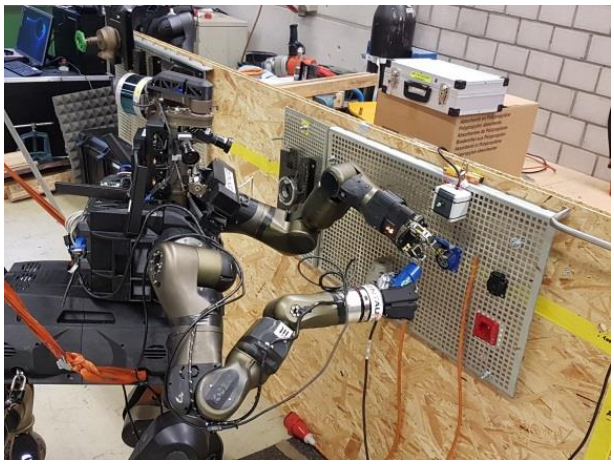


Figure 10: Centauro performing the plug task. Left: Standard 230 V household plug.
Right: CEE-Type 230 V plug.

3.8 Task M4: Fixation of a shackle

A metal ring was mounted at a wall in a height of 100 cm. The robot started in a distance of 100 cm with a shackle in its left hand and the corresponding screw, mounted to a grasping adapter, in its other hand. The robot was to approach the workspace fix the shackle to the ring which required to turn the screw by five rotations. The task execution is depicted in Figure 11.

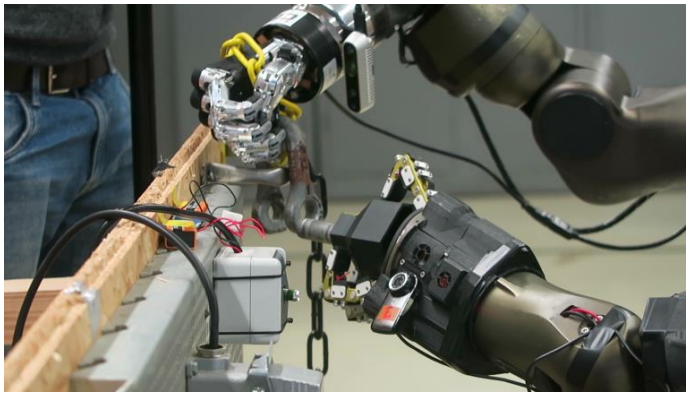


Figure 11: Centauro fixing a shackle to a metal ring.

3.9 Task M5: Screw driver

A wooden board with two pre-mounted screws was to be screwed to a wooden block at the wall in a height of about 100 cm. The robot started in 100 cm distance to the wall with the wooden board in left hand and an electrical screwdriver in his right hand. It was to position the board, and subsequently screw the screws which also included triggering the tool. Figure 12 shows Centauro during screwing.

Figure 12: Centauro screwing a screw to fix a wooden board to a wooden block.

3.10 Task M6: Driller

The robot was to drill three holes at defined positions in a wooden block at a height of 100 cm. In the start configuration, the robot already carried the two-handed driller in its hands and was positioned 100 cm away from the wooden block. Figure 13 shows how the driller tip approaches the wooden block.

Figure 13: Centauro approaching the wooden block with the driller tip.

3.11 Task M7: Pipe star

A “pipe star” (see Figure 14) which is a standard test object for the evaluation of disaster response platforms was placed on the ground. The robot was to approach the object and inspect each of the five pipes by touching it in a certain orientation and provide the operators a view in the inside of each pipe where a symbol – a so called Landoltring – was to be observed. The latter subtask was to be solved by moving on of the robot cameras to a suitable position.

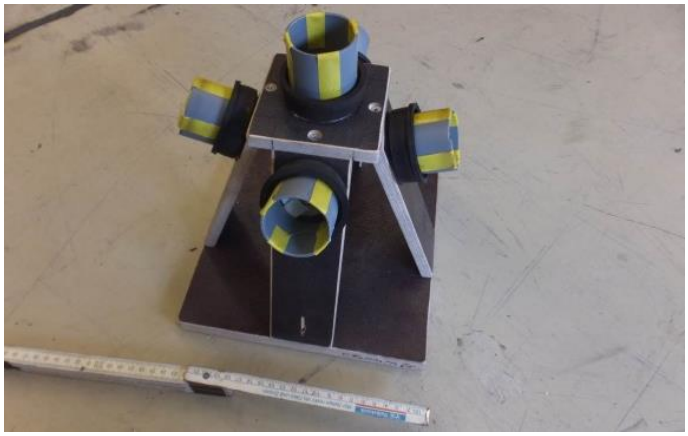


Figure 14: The used pipe star.

3.12 Task A1: Autonomous locomotion

The robot started 200 cm in front of a field of gravel and several obstacles. A flight of stairs, consisting of two steps and ending in a platform was positioned in some distance behind the gravel. First, the operator was to define a goal pose on the platform. The robot was then to plan two path alternatives to the operator. The operator was to choose one of these alternatives with the robot finally was to execute. Figure 15 shows how Centauro climbed stairs to reach the final goal pose after gravel was surrounded by omnidirectional driving.

Figure 15: Centauro autonomously climbing stairs after navigating around gravel.

3.13 Task A2: Autonomous manipulation

A two-handed driller was placed on a table. The robot started directly in front of this table (see Figure 16). It was to autonomously grasp the driller, trigger it, lift it and move it around.

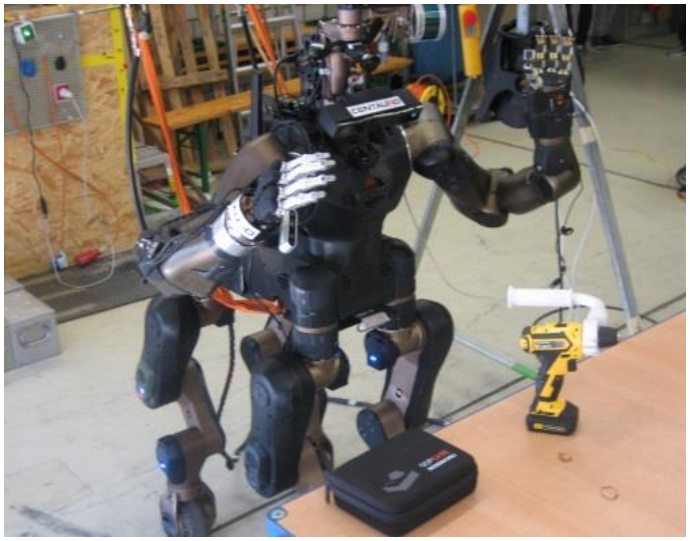


Figure 16: Centauro in front of the two-handed driller which it was to grasp autonomously.

3.14 Task IM1: Integrated mission

The integrated mission comprised multiple selected tasks. It was specified after the evaluation of the single tasks.

To provide a maximum of flexibility and to come as close to a realistic setup as possible, it was planned to perform the IM1

- with power supply by battery,
- with data connection by WiFi, and
- without crane and safety structure.

The robot was to start on the KHG courtyard in a distance to the building of about 30 m with a radiation measurement device in its hands. It was then to approach the building where it would find a radiation source to measure and read out the measurement device screen output through a robot camera. After dropping the device, the robot was to open one of the electric garage doors by pressing the corresponding button. Consequently, it was to enter the building and open an unlocked door with a handle. Subsequently, the robot was to grasp a mobile overview camera attached to a buoy and pull this through the door into the next room where it was to be positioned at a location that provides good overview.

In the new room the robot was to find a lever type valve with a 20 cm high platform in front which was blocked by a hand lift truck. The robot was to pull this lift truck away from the workspace, climb the platform with its front feet and turn the valve. Next, it was to leave the platform and disconnect an electrical plug. In another part of the room, the robot was to approach a table on which it was to find an electrical screw driver. It was to grasp this screw driver and use it to unscrew a wooden board which blocks the robot's way. To avoid the wooden board from falling down, the robot was to grasp it with its other hand before unscrewing and place it at a suitable place after unscrewing.

Finally, the robot was to leave the building through the now traversable passage and through another garage door and climb a flight of stairs with three steps which ends in a platform. A van was parked next to this platform leaving a gap of about 30 cm. The robot was to overcome this gap to enter the trunk of the van which was the goal position of this mission.

4 Evaluation Results

During the CENTAURO Final Evaluation test 17 tasks were performed. Eleven tasks have been carried out with complete success, two tasks were almost complete, three tasks have been performed with partial success, and one task failed (Table 1).

Table 1: Results of the Final Evaluation.

Nr.	Task name	Task object	Performance level			
			100%	99 - 90%	89 - 1%	0%
1	L1	Regular door with handle and lock	X			
2	L2	Step-field with debris	X			
3	L3	Stair	X			
4	L4	Gap	X			
5	M1	Valve (gate type)			X (60%)	
7		Valve (lever type)	X			
8	M2	Fire hose	X			
9	M3	230 V Connector (standard)	X			
10		230 V Connector (CEE)	X			
11	M4	Shackle	X			
12	M5	Screw driver	X			
12	M6	Use of a drill		X (90%)		
13	M7	Pipe star (position and orientation)		X (95%)		
14		Pipe star (visual)	X			
15	A1	Autonomous locomotion			X (75%)	
16	A2	Autonomous manipulation			X (75%)	
17	IM1	Integrated mission				X
		Summary	11	2	3	1

From the five tasks with non-complete success (M1, M6, M7, A1, A2), two have a performance level of over 90%. Three tasks (M1 “Valve gate type”, A1 “Autonomous locomotion”, and A2 “Autonomous manipulation”) are assessed as partial success and Task IM1 “Integrated mission” failed. An analysis of the reasons for partial success and failure is done in Section 5.

In summary, about 76% of the tasks (13 of 17) were performed successfully.

Table 2 reports the operation time for each of the tasks performed at the Final Evaluation. Again, an analysis is provided in Section 5. Table 3 lists the used control interfaces for the individual tasks.

Table 2: Operation times of the tasks performed at the Final Evaluation.

Nr.	Task name	Task object	Operat. time			Perf.	Remark
			h	min	sec		
1	**L1**	**Regular door with handle and lock**	0	13	30	100	
2	**L2**	**Step-field with debris**	**1**	**27**	**38**	100	See Analysis 5.1
3	**L3**	**Stair**	0	10	2	100	
4	**L4**	**Gap**	0	3	26	100	
5	**M1**	**Valve (Gate type)**	0	23	30	60	One turn only in each direction See Analysis 5.2
7		**Valve (lever type)**	0	6	50	100	
8	**M2**	**Fire hose**	0	10	10	100	
9	**M3**	**230V-Connector (standard)**	0	6	50	100	
10		**230V-Connector (CEE)**	0	10	0	100	
11	**M4**	**Shackle**	0	24	35	100	
12	**M5**	**Screw driver**	0	6	21	100	
12	**M6**	**Use of a drill**	0	2	50	90	On/off switch not used
13	**M7**	**Pipe star (pos+orient)**	0	14	23	95	Pipe on top only reached from one side
14		**Pipe star (visual)**	0	6	9	100	
15	**A1**	**Autonomous locomotion**	0	2	50	75	Stopped with only one leg on the platform, see Analysis 5.3
16	**A2**	**Autonomous manipulation**	0	0	0	75	Drill lost balance, see Analysis 5.4
17	**IM1**	**Integrated mission**	0	0	0	0	Problem of wireless data transmission, see Analysis 5.5

Table 3: Used control interfaces for individual tasks.

Nr.	Task name	Task object	Used control interfaces
1	**L1**	**Regular door with handle and lock**	Joystick + 6D mouse
2	**L2**	**Step-field with debris**	Joystick + Semiautonomous stepping controller + 6D mouse + Keyframe editor
3	**L3**	**Stair**	Joystick + Keyframe editor
4	**L4**	**Gap**	Joystick + Keyframe editor
5	**M1**	**Valve (Gate type)**	Joystick + Semiautonomous stepping controller + Fullbody telepresence station
7		**Valve (lever type)**	Joystick + Semiautonomous stepping controller + Fullbody telepresence station/6D mouse
8	**M2**	**Fire hose**	Joystick + 6D mouse
9	**M3**	**230V-Connector (standard)**	Joystick + Fullbody telepresence station/6D mouse
10		**230V-Connector (CEE)**	Joystick + 6D mouse
11	**M4**	**Shackle**	Joystick + 6D mouse
12	**M5**	**Screw driver**	Joystick + 6D mouse
12	**M6**	**Use of a drill**	Joystick + 6D mouse
13	**M7**	**Pipe star (pos+orient)**	Joystick + 6D mouse + Keyframe editor
14		**Pipe star (visual)**	Joystick + 6D mouse + Keyframe editor
15	**A1**	**Autonomous locomotion**	Autonomous hybrid driving-stepping locomotion planner
16	**A2**	**Autonomous manipulation**	Autonomous bimanual manipulation controller
17	**IM1**	**Integrated mission**	-

5 Analysis

5.1 Long Operation Time for Task L2 “Step field”

Overcoming the step field took a long time since no optimal user interface was available and thus, numerous manual adjustments were required. The semi-autonomous stepping controller was applicable to the step field itself but as soon as the robot had to step on one of the wooden bars, precise manual foot adjustment and balancing by keyframe editor and 6D input device was required to position the individual feet on suitable footholds.

In addition, one of the RGB cameras mounted under the robot body lost connection. The operators used the RGB camera at the robot wrist instead. This worked sufficiently well to assess the robot state but required frequent additional adjustments to obtain the necessary field of view.

5.2 Partial Success of Task M1 “Gate type valve”

The gate type valve was operated using the exoskeleton-interface. Due to mechanical problems with the wires of the drives, the valve could only be turned by one rotation in both directions. After switching to the third-person operator interfaces (6D mouse), the task was completed.

5.3 Partial Success of Task A1 “Autonomous locomotion”

The robot started in front of a patch of gravel and successfully navigated around it to climb a flight of stairs. The robot lost balance when trying to reach the first step with the second rear foot. The reason was that some hardware components such as the battery and computing units moved to different locations but these changes were not included in the digital robot model (URDF file). Hence, the weight distribution of the real robot and the simulated robot differed and the controller which was parametrized in the simulation did not know about this difference.

5.4 Partial Success of Task A2 “Autonomous manipulation”

The robot started in front of an unknown drill tool with two handles. It successfully grasped the drill with both hands and lifted it. Due to a slight misalignment of the right-hand grasp, it failed to switch the drill on. The robot put the drill back on the table, but the drill lost balance after the robot opened its hands.

5.5 Failing Task IM1 “Integrated mission”

The root of the failure in this task is still under investigation. It is probably related to the fact that the long distance between the operator station and the robot caused a limited bandwidth for the wireless data link which resulted in dropped messages of joint references and finally resulted in jumps in those references. This caused the ankle yaw joints to accelerate strongly and damage the mechanical stop of those joints.

6 Conclusions

The Final Evaluation Camp has shown that the CENTAURO system complies with the specified functionality. About 76 % of the tasks could be performed with success.

The overall approach of the CENTAURO system has been verified. Especially the use of two arms has enlarged the functionality and enhanced the range of tasks which could be performed. An example is the plugging and unplugging of the 230 V standard connector. Without using a second hand it is impossible to solve such a task.

The hybrid wheeled-legged locomotion of the Centauro robot was a well-chosen approach for the challenging and manifold disaster-response typical locomotion tasks. The hybrid driving-stepping locomotion is more flexible than the locomotion of tank-like systems. In comparison to purely legged systems, the energy efficient and fast omnidirectional driving was superior in many cases while legged locomotion was available for more challenging situations.

The evaluation has also shown that the operator interface – including the kinematic and dynamic simulation of the robot – plays an important role for the performance of the whole disaster-response system. Hence, future developments of the ergonomics could further improve the system performance. The present human-machine-interface was adapted to the skills of an experienced software engineer. Professional rescue workers might have different capabilities – the interfaces should be usable by a wide variety of operators. A deeper examination of the operator requirements and the human-robot interface could help to further improve the capabilities of the CENTAURO system towards a powerful disaster-response system, able to perform complex locomotion and manipulation tasks in hostile environments instead of rescue workers in order to mitigate the effects of disasters.

Annex A: Evaluation Protocol

Test protocol **Final evaluation CENTAURO**						
Task-Number						
Task-Name						
Modus	**Teleoperated** ☐	**Autonomous** ☐				
100%-criteria						
Max. trial number		**Trial number**				
Name of operators						
Name of PAL						
Name of referee						
Starting parameters	**ok** ☐	**not ok** ☐				
Starting time						
End time						
Operational time						
Number of interacts	**Operator**		**PAL**		**Referee**	
End of test	**100%-criteria** ☐	**Operator** ☐	**Referee** ☐			
Performance level						
Remarks[1)] 1) If not possible record on backside or separate paper						
Date	Sign of referee					

Annex B: Evaluation tasks

Locomotion

Nr.	Task object	Task Description	Difficulty No of trials	Op-Mode	Equipment	Starting point	"100%"- criteria	Remarks
L1	**Regular door** with handle and lock 200 cm x 90 cm Hinges on right side Locked with a key No Closing mechanism 240 degree rotation needed to unlock.	Opening the door away from the robot. Unlock with specially prepared key (adapter). Use handle. Keep door open. Move through the door.	6 2 trials	teleoperated	Specially equipped key	1 m in front of the door	Door is open and robot has moved through the door	IIT makes an adaptor of the key to the Heri-hand. KHG delivers specification of key adaptor. SSSA mainly interested in the unlocking part. Switch from exoskeleton to UBO interface needed. UBO prepares
L2	**Step-field** Width 150 cm Length 250 cm Made of concrete blocks max. height difference: 20 cm Debris on the field: 5 wooden beams (LxBxH:100x10x10cm)	Walking over the step field	8 3 Trials	teleoperated	Concrete blocks Debris	1 m in front of the step-field	Walk completely over the step-field without falling	KHG provides debris and bricks UBO semi-autonomous stepping Go in different directions over the step-field
L3	**Stair** 3 steps Width 100 cm step height 20 cm, depth 30 cm landing on a platform	Walking up a stair	9 2 Trials	teleoperated	Concrete blocks	1 m in front of the stair	Walk up the stair to the platform without falling	UBO motion primitives IIT makes sure that gantry works for stairs

Nr.	Task object	Task Description	Difficulty No of trials	Op-Mode	Equipment	Starting point	"100%"- criteria	Remarks
L4	**Gap** Build from concrete blocks width 50 cm	Overcoming the gap	4 3 Trials	teleoperated	Concrete blocks	On one platform in frnt	On the other platform behind the gap	UBO motion primitives

Manipulation

Nr.	Task object	Task Description	Difficulty No of trials	Op-Mode	Equipment	Starting point	"100%"- criteria	Remarks
M1	**Valve (gate type)** valve in center position mounted on a plate fixed at a workbench 120 cm above floor level wheel orientation adjustable uneven ground in front of the valve (front and back legs not at the same level	Open and close the valve (multiple turns of hand wheel)	5 2 Trials	teleoperated	Valve	1 m in front of the platform	Open and close the valve	Front legs elevated 20 cm relative to the back legs. Platform 100x60x20 Switch between stepping and left-hand manipulation
	Valve (lever type) lever length 10 cm see M1a	Open and close the valve (90° turn of lever)	4 2 Trials	teleoperated	Valve	1 m in front of the workbench	Open and close the valve	Same as above
M2	**Fire hose** Bajonett type, Fixed part mounted on a support construction in a clamp, 100 cm above the floor, orientation adjustable, Loose hose part in the gripper Use of a special tool (hook wrench) Without a seal	Connect the fire hose (push and turn 45°)	8 2 Trials	teleoperated	Fire hose Hook wrench	1m in front of the workbench Loose hose part in the left gripper, tool in the right hand	Connect the fire hose (30°)	Holes in the hose at 60° separation. Foam protection on tool by UBO
M3	**230V-Connector** Standard household "Schuko"-plug in one gripper. Outlet at reachable location with the second gripper and in a predefined orientation	Connect and disconnect the connector	7 2 Trials	Teleoperated	Standard 230V-connector	1m in front of the workbench Loose end easily accessible without moving legs	Connect and disconnect the household 230V-connector	No repositioning of legs should be required

Nr.	Task object	Task Description	Difficulty No of trials	Op-Mode	Equipment	Starting point	"100%"- criteria	Remarks
	230V-Connector CEE-Type with lid. Fixed part on the wall. Plug at reachable location with the second gripper and in a predefined orientation	Connect and disconnect the connector	8 2 Trials	Teleoperated	CEE 230V-connector with lid	1 m in front of the workbench Loose end easily accessible without moving legs	Connect and disconnect the 230V-CEE-connector	Same as above
M4	**Shackle** Closing of a shackle. Vertical ring fixed on wall M12 pin	Close a shackle	9 3 Trials	teleoperated	Shackle	1m in front of the workbench Shackle in one hand. Pin in the other hand	Metal ring hooked in the shackle Screw locked 4-5 turns	Extension of the pin may be necessary by SSSA
M5	**Screw driver** Wooden board (thickness 5mm) screwed in a wooden block. 1 m above the floor, orientation adjustable Board with 2 premounted screws in one hand, screw driver in the other, Torx 25 screw driver	Turn screws completely in the woodblock	8 3 Trials	teleoperated	TORX-25-screw driver Screws Woodblock	1m in front of the workbench Board in one hand and screw driver in the other Board approx. 10x50x2 cm	Screws completely turned in the wooden block	Space for robot hand fingers is required Screw in the woodblock
M6	**Use of a drill** Wooden block mounted on a support construction in a clamp 100 cm above the floor horizontal drill Drill diameter 8mm Use of a drill 2 handed driller with battery	Drill a hole (complete length of driller)	5 3 Trials	teleoperated	2-handed-electric driller Driller 6 Woodblock	1m in front of the workbench Drill is the robot hands A mark for where the hole should be made	Hole with complete length of driller drilled in the wooden block	Extension for 2 handed operation by UBO Hole in the woodblock 1cm from the mark

Nr.	Task object	Task Description	Difficulty No of trials	Op-Mode	Equipment	Starting point	"100%"- criteria	Remarks
M7	**Pipe star** Pipes arranged like a star. The star positioned 1m in front of the robot on the ground. Try to grasp the pipes with one hand. Orientation of the hand correlates to the direction of the pipe	Evaluates workspace of the robot	5 3 Trials	teleoperated	KHG-„SMF-Halle	1m in front of the pipe star	All pipes grasped with one hand	M9a and M9b can be combined All pipes grasped with the correct position
	Pipe star The star arranged 1m in front of the robot on the bottom.. In the pipes in a certain depth: Landolt rings: Try to look in each pipe and solve the eye test	Evaluates vision space of the robot	5	teleoperated	KHG-„SMF-Halle	1m in front of the pipe star	All Landolt rings detected correctly	See above All openings in the Landolt rings seen

Supervised Autonomous Tasks

Task A1: Autonomous locomotion
Scenario
The robot stands in front of multiple fields of gravel/grass which have to be traversed. There are some difficulties:

- In addition, some obstacles which cannot be traversed, block certain areas
- The desired goal pose is located on an elevated platform which can be reached by climbing a stair with 2 steps

100%-criteria
Terrain classification detects the gravel/grass/obstacles/stairs and generates a terrain class map:

- A height map is generated from registered laser scanner point clouds
- Terrain classes and height information are merged to a cost map
- The operator inputs the desired goal pose (x,y,orientation) through a VEROSIM interface
- The planner plans multiple paths with different costs for gravel/grass and outputs two solutions:
  - a) low costs to traverse gravel/grass
  - b) high costs to traverse gravel/grass
- The operator chooses option b) which is then executed by the robot

> **Difficulty/Number of trials**

- 8/3

Task A2: Autonomous manipulation

Scenario

The robot stands in front of a table and should autonomously grasp a tool.

- The surface of the table of standard height (~75 cm) is in the workspace of the robot.
- There is a 2-handed-driller located on the table. The tool is in such position that it is possible to grasp it directly (maybe with one hand only) without any additional manipulations.
- The tool has to be held with both hands in order to be used properly.
- There is an obstacle on the table, obstructing an easy direct way of approaching a pre-grasp pose.
- The task is to successfully pick up the tool, lift it, switch it on and off, place it back.

100%-criteria

- The tool is recognized and its pose is estimated.
- Necessary grasping poses are generated using non-rigid registration.
- Initial grasping trajectories are generated using keyframe interpolations
- The trajectories are optimized under multiple objectives.
- Trajectory is executed, followed by the grasping, lifting, switching on/off and placing the tool back onto the table.
- Note, that the tool does not have to be grasped with two hands directly from the table. It is possible to first lift it up with one arm and involve the other arm afterwards.

Difficulty/Number of trials

- 8/3

Annex C Protocols

Test protocol Final evaluation CENTAURO						L1
Task-Number	~~C2~~	= L1				
Task-Name	Regular door -outward					
Modus	**Teleoperated** [X]	**Autonomous** [ ]	**Simulation** [ ]			
100%-criteria	Unlock door, open, drive through,					
Max. trial number		**Trial number**	1			
Name of operators	Max, Chris					
Name of PAL						
Name of referee	Karl					
Starting parameters	**ok** [X]	**not ok** [ ]				
Starting time	19.25					
End time						
Operational time	13:30					
Number of interacts	**Operator**		**PAL**		**Referee**	
End of test	**100%-criteria** [X]	**Operator** [ ]	**PAL** [ ]	**Referee** [ ]		
Performance level[%]	100%					

Remarks[1)]

No crane

On battery

1) If not possible record on backside or separate paper

Date	11/10-18	Sign of referee	

4 x

Test protocol Final evaluation CENTAURO					L2
Task-Number	L1				
Task-Name	Step-field				
Modus	**Teleoperated** [X]	**Autonomous** [ ]	**Simulation** [ ]		
100%-criteria					
Max. trial number		**Trial number**	4		
Name of operators					
Name of PAL					
Name of referee	Karl				
Starting parameters	**ok** [X]	**not ok** [ ]			
Starting time	15.40				
End time					
Operational time	1:25:38				
Number of interacts	**Operator**		**PAL**		**Referee**
End of test	**100%-criteria** [X]	**Operator** [ ]	**PAL** [ ]	**Referee** [ ]	
Performance level[%]	100%				
Remarks[1] Gauntlet for safety meas.					

1) If not possible record on backside or separate paper

Date	10/10-18	Sign of referee	

Test protocol Final evaluation CENTAURO					L3
Task-Number	L3				
Task-Name	Stair - up				
Modus	**Teleoperated** ☒	**Autonomous** ☐	**Simulation** ☐		
100%-criteria	Climb stairs and stop at top				
Max. trial number		**Trial number**	1		
Name of operators	Max, Chris.				
Name of PAL	Michael				
Name of referee	Karl				
Starting parameters	**ok** ☒	**not ok** ☐			
Starting time	18,40				
End time					
Operational time	10:02				
Number of interacts	**Operator**		**PAL**		**Referee**
End of test	**100%-criteria** ☒	**Operator** ☐	**PAL** ☐	**Referee** ☐	
Performance level[%]	100%				

Remarks[1)]

Only 3 steps in staircase

1) If not possible record on backside or separate paper

Date	11/10-18	Sign of referee	

L4
Gap

Test protocol Final evaluation CENTAURO						L 4
Task-Number	L4					
Task-Name	Gap					
Modus	**Teleoperated** ☒	**Autonomous** ☐	**Simulation** ☐			
100%-criteria	Walk over the gap - no falling					
Max. trial number		**Trial number**	1			
Name of operators	Christian, Max					
Name of PAL						
Name of referee	Karl					
Starting parameters	**ok** ☒	**not ok** ☐				
Starting time	18:46					
End time	/					
Operational time	3:26					
Number of interacts	**Operator**		**PAL**		**Referee**	
End of test	**100%-criteria** ☒	**Operator** ☐	**PAL** ☐	**Referee** ☐		
Performance level[%]	100%					

Remarks[1)]

No gantry +
Battery used (without cable)
Teleoperated w/o (without) using simulator

1) If not possible record on backside or separate paper

Date	10/10-18	Sign of referee	

Test protocol Final evaluation CENTAURO						
Task-Number	62a		11			
Task-Name	Valve-gate					
Modus	**Teleoperated** [X]		**Autonomous** [ ]		**Simulation** [ ]	
100%-criteria	Open + close gate-valve					
Max. trial number		**Trial number**	2			
Name of operators	Nasernia					
Name of PAL	Narvab					
Name of referee						
Starting parameters	**ok** [X]		**not ok** [ ]			
Starting time	16.10					
End time						
Operational time	23:30					
Number of interacts	**Operator**	.	**PAL**		**Referee**	
End of test	**100%-criteria** [X]		**Operator** [ ]		**PAL** [ ]	**Referee** [ ]
Performance level[%]	60%					

Remarks[1)]
~1 turn each direction

1) If not possible record on backside or separate paper

Date	11/10-18	Sign of referee	

Test protocol Final evaluation CENTAURO							M1
Task-Number	~~Task~~ M1						
Task-Name	Valve – lever type						
Modus	**Teleoperated** ☒	**Autonomous** ☐	**Simulation** ☐				
100%-criteria	Open + Close lever (~90°)						
Max. trial number		**Trial number**	1				
Name of operators	Massimiliano (exoskel.), Chris., Max (Bonn)						
Name of PAL	Navvab						
Name of referee	Karl						
Starting parameters	**ok** ☒ starting w/ legs on platform	**not ok** ☐					
Starting time	16:39						
End time							
Operational time	6:50						
Number of interacts	**Operator**		**PAL**		**Referee**		
End of test	**100%-criteria** ☒	**Operator** ☐	**PAL** ☐	**Referee** ☐			
Performance level[%]	~~70%~~ ~~100%~~ 6/8 Bonn 100%						

Remarks[1)]

30° down by exoskeleton, broken afterwards

→ Bonn continues task (operates using wrist)

* SAAA stab the mirror after 70 % of active exoskel failed, USB finished the task

1) If not possible record on backside or separate paper

Date	11/10 – 18	Sign of referee	

Test protocol Final evaluation CENTAURO						172
Task-Number	M1					
Task-Name	Fire hose - w/o seal					
Modus	**Teleoperated** ☒	**Autonomous** ☐	**Simulation** ☐			
100%-criteria	Connect and fasten hose using tool					
Max. trial number		**Trial number**	3			
Name of operators	Max, Christian					
Name of PAL	Tobias					
Name of referee	Karl					
Starting parameters	**ok** ☒	**not ok** ☐				
Starting time	8.50					
End time						
Operational time	10:10					
Number of interacts	**Operator**		**PAL**		**Referee**	
End of test	**100%-criteria** ☒	**Operator** ☐	**PAL** ☐	**Referee** ☐		
Performance level[%]	100%					

Remarks[1)]

w/ crane

1) If not possible record on backside or separate paper

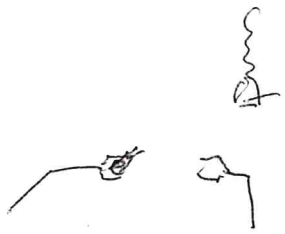
Date	12/10 - 18	Sign of referee	

Test protocol Final evaluation CENTAURO						M3
Task-Number	M3a					
Task-Name	230V-connector – lose outlet					
Modus	**Teleoperated** ☒	**Autonomous** ☐	**Simulation** ☐			
100%-criteria	Plug the contacts together					
Max. trial number		**Trial number**	1			
Name of operators	Max, Chris					
Name of PAL	Michael					
Name of referee	Karl					
Starting parameters	**ok** ☒	**not ok** ☐				
Starting time	17:08					
End time						
Operational time	6:50					
Number of interacts	**Operator**		**PAL**		**Referee**	
End of test	**100%-criteria** ☒	**Operator** ☐	**PAL** ☐	**Referee** ☐		
Performance level[%]	100%					

Remarks[1)]

No crane, plug freehanging from ceiling, no known orientation

Driving required to reach



1) If not possible record on backside or separate paper

Date	11/10-18	Sign of referee	

220
CC

Test protocol Final evaluation CENTAURO						h3
Task-Number	M3b					
Task-Name	230V - Connector CEE-Type					
Modus	**Teleoperated** ☒	**Autonomous** ☐	**Simulation** ☐			
100%-criteria	Plug-in socket light ↓					
Max. trial number		**Trial number**	1			
Name of operators	Max, Chris					
Name of PAL	Tobias					
Name of referee	Karl					
Starting parameters	**ok** ☒	**not ok** ☐				
Starting time	18:08					
End time						
Operational time	10:00					
Number of interacts	**Operator**		**PAL**		**Referee**	
End of test	**100%-criteria** ☒	**Operator** ☐	**PAL** ☐	**Referee** ☐		
Performance level[%]	100 %					

Remarks[1)]

w/ Crane

1) If not possible record on backside or separate paper

Date	11/10 -18	Sign of referee	

Test protocol Final evaluation CENTAURO						M4
Task-Number	M4					
Task-Name	Shackle					
Modus	**Teleoperated** ☒	**Autonomous** ☐	**Simulation** ☐			
100%-criteria	Close around ring + >6 turns					
Max. trial number		**Trial number**	1			
Name of operators	Christian, Max					
Name of PAL	Michael					
Name of referee	Karl					
Starting parameters	**ok** ☐	**not ok** ☐				
Starting time	14.50					
End time						
Operational time	24:35					
Number of interacts	**Operator**		**PAL**		**Referee**	
End of test	**100%-criteria** ☒	**Operator** ☐	**PAL** ☐	**Referee** ☐		
Performance level[%]	100%					

Remarks[1)]

No crane

Shackle with special grip adapter

1) If not possible record on backside or separate paper

Date	11/10 – 18	Sign of referee	

Test protocol Final evaluation CENTAURO							M5
Task-Number	M5						
Task-Name	Screw-driver						
Modus	**Teleoperated** ☒	**Autonomous** ☐	**Simulation** ☐				
100%-criteria	Score						
Max. trial number		**Trial number**	1				
Name of operators	Max, Christian						
Name of PAL	Michael						
Name of referee	Karl						
Starting parameters	**ok** ☒	**not ok** ☐					
Starting time	13.56						
End time							
Operational time	6:21						
Number of interacts	**Operator**		**PAL**		**Referee**		
End of test	**100%-criteria** ☒	**Operator** ☐	**PAL** ☐	**Referee** ☐			
Performance level[%]	100%						

Remarks[1)]

w/o Crane

two screws fixed

1) If not possible record on backside or separate paper

Date		Sign of referee	

Test protocol Final evaluation CENTAURO						M6
Task-Number	M6					
Task-Name	Use of drill					
Modus	**Teleoperated** [x]	**Autonomous** [ ]	**Simulation** [ ]			
100%-criteria	Hole full-length at mark					
Max. trial number		**Trial number**	2			
Name of operators	Max, Christian					
Name of PAL	Michael					
Name of referee	Karl					
Starting parameters	**ok** [x]	**not ok** [ ]				
Starting time	10.54					
End time						
Operational time	1:55					
Number of interacts	**Operator**	0	**PAL**	0	**Referee**	0
End of test	**100%-criteria** [x]	**Operator** [ ]	**PAL** [ ]	**Referee** [ ]		
Performance level[%]	90%					

Remarks[1)]

Hole #2
w/ cable
drill cont. drilling &

Slightly off mark (see image) &

1) If not possible record on backside or separate paper

Date	10/10 -18	Sign of referee	

Test protocol Final evaluation CENTAURO						
Task-Number	~~G7a~~	17				
Task-Name	Pipe star - grasp					
Modus	**Teleoperated** ☒	**Autonomous** ☐	**Simulation** ☐			
100%-criteria	Grasp each pipe ~~ed~~ in the direction of it					
Max. trial number		**Trial number**	1			
Name of operators	Christian, Max					
Name of PAL	Michael					
Name of referee	Karl					
Starting parameters	**ok** ☒	**not ok** ☐				
Starting time	17,52					
End time						
Operational time	14123					
Number of interacts	**Operator**		**PAL**		**Referee**	
End of test	**100%-criteria** ☒	**Operator** ☐	**PAL** ☐	**Referee** ☐		
Performance level[%]	95%					

Remarks[1)]

Pipes:

111 sides OK

1 top - Just from side

No gaunty

1) If not possible record on backside or separate paper

Date	10/10-18	Sign of referee	

Test protocol Final evaluation CENTAURO						n7
Task-Number	~~Star~~ Pipe n7					
Task-Name	Pipe star - Visual					
Modus	**Teleoperated** ☒	**Autonomous** ☐	**Simulation** ☐			
100%-criteria	Look into pipe and see pattern					
Max. trial number		**Trial number**	1			
Name of operators	Max, Christian					
Name of PAL	Michael					
Name of referee	Karl					
Starting parameters	**ok** ☒	**not ok** ☐				
Starting time	17,40					
End time						
Operational time	6:09					
Number of interacts	**Operator**		**PAL**		**Referee**	
End of test	**100%-criteria** ☒	**Operator** ☐	**PAL** ☐	**Referee** ☐		
Performance level[%]	100%					

Remarks[1)] No gantry

III sides OK

I top OK

1) If not possible record on backside or separate paper

Date	16/10-18	Sign of referee	

A2
Loco

Test protocol Final evaluation CENTAURO					A1
Task-Number	A2				
Task-Name	Locomotion				
Modus	**Teleoperated** ☐	**Autonomous** ☒	**Simulation** ☐		
100%-criteria	Plan multiple paths - execute safe safely				
Max. trial number		**Trial number**	1		
Name of operators	Max, ~~Robotics~~				
Name of PAL	Michael				
Name of referee	Karl				
Starting parameters	**ok** ☒	**not ok** ☐			
Starting time	12.12				
End time					
Operational time	3:17				
Number of interacts	**Operator**		**PAL**		**Referee**
End of test	**100%-criteria** ☐	**Operator** ☒	**PAL** ☐	**Referee** ☐	
Performance level[%]	~~3:17~~ 75% ~~80%~~				

Remarks[1)]

Time excludes planning + mapping time

Gauntry for safety

Stopped with only front leg on platform (localization lost)

1) If not possible record on backside or separate paper

Date	11/10-13	Sign of referee	

Test protocol Final evaluation CENTAURO					P2
Task-Number	A2				
Task-Name	Grasping / Manipulation				
Modus	**Teleoperated** ☐	**Autonomous** ☒	**Simulation** ☐		
100%-criteria	detect, grasp, pickup, use, put down				
Max. trial number		**Trial number**	1		
Name of operators	Diego, Max, Dmytro				
Name of PAL	Michael				
Name of referee	Karl				
Starting parameters	**ok** ☒	**not ok** ☐			
Starting time	12.25				
End time					
Operational time	0:55				
Number of interacts	**Operator**		**PAL**		**Referee**
End of test	**100%-criteria** ☐	**Operator** ☐	**PAL** ☐	**Referee** ☐	
Performance level[%]	–				

Remarks[1)]

w/ crane
Failed to start drill
Drill fell after putting it down

1) If not possible record on backside or separate paper

Date	12/10-18	Sign of referee	

1/1

Test protocol Final evaluation CENTAURO						
Task-Number	1/1					
Task-Name	Integrated mission					
Modus	**Teleoperated** ☐	**Autonomous** ☐	**Simulation** ☐			
100%-criteria						
Max. trial number		**Trial number**				
Name of operators						
Name of PAL						
Name of referee						
Starting parameters	**ok** ☐	**not ok** ☐				
Starting time						
End time						
Operational time						
Number of interacts	**Operator**		**PAL**		**Referee**	
End of test	**100%-criteria** ☐	**Operator** ☐	**PAL** ☐	**Referee** ☐		
Performance level[%]						

Remarks[1)]

Not started due to problems with wireless link

1) If not possible record on backside or separate paper

Date		Sign of referee	