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IBEX - A Tele-operation and Training Device for Walking Excavators

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***Abstract*— This paper describes a novel tele-operation and training device for walking excavators based on a compact 3DOF motion platform. Thanks to an innovative setup optimized for high mobility, with two lever arms for differential roll and pitch actuation as well as a continuous rotation mechanism for yaw, the movement of the remote walking excavator can be accurately replicated in any situation. For realistic yet comfortable visual feedback, three foldable screens provide a view around the unmanned excavator. With this augmented feedback, an operator can work as if he was sitting in the actual machine. The platform is successfully tested by experienced and unexperienced users. To this end, a realistic simulation using CM Labs vortex environment is implemented and a series of scenarios are tested. As such, ibex additionally serves as ideal training device for walking excavator pilots.**

I. INTRODUCTION

An increasing number of environmental disasters seeks for powerful and highly mobile machines to secure and clean-up affected areas. Examples range from tragedies like Fukushima 2011 to earthquakes, floods or landslides that happen almost every day worldwide. Very often, such disasters are not a single event but result in areas that remain dangerous for an extended period of time. Beside high body counts, this often causes very high (economic) costs and it can take long time to remedy the damage. Before clean-up operations can start and human rescue teams can be deployed, complete areas must be secured, which is often coupled to complex geological, meteorological, seismological or even nuclear analysis. Despite greatest care, human rescuers still have to risk their life and deadly incidents are not a rare case.

Different research programs and large scale projects (e.g. DARPA Robotics Challenge [1], nifti [2], tradr [3], sherpa [4]) tackle this issue by providing robotic devices that can (autonomously) access disaster areas. Most of the ongoing research focus on small-scale machines for situation assessment and at most some low force manipulation tasks. For all heavy duty clean-up operation, classical construction site machinery is used. These machines are typically human operated and only few unmanned or teleoperated solutions exist [5].

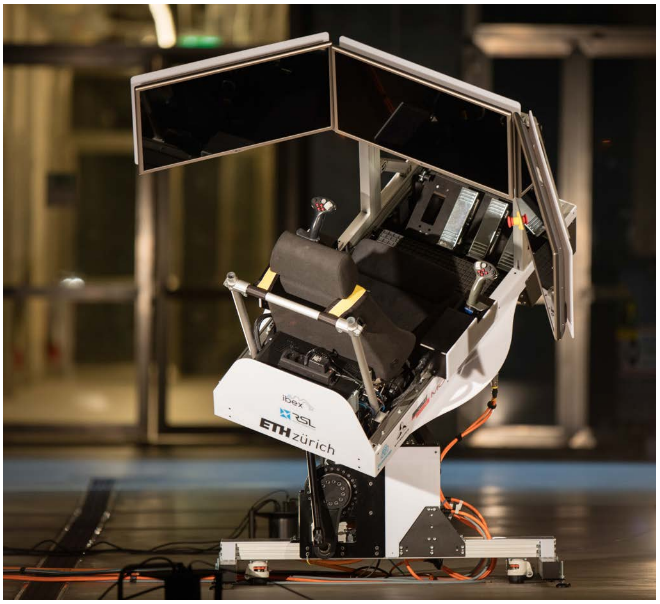

Fig. 1. Ibex: a teleoperation platform for walking excavators with precise motion feedback

Due to the large number of earth-flow disasters caused by volcanic eruptions, typhoons, or earthquakes, Japan has become a leading country in development of unmanned excavators. Pushed by this need, several research institutes and large scale companies [6] have transformed classical tracked excavator systems into robots that can be teleoperated. The first vehicles were developed and deployed after the eruption of the Mt. Unzen in 1993 [7]. The same technology has also been used in 2000 to prevent a second disaster during Mt Usuzan eruption [8] as well as after the Great East Japan Earthquake in 2011 [6]. The classical settings consist of a remote control room in a safe area, mobile repeaters for wireless transmission, and the operator-less excavator. With such setup, it is possible to control machine over distances up to 100 km [9].

A key challenge for remote construction vehicles is deployment. Due to disasters, roads can be blocked which makes it very hard for machinery with limited mobility to reach the site of operation. As a result, the development of large disassemblable hydraulic excavators has become of interest as the smaller components can be transported by a helicopter [6].

As already described in [10], a key challenge for teleoperation is to provide the operator with extensive feedback for all senses in order to achieve a high level of controllability. This becomes particularly important if the machine is moved on uneven ground. Today, even the most advanced systems [9] are limited to vision (and partially audio) feedback.

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Fig. 2. Typical setup for teleoperation of construction machinery for disaster recovery work (picture THW)

II. APPROACH

In order to overcome the current limitations of machine mobility and operator feedback, we developed the mobile teleoperation platform *ibex* to provide accurate motion and visual feedback of a remote excavator. Ibex is particularly built for operation of walking excavators, which are probably the most versatile construction machines of all, but can also be used for traditional tracked excavators. It is designed compactly to fit in a small car trailer which ensures quick and simple deployment in case of an emergency situation. Thanks to a clever arrangement of the actuation, a large range of possible motions of a walking excavator can be reproduced. In order to keep latency of visual feedback minimal, the system is equipped with multiple cameras and analog video transmission. Beside teleoperation, ibex can also be used for operator training. To this end, we implemented a detailed simulation based on CM Labs Vortex [11] including earth work [12] which is coupled to the realistic motion feedback.

III. WALKING EXCAVATOR

The M545 is the latest generation of multi-purpose machines developed by Menzi Muck AG[1]. They feature four individually controllable legs with three degrees of freedom and wheels, as well as additional supports at the feet. This provides the machines with extraordinary mobility, making them perfectly suited to access any terrain.

While manned walking excavators are used in various disaster recovery missions all around the world, so far only two remote controlled machines exist. They are used by the German Federal Agency for Technical Relief (THW) to access hazardous areas. Since there is no feedback system at all, the operator needs to stand in line of sight in order to control the excavator (Fig. 2). In contrast to tracked excavators as traditionally used (e.g. [5], [6], [7], [8], [9]), the remote operator needs to coordinate all four limbs to move the machine aside from carrying out the actual working task. This is particularly challenging without motion feedback, and is further aggravated since the operator can only see the two legs facing his direction. As a result, operation becomes challenging and inefficient, and only a fraction of the actual machine performance can be utilized. In fact, even for operators sitting in the machine it is very hard to keep track of the position of all legs purely based on visual feedback, making them heavily rely on their sense of motion to estimate whether all four wheels are in ground contact. In conclusion, teleoperation of walking excavators would greatly profit from motion feedback.

TABLE I

MAXIMUM ANGLES, ANGULAR RATES, AND ANGULAR ACCELERATION OF THE M545 AND IBEX.

	max angle		max rot rate		max rot acceleration	
	M545	ibex	M545	ibex	M545	ibex
roll/pitch	$\pm 45^{\circ}$	$\pm 45^{\circ}$	$\pm 60^{\circ}/\mathrm{s}$	$\pm 87^{\circ}/\mathrm{s}$	$\pm 30^{\circ}/\mathrm{s}^2$	$\pm 57^{\circ}/\mathrm{s}^2$
yaw	∞	∞	$\pm 60^{\circ}/\mathrm{s}$	$\pm 95^{\circ}/\mathrm{s}$	-	-

A. Specifications from manned machine operation

In order to determine the appropriate specification for all possible motions an operator of a Menzi Muck M545 can experience, we took a professional, very experienced driver on a test run. While performing extreme maneuvers, we recorded the body motion using an onboard IMU. The measurements unveiled that the horizontal motion and acceleration is negligible compared to changes in orientation. Due to the mobile legs, the cabin can achieve large roll and pitch angles as well as high angular speeds during fast maneuvers. All specifications are listed in table I. With a maximum acceleration of $1\,\mathrm{m}/\mathrm{s}^2$, the measured values are above what a human can feel [13] but significantly lower than accelerations in a car, which are about $5\text{-}7\,\mathrm{m}/\mathrm{s}^2$ [14]. Combining these measurements with the feedback by the user resulted in the decision to neglect the linear accelerations and velocities and to focus on the representation of high angles and angular rates. To the best of our knowledge, there are no commercially available solutions (e.g. [15], [16]) that would satisfy our requirements. In particular all designs based on the most common Stewart concept [17] show very different characteristics than what the motion of a walking excavator requires. The only solutions achieving the high angles and fast rotations are based on gimbal setup (e.g. [18]) or large scale industrial robot arms [19]. Unfortunately, these setups are very big and will not fulfill our space requirements.

IV. SYSTEM DESCRIPTION

The presented motion platform ibex is illustrated in Fig. 1. It features 3 degrees of freedom (DOF) and has a total weight of 450 kg. In the following, we provide a detailed description of the key elements namely the base, the central bearing system, and the cockpit.

A. Base with differential roll and pitch actuation

The base illustrated in Fig. 3 was designed to bear static and dynamic loads of the motion platform while offering a safe stand. It houses the two power-trains composed of *MOOG G3-V6* motors and *Wittenstein TPK+50 High Torque*

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[1] http://www.menzimuck.com

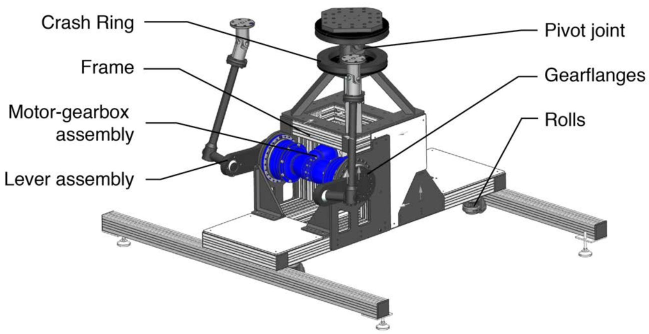


Fig. 3. Static base assembly overview

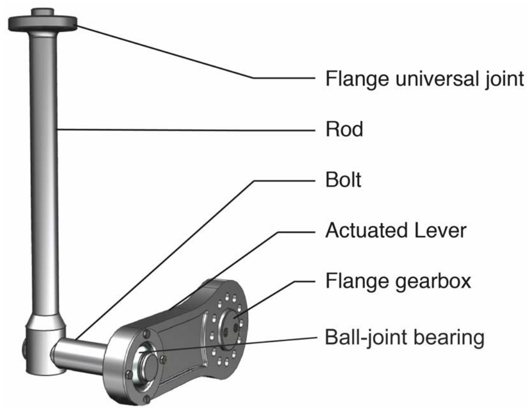
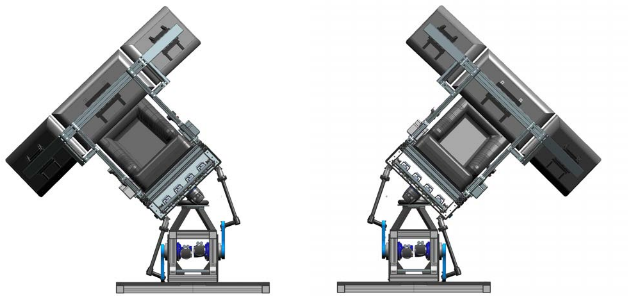
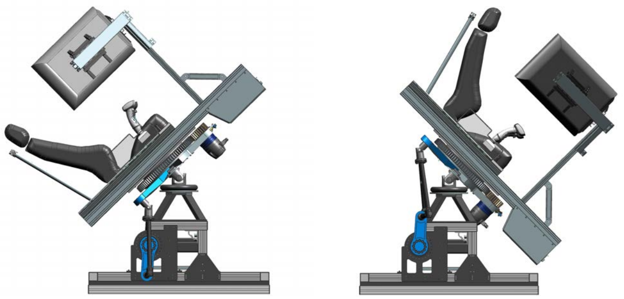


Fig. 4. Lever assembly for differential actuation of roll and pitch.



(a) 45° roll (b) -45° roll



(c) 45° pitch (d) -45° pitch

Fig. 5. Ibex reaches a maximum angle of ±45° in roll and pitch.

bevel gears for roll and pitch movement. The frame is built from aluminum profiles. The gearbox flanges and the pyramid-shaped support structure for the pivot joint are made from stainless steel.

To make the system compact and to achieve roll and pitch angles of 45° (Fig. 5), the base is designed in the shape of a cone. Two symmetric eccentric lever assemblies made from aluminum parts are used for differential actuation (Fig. 4). The dimensions of the lever assembly were optimized with respect to the angle specifications, potential body collisions, and actuator loads. In order to keep the system as compact as possible, the extreme positions were chosen to be at the upper and lower singularity positions. Due to the large motion of the central bearing system and cockpit, the connection at the top of the rod had to be designed as a universal joint. To keep the average load on the two roll and pitch actuators minimal, the central bearings system and cockpit are supported by a universal respectively pivot joint (Figs. 3 and 6).

The selection of roll and pitch motors and gears was based on an NX motion simulation [20]. To determine the dynamic forces, the motion platform including a dummy human model of an average size male person was moved according to the measurements of test run conducted by the trained operator. A maximum torque of 240 Nm for the differential roll and pitch actuators was identified. With a safety factor of 2.5, this results in 600 Nm torque requirement.

Based on these requirements, we selected a *TPK+50 High Torque bevel gearbox* by *Wittenstein* with an overall gear reduction of 462:1. Despite the large gear ratio, continuous and maximum speed are achieved and a typical motion cycle is almost entirely in region of continuous operation.

Due to the high gear ratio, the motor needs to provide relatively low torque to move the system. However, we identified the inertia ratio $\lambda = \frac{J_{load}}{J_{motor}}$, which is an indicator for controllability, as the relevant parameter in choosing the right motor. Since a human is sitting on ibex, undesired two-mass oscillations occurring due to the gearbox compliance must be avoided by all means. According to the *best practice in Wittenstein's design guidelines*, a maximum allowable λ of 10:1 was taken. To fulfill all requirements, *moog G3-V6* motors were chosen for roll and pitch actuation, which were the smallest motors of the series fulfilling the inertia ratio requirement.

B. Central bearing system with permanent yaw rotation

In order to give a realistic motion feedback, the cockpit rotation in yaw direction is implemented similar as in the real excavator. A large four-point bearing with external toothing (*Schaeffler VSA200414-N-RL0*) provides high stiffness with a single bearing and direct support of the cockpit. For continuous yaw actuation with a maximum speed as high as on the real excavator, a *Wittenstein TPM*$^+$ *dynamic 025* motor was selected. Finally, to provide data, power and emergency signal transmission from the static base to the rotating cockpit, a combination of an *SRA-73798* (CAN and Ethernet) and an *SC104* (power and emergency stop) by *LTN Precision* is implemented.

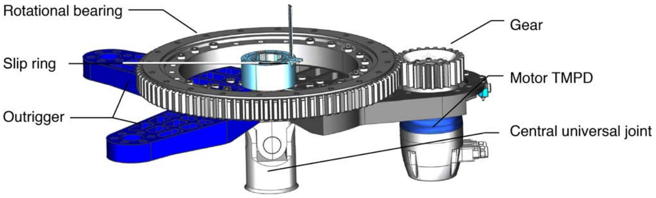


Fig. 6. The central bearing systems enables permanent rotation of the cockpit and supports the cockpit by a universal joint.

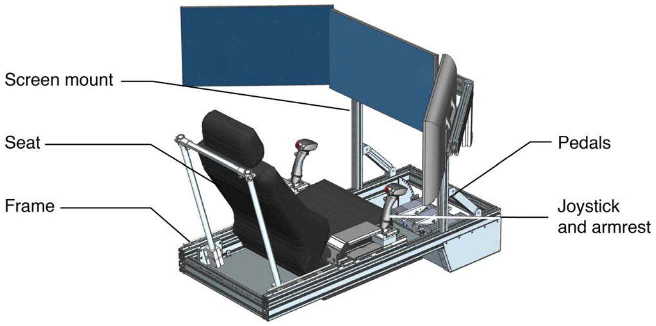


Fig. 7. The cockpit consists of a chair, three screens, excavator joysticks as well as pedals.

C. Cockpit

To minimize space requirements and balance the weight, the chair is mounted centrally on the pivot joint. Three screens are used for visual feedback (Fig. 7). They are mounted in a U-arrangement, while the outer two screens can be individually folded according to the operator preferences as well as for transport. Thereby, the system can be made very compact to fit through regular doors. The rigidly mounted chair features a four-point safety belt to keep the operator safely in moving platform. To adapt to operator size as well as to simplify entering, the three pedals as well as the two joysticks can be moved in horizontal direction. As joysticks we implemented a modified version of the ones used in a real excavator. Instead of the hydraulic piloting stage for the two main motions, a Logitec basis with position sensors was used and the spring providing restoring force was tuned accordingly. Since screen signal transmission through slip-rings is hardly possible, it was decided to have the main computer in the cockpit (behind the chair).

D. Trailer

To have very short deployment time in case of an emergency situation, the complete system is integrated in a custom car trailer ready for immediate use (Fig. 8). Due to the large range of motion, the side walls can be folded out during operation of the platform.

E. Electronics

The triple phase servo drives (*MOOG MSD392*) and the residual current devices (RCD) required for human safety are integrated in an external control cabinet (Fig. 9). Beside the power input to the servo drives which are fused at 300mA RCD, the cabinet features a 30mA RCD general purpose 230V power supply for onboard PC, screens and voltage converters. Additional in- and output signals are emergency stop triggers for the motor controls as well as the CAN signal line between the onboard computer and the servo drives. Finally, a router installed in the cabinet provides network access over LAN to the onboard computer. The entire control cabinet was certified by an external examiner according to EN 61439-1.

Fig. 8. ibex is mounted in a custom trailer with side walls that can be folded out.

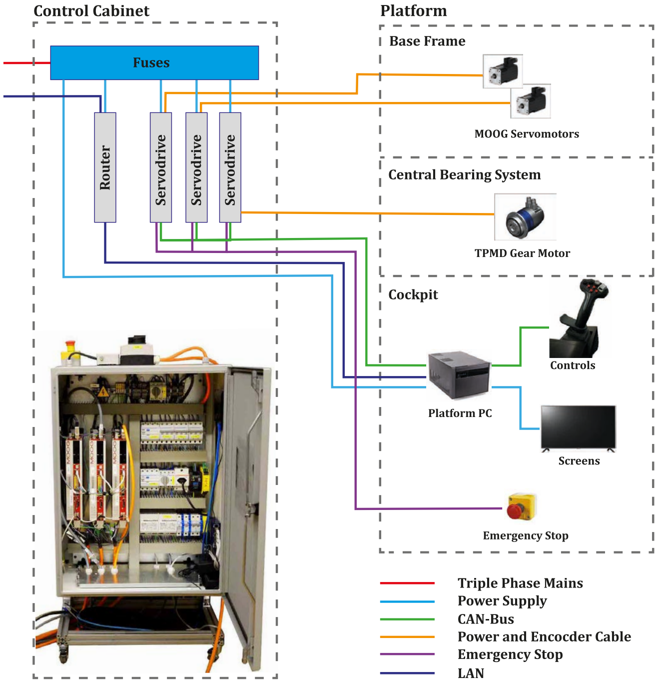


Fig. 9. Schematic depiction of the power and data connections between the control cabinet and the motion platform.

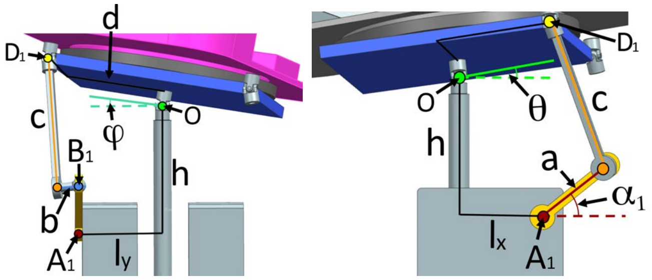


Fig. 10. Angle definition of lever assembly kinematics

V. MODELING AND CONTROL

The platform is driven using standard inverse kinematics control. Due to the selected setup, the cabin yaw orientation can be directly mapped to motor angles of the central bearing unit. For roll (φ) and pitch (θ) motion, an analytical model was derived to identify the corresponding lever arm angles (α_i).

Following the illustration in Fig. 10 for one side of the levers ($i = 1$), we can identify the vectors

$$\mathbf{OD}_1 = \begin{pmatrix} \cos(\theta) - \sin(\theta)\sin(\varphi) \\ -\cos(\varphi) \\ \sin(\theta) + \cos(\theta)\sin(\varphi) \end{pmatrix} d =: \begin{pmatrix} x_{D1} \\ y_{D1} \\ z_{D1} \end{pmatrix} \tag{1}$$

and

$$\mathbf{OB}_1 = \begin{pmatrix} a\cos(\alpha_1) + l_x \\ -l_y \\ a\sin(\alpha_1) - h \end{pmatrix} \tag{2}$$

as well as the length constraint

$$\left\| \mathbf{OD}_1 - \mathbf{OB}_1 \right\|_2 = b^2 + c^2. \tag{3}$$

This can be analytically solved for the lever angle

$$\alpha_1 = 2\left(\arctan\left(\frac{A_1 \pm \sqrt{A_1^2 + B_1^2 - C_1^2}}{B_1 + C_1}\right)\right), \tag{4}$$

with

$$A_1(\theta,\varphi) = z_{D1} + h \tag{5}$$
$$B_1(\theta,\varphi) = x_{D1} - l_x \tag{6}$$
$$\begin{aligned} C_1(\theta,\varphi) = &-\tfrac{1}{2a}\left(b^2 + c^2 - 2d^2 - a^2 - l_x^2 - l_y^2 - h^2\right. \\ &\left.-2\left(-x_{D1}l_x + y_{D1}l_y + z_{D1}h\right)\right). \end{aligned} \tag{7}$$

The analog approach can be taken to calculate the lever angle of the other side.

VI. SOFTWARE

The software framework is built upon the Robot Operating System (ROS). Thanks to the modular setup, the ibex platform can be operated either as remote control device or together with a physics simulator using the same control implementation.

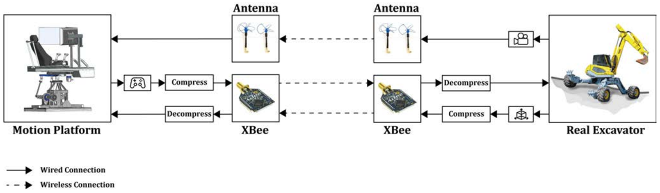


Fig. 11. Communication overview

A. Teleoperation and wireless transmission

During teleoperation it is critical to achieve reliable long distance wireless transmission. Together with end-users and in regard of the common areas of application, it was decided to aim for a minimum of 500 m distance. Delays must be kept as low as possible and constant. For safe operation it is necessary to keep the time delay between platform and real excavator below 500 ms. More important and critical is to keep time synchronization between image and motion feedback almost perfect since delays of more than 5 ms already cause motion sickness [21], [22].

In order to meet these requirements, we realized the setup illustrated in Fig. 11. For transmission of joystick and actuator commands, an *XBee-PRO 868* solution was implemented. With a channel frequency of 868 MHz, it is possible to transmit 24 kbits per second over a distance of up to 40 km in outdoor situation. In order to keep the transmission data as low as possible, the ROS messages are heavily compressed before sending. With a control frequency of the excavator of 100 Hz, the required data throughput is 14.4 kbps, which is well below the possible rate.

For video and audio transmission, existing digital compression and transmission equipment can hardly satisfy the requirements and in particular changing delays would cause significant time synchronization problems. To avoid these issues, an analog solution operating on the 5.8 GHz band was implemented. Since in Switzerland it is only permitted to use transmitters up to 25 mW power [23], the current solution is based on three *Immersion RC 25mW Race Band* transmitter. The receiver side features a *diversity* system as it provides the possibility of attaching multiple independently operable antennas. In our case, this is on one side a patch antenna with a narrow, directed beam that has a 35° width and a high gain of 13 dBi. The second is an omni-directional cloverleaf antenna that transmits or emits the signal in a torus shape. Since signals from multiple cameras must be sent simultaneously, the band of multicopter races is used, which offers 8 channels with a channel width of 37 Mhz each.

B. Simulation and operator training

Beside teleoperation, ibex is also an ideal platform for operator training. To this end, the *Menzi Muck M545* excavator was modeled in *CM Labs Vortex* simulator [11], which is one of the most advanced and realistic simulation engines. It allows to create realistic sceneries including earth work simulations [12].

The simulation environment was also used to evaluate different camera configurations. The three screens provide

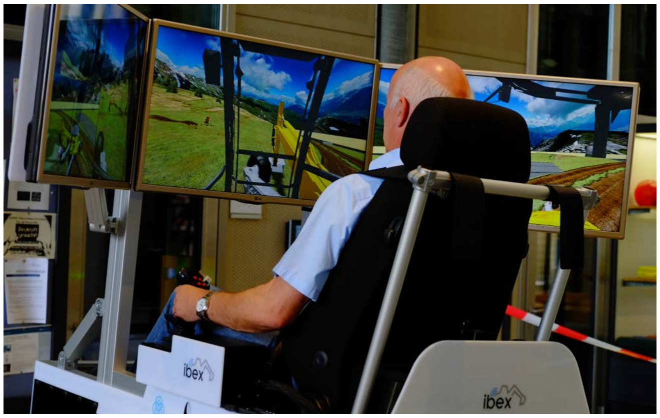


Fig. 12. User training with Vortex simulator

the possibility to display further information such as a third person view on the robot, which greatly improved the situational awareness for the operator.

VII. SAFETY CONCEPT

Since ibex is operated by humans, several safety mechanisms are integrated. The motors feature mechanical breaks that are engaged if the system is unpowered, at zero velocity, or if the servo drives are in a false state. An emergency stop signal line from the operator and a bystander are connected to the servo drives causing a quick stop followed by activation of the mechanical breaks. Furthermore, beside software joint limits implemented on the servo drives, end stop switches connected to the emergency stop line are installed at the upper and lower singularity point of the lever actuator. In the high-level software including the simulation, it is continuously checked for system crashes, software exceptions or outlier values before sending new joint angle commands. And finally, at the very last level, a clash ring between the base and central bearing system prevents snapping of the cockpit in case of a mechanical failure.

VIII. RESULTS AND CONCLUSION

The presented 3DOF motion platform and simulator was successfully tested using untrained as well as trained operators. An illustrative movie showing the system in action can be found the at https://youtu.be/XWLsp_M_Lrk.

As indicated in table I, all specified requirements of the motion platform could be achieved or exceeded. First user feedback was consistently positive but further studies need to be carried out for an in-depth analysis. It turned out that one of the key challenges is to visually provide good 3D situational awareness - both for simulation and teleoperation.

In the next months, the platform is further tested in combination with the real excavator and extended with additional sensory feedback (e.g. camera and audio stream) before it will be ready for disaster recovery missions.

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