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PRACTICAL EVALUATION OF A CONTROL CONCEPT FOR A REMOTE CONTROLLED 1.8T EXCAVATOR USING A 3D INPUT DEVICE

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ABSTRACT

Tele-remote control of excavators poses challenges for operators. While conventional operation already requires complex motor skills and thus extensive training, both the feeling for the machine and the 3D view are missing in a tele-remote scenario. This can result in operators being unable to estimate distances and performing movements more slowly and less accurately. Possible solutions to facilitate the operation of remote-controlled construction machinery are to improve visibility conditions through more sophisticated camera systems, or to provide motion feedback to the operator station. However, these solutions may be limited, for example, by higher demands on data transmission. Another solution could be to adapt the control of the machine. Therefore, this paper presents a control concept for a tele-remote operated excavator using a 3D-input device. First the test machine and the general structure of the control concept are introduced. For controlling the tool-position, an approach with direct position control and one with secondary velocity control are presented. For evaluation, both approaches are tested and compared. Finally, operator trials are presented and the usability of the concept is evaluated.

p_r	Pressure rod side
p_p	Pressure piston side
x	Piston position
$\dot{x}$	Piston velocity
$\ddot{x}$	Piston acceleration
y	Controller output

1. INTRODUCTION

The construction industry is increasingly struggling with staff shortages. The often monotonous and physically demanding work, combined with the resulting early retirement of employees, together with demographic change, is leading to a shortage of skilled workers. In addition, labor productivity in the construction industry has been stagnant for decades compared to other industries, leading to higher costs and a further aggravation of the shortage of skilled workers. [1]

While the automation of mobile machines is still a challenge [2], there has been a lot of progress in making mobile machines more efficient and environment friendly and the construction industry more attractive [3, 4]. Another possible building block to simplify the recruitment of skilled workers could be remote control of construction equipment. Operators no longer have to work onsite in the dangerous health-endangering construction environment and a flexible deployment of the workforce is possible. However, the operation of remote-controlled construction machinery can present challenges to operators. The 3-dimensional view is limited and the feeling for the machine is missing. Precision and working speed suffer as a result. [5, 6]

One way of facilitating the operation of remote-controlled construction machinery is to improve the viewing conditions, for

NOMENCLATURE

e	Control deviation
i_r	Current of the pilot valve rod side
i_p	Current of the pilot valve piston side
l	Length set point
TCP	Tool center point excavator
TCP_{ID}	Tool center point input device

example by using stereo- or 3D-cameras. Another option is imprinting machine movements on the operator's station [7]. However, these solutions place high demands on data transmission and require complex operator stations.

Another solution might be, to change the operating mechanisms of the construction machine. To date, almost all construction machines, such as excavators or wheel loaders, are operated by means of joysticks that control individual axes of the boom. As a departure from this operating principle, the use of haptic 3D input devices has been investigated in the past [8]. The operation with a haptic 3D input device enables the operator to receive direct feedback regarding the position of the tool in 3-dimensional space and to directly manipulate the tools position. Therefore, this paper presents a concept and the experimental validation of a controller architecture for operating a tele-remote controlled excavator using a 3D input device. In addition, it is investigated to what extent the operation of the tele-remote-controlled machine is facilitated by the operation concept.

The paper starts with a description of the test setup, including test machine and 3D input device and the controller architecture. A velocity-controlled and a position-controlled approach of the boom movement are presented, as well as the required position controller for the input device. Finally, the paper presents test results for the control approaches and operator tests for tele-remote controlling the excavator with the 3D input device.

2. TEST MACHINE

A 1.8 t Volvo EC18 excavator functions as a test machine, which is displayed in figure 1. For the investigations carried out the excavator is controlled by the 3D Systems Touch six Degrees of Freedom 3D input device shown in figure 3.



FIGURE 1: test excavator

As it is usual in this performance class, the Volvo EC18 is originally equipped with a purely hydraulic mechanical load-sensing system. Since this control system does not allow any

electric control of the actuators, the hydraulic load-sensing pilot valves are replaced by electrohydraulic proportional pressure reducing valves of the HydraForce EHPR98 type. FIGURE 2 shows the hydraulic system of the excavator. Each pilot valve actuates one actuator in one direction of motion. A current-controlled valve driver proportionally controls the pilot valves. For a fast response, the controller imprints a current even at zero stroke and superimposes a dither signal.

The actuators are additionally equipped with displacement sensors and pressure sensors, each on the piston and rod side. In addition to position and velocity, the displacement sensors can also calculate and pre-filter the acceleration.

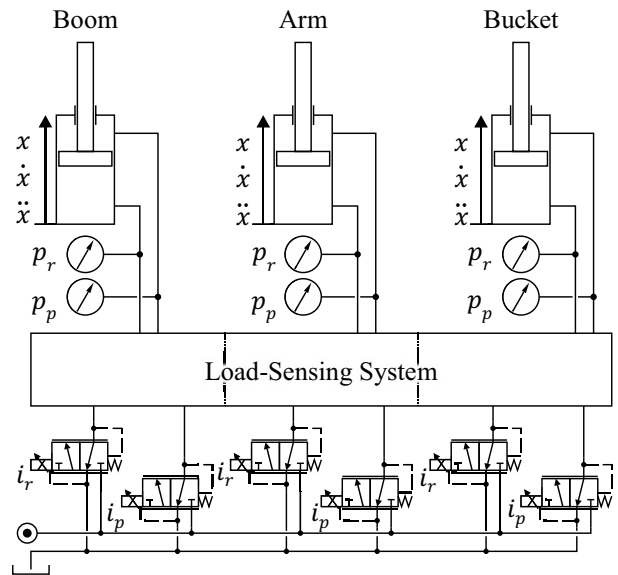


FIGURE 2: Illustration of the hydraulic layout

The excavator can be controlled via conventional joysticks from the operator's seat, as well as via a CAN interface and an industrial computer mounted on the back. In the following, a real time code generated from a Matlab Simulink model, running on the industrial computer, is used for the control and measurement algorithms on the excavator.

The 3D input device, shown in figure 3, consists of a rotating base and an arm with two segments. An input pen is attached to the end of the arm. The 3D input device was chosen as a prototype because the degrees of freedom correspond to those of the excavator. Each joint between the segments and the base includes a stepper motor, which can apply a torque to the respective joint. In addition, the joints have rotary encoders to record the position. The device can output the positions of the individual joints and their velocity. An USB port functions as interface for the specification of torques and the measurement of positions.



FIGURE 3: 3D input device

3. CONTROLLER DESIGN

The aim of the the 3D input device is for the operator to specify the tool position in relation to the machine. At the same time, the person should get a feeling for the position and movement of the tool through the device. Thus, both the 3D input device and the bucket tip of the excavator need to be controlled.

In the approach presented here, the input device follows the bucket tip of the excavator. If the operator now disturbs the position control of the input device by moving it, he feels a resistance. The excavator receives the new normalized actual position of the device as a target value for the bucket tip and adjusts it. The resistance felt by the operator is reduced. The operator can thus feel the tool position.

General Controller Architecture

The general structure of the controller is shown in Figure 4. The control of the input device (ID) deployed on an external PC communicates with the control of the excavator via a UDP interface. While the input device controller runs with 100 Hz, the excavator controller is able to run with up to 1 kHz. The controller of the 3D input device receives the normalized position of the excavator shovel tip and the excavator receives the normalized position of the input device pen, as well as its current velocity. In the following, the bucket tip is called tool-center-point (TCP) and the outermost joint of the input device's arm is called tool-center-point input device (TCP_{ID}).

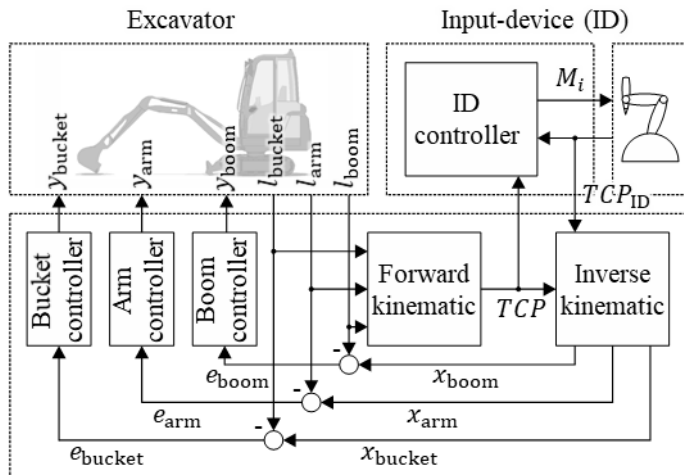


FIGURE 4: General controller structure

In the first step, the controller of the excavator calculates the position of the TCP from the measured deflection of the individual drives based on the forward kinematics of the excavator. The TCP of the input device is then used to calculate the set points for the drives in order to readjust the position of the bucket tip.

Two control approaches are investigated. One is a purely position-controlled approach and the other is a position-controlled approach with secondary velocity control. While the position-controlled approach directly adjusts the target position, for the second control approach a velocity vector towards the target position is calculated. The secondary velocity controller then regulates the velocity to reach the target position.

Set point calculation

Figure 5 shows the test machine in the used coordinate system. As the sensors of the test machine measure the cylinder displacement, the angles α , β and γ of the excavator arm are calculated based on the cylinder measurements. The forward kinematic for calculating TCP in the displayed cartesian coordinate system is then solved analytically.

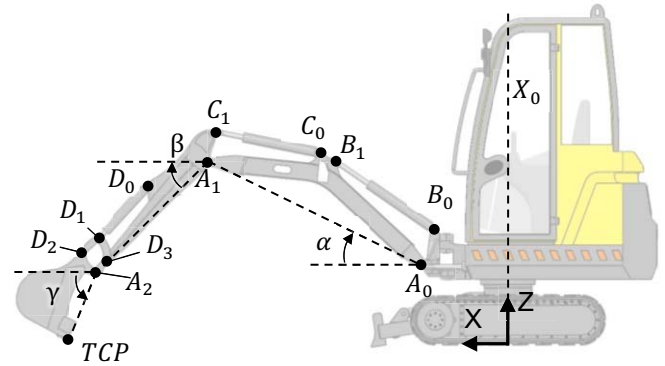


FIGURE 5: Excavator coordinate system

Figure 6 shows the input device in the used coordinate system. The input device directly measures the angles α and β . As for the excavator the TCP_{ID} is calculated analytically.

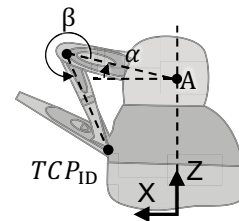


FIGURE 6: Excavator coordinate system

To map the coordinate systems of excavator and input device TCP and TCP_{ID} are normalized according to (1) and (2). x_{max} and z_{max} mention the maximum length or height that can

be reached with the excavator bucket tip or the pen of the input device. $\overline{TCP}_n$ is then send to the input device and $\overline{TCP}_{n,ID}$ to the excavator via UDP. By multiplying with x_{max} and z_{max} the set points are calculated.

$$\overline{TCP}_n = \overline{TCP} \circ \begin{vmatrix} x_{max}^{-1} \\ z_{max}^{-1} \end{vmatrix} \quad (1)$$

$$\overline{TCP}_{ID,n} = \overline{TCP}_{ID} \circ \begin{vmatrix} x_{max,ID}^{-1} \\ z_{max,ID}^{-1} \end{vmatrix} \quad (2)$$

Position controlled approach

The position set points for the arm and boom cylinders can be calculated using the inverse kinematic of the excavator arm. It should be noted that in the implementation considered here, the operator controls the bucket cylinder directly using the keys on the input pen.

Figure 7 shows the general layout of the position controller and the main characteristics of the plant. The controller for arm and boom are designed as a PI-controller with limited Integrator.

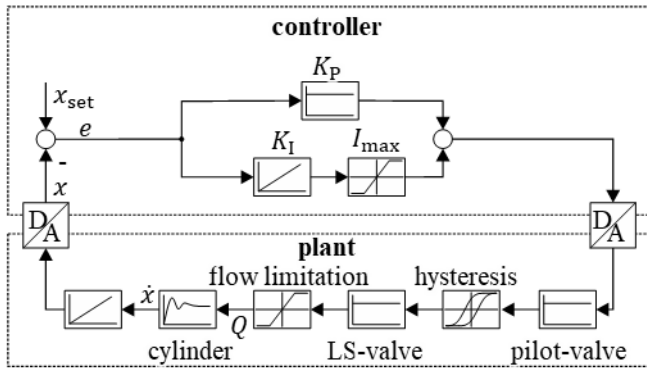


FIGURE 7: Layout position Controller

The relevant influences for the control task are especially valve and cylinder hysteresis and the limitations in volume flow and valve dynamics. The pilot valves themselves show a hysteresis in the order of 4%. Due to the installed load-sensing valves and effects such as cylinder friction, the overall hysteresis for the boom is about 30% and for the stick about 12%. The maximal reachable cylinder velocities are 110 and 85 mm/s for the boom cylinder and 160 and 135 mm/s for the arm cylinder depending on the direction. In good approximation, the cylinder velocity follows the flow signal with a second order behavior. Based on the step responses of the arm the natural frequency can assumed to be around 16.6 Hz and the pilot valves feature a -90° phase shift at a frequency of around 50 Hz for 50% signal. The pilot valves are thus only about three times faster than the system. Together with the delay caused by the load-sensing valves, it must be assumed that the actuating system limits the performance of the controller.

Position control approach with secondary velocity control

The position controller with secondary velocity control is designed in the form of a two-loop position controller with subordinate velocity control. In contrast to the purely position-controlled approach, the PI controller specifies a velocity based on the control deviation, which is then controlled by a subordinate control loop. The velocity v_{PI} specified by the PI controller is weighted with the factor K_C according to (3) and added to the velocity vector v_{ID} . The vector v_{ID} corresponds to the actual velocity of the input device. The velocity vector v_{set} thus transiently approaches the path of the set point. The resulting set velocity v_{set} then serves as the set point for the lower-level velocity controller.

$$\bar{v}_{set} = \bar{v}_{PI} \cdot K_C + \bar{v}_{ID} \quad (3)$$

In principle, the resulting speed to valve opening is bounded-input bounded-output stable. As shown in figure 8 this makes it possible to determine a characteristic map for the relationship between valve opening and static speed. This map can be used to implement a set point switch-on. The P-controller now compensates for the map error and increases the dynamics.

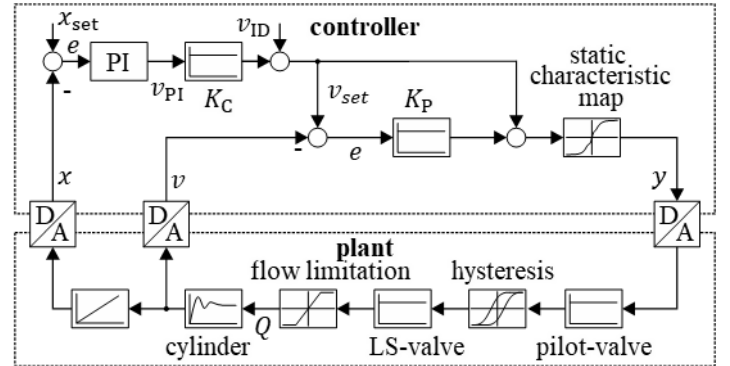


FIGURE 8: Layout secondary velocity Controller

Even without a P-controller, the excavator can follow the 3D input device with correspondingly low dynamics and a control error. The use of an additional integrating component in the controller could eliminate the remaining control deviation. However, an integrating component in the controller leads to a significant amplification of the oscillation tendency and sometimes to stability problems.

Valve Hysteresis

As mentioned before the utilized pilot valves have a valve hysteresis of about 4% with a correctly selected dither. Due to the positive overlap of the LS valves, as well as friction effects in the cylinders, hysteresis of up to 30% occurs. The hysteresis leads to a permanent control deviation and a poor follow behavior of the system. In order to realize a suitable control nevertheless, the hysteresis width (b_{hys}) is added to the valve control value depending on the direction according to (4). For the position-controlled approach, the full hysteresis width is

selected for b_{hys} , whereas only the width of the hysteresis of the pilot valves is selected for the approach with subordinate speed control.

$$y' = \begin{cases} y + b_{hys} & |\dot{y}| > 0 \\ y - b_{hys} & |\dot{y}| < 0 \end{cases} \quad (4)$$

As a method to avoid oscillations, a dead band is connected downstream of $\dot{y}$. The switching on of the hysteresis reduces the dynamics of the actuation system, but still allows sufficiently fast control for the considered application. A higher control quality could be achieved by a subordinate position control of the main valve spool.

Controller of the 3D input device

As shown in figure 9, the 3D device is actuated by controlling the motor torque of each joint. An internal current controller regulates the motor torque itself. The set values for α and β are calculated using the inverse kinematic of the input device. Input is the normalized position of the excavator bucket tip. The set point switch-on has to be chosen correctly to avoid drifting.

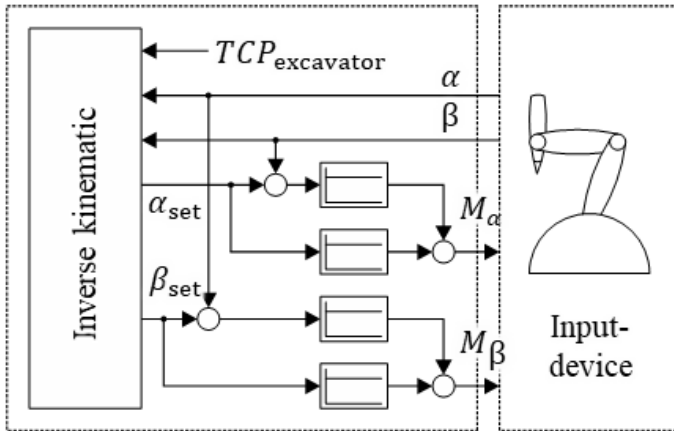


FIGURE 9: Layout 3D-input device controller

Controller evaluation

Figure 10 shows a step response of the position controlled approach and Figure 11 of the approach with secondary velocity control. Each figure shows a step in in x and z direction.

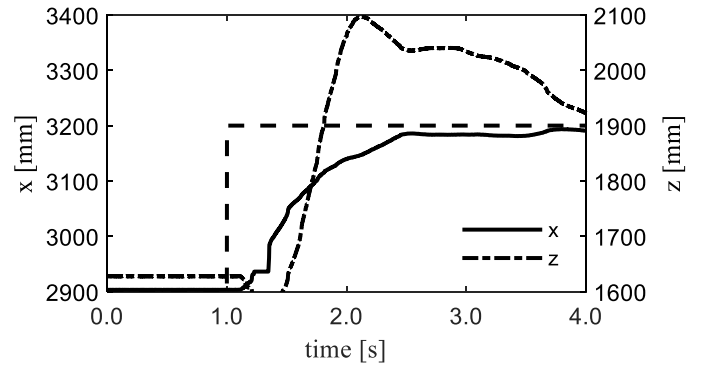


FIGURE 10: Step response position controller

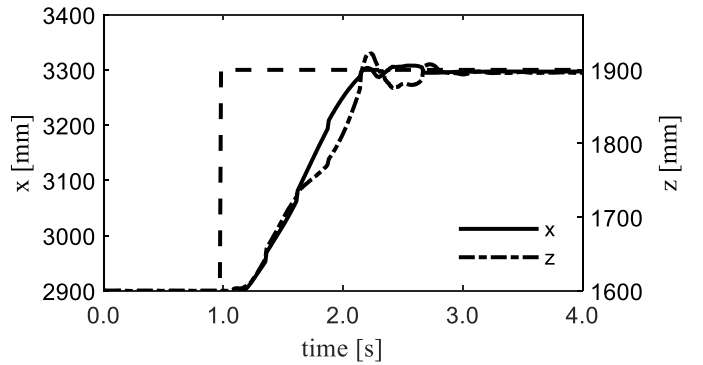


FIGURE 11: Step response position controller with secondary velocity control

In particular, the large mass of the boom and the non-uniform motion of the actuators of the boom and arm, leads for the purely path-controlled approach to a significant overshoot when viewed in Cartesian coordinates, as shown in Figure 10. Since the discontinuities of the actuators cannot be taken into account in any way for this approach, comparatively high integrator parameters must be selected. The system therefore tends to oscillate and overshoot or with lower parameters to large control deviations. The subordinate velocity control can partially consider the discontinuities by means of the characteristic map. With the subordinate speed control, better control qualities can be achieved and the system tends to oscillate and overshoot less. For the approach with subordinate velocity control, the settlement time for a jump height of about 400 mm in both directions is about 1 second. The control parameters could be selected more aggressively and the reset time thus shortened. However, this would lead to large accelerations on the excavator and thus might lead to unpleasant operating behavior.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The control concept presented here is intended to facilitate tele-remote control of the excavator. The operator controls the position of the tool directly, instead of indirectly via the individual axes of the arm. It is expected, that this control approach compensates to some extent for the lack of 3D vision in tele-remote operation. In order to evaluate the operability, operator tests were thus carried out.

Experimental setup

The experimental remote control station, shown in figure 12, consists of a monitor for transmitting a camera image from the excavator, the input device, Joysticks and a control PC. The excavator can thus be controlled remotely via the joysticks as well as via the 3D input device. A Sony alpha 6400 is mounted in the excavator for the camera image. The video image is transmitted via an HDMI to HDMI Wi-Fi-interface to the remote control monitor. The camera perspective is chosen slightly sideways so that the operator has the bucket in view.

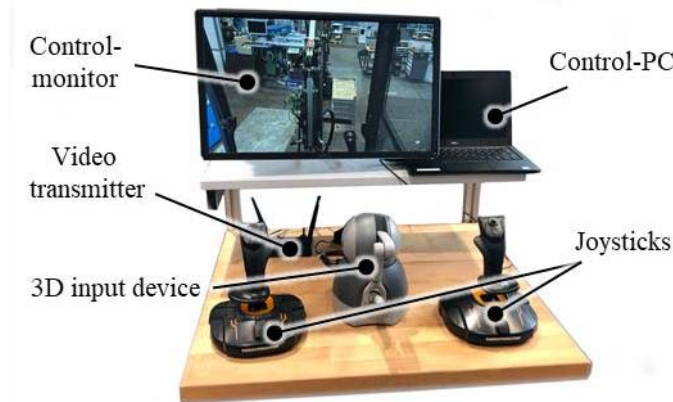


FIGURE 12: Experimental remote control station

For the purpose of evaluating the concept presented here, operator tests were carried out in which the excavator was remotely controlled by three different operators, each with joysticks and with the input device controlled via video image. In 10 trials, per device, a level path was to be traversed with the bucket tip. All operators were younger than 30 years and had little experience in excavator driving. Two of the operators had already controlled the excavator with the input device, whereas the operation was new for the third.

Test results

Figure 13 shows the deviation from the mean height Δz over the length x for a selected trip with joysticks and the 3D input device. For comparison purposes, the averaged standard deviations (STD) over the 10 trips of all operators for both control principles are shown.

All operators had difficulty maintaining height when operating the excavator with the joysticks. The standard deviations averaged over all runs with the joysticks were 93 mm for the first, 99 mm for the second and 142 mm for the third operator. The minimum and maximum height varied by 553, 683 and 971 mm. According to the description of the operators, the deviations were on the one hand due to the lack of depth perception and on the other hand to the complex motor skills. All operators found it easier to maintain the height with the 3D input device, since here a reference for the position of the tool in the 3-dimensional space is available. This is also reflected in the measured standard deviations, which were 22 mm for the first,

32 mm for the second and 77 mm for the third operator. The minimum and maximum height of the bucket tip varied by 465, 126 and 247 mm.

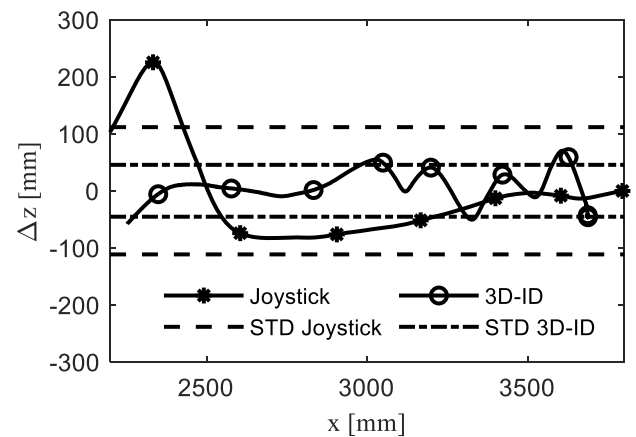


FIGURE 13: Exemplary results from Operator tests

Although moving the bucket in the plane was easier for the operators overall, some limitations of the system become apparent. For example, the range of motion of the input device limits the sensitivity with which the tool can be guided. In contrast to conventional operation via joysticks, the positions of the input device and bucket are directly coupled. For precise work, the input device must therefore be guided sensitively.

In addition, matching the controller to the operator's needs is critical to ensure a good user experience. For example, high integrator parameters lead to fast response of the controller, but also cause a constant disturbance at the input device. Good operability is thus no longer guaranteed. Likewise, too strong feedback, due to too high control factors at the input device, makes operation more difficult. Therefore, when designing the controller, attention must be paid not only to the subsequent behavior of the system, but also to the needs of the human operator. Possible solutions to make teleoperation more robust and more convenient for the user are the use of a master-slave architecture, with appropriate filtering of the set points. Examples of this can be found in [9] and [10].

5. CONCLUSION

A control concept for controlling an excavator using a 3D input device for the specific use case of tele-remote operation was presented. A position controlled approach and a position-controlled approach with secondary velocity control are tested with a 1.8 t excavator and both approaches are compared. Finally, tele-remote operation with the 3D input device is compared to operation with conventional joysticks in operator experiments.

It can be concluded that haptic operation of construction machines, especially in the context of tele-remote operation, has the potential to reduce difficulties in tele-operating the machine, for example due to a lack of feeling for the machine, as well as a lack of depth perception. It thus represents a promising alternative solution approach in addition to the much-discussed

improvement of perception through elaborate camera or feedback systems.

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REFERENCES

- [1] Gerlmaier, A., Latniak, E. *Arbeiten in der Bauwirtschaft – wer schafft es bis zum regulären Renteneintritt und wer nicht?: Risikoindikatoren und alterskritische Berufe*, IAQ-Report, <https://doi.org/10.17185/dupublico/45682>, 2012
- [2] Dadhich, S., Bodin, U., & Andersson, U., *Key challenges in automation of earth-moving machines*, Automation in Construction, <https://doi.org/10.1016/J.AUTCON.2016.05.009>, 2016.
- [3] Deuster, S., Schmitz, K. *Bio-Based Hydraulic Fluids in Mobile Machines: Substitution Potential in Construction Projects*, Proceedings of the ASME/BATH Symposium on Fluid Power and Motion Control, <http://doi.org/10.1115/FPMC2019-1636>, 2019.
- [4] Opgenoorth, A., Quabeck, S., de Doncker, R. W., Schmitz, K. *Challenges and possibilities of the integration of electric drives in mobile machinery*, 12th International Fluid Power Conference, IFK 12, <https://doi.org/10.25368/2020.55>, 2020.
- [5] Benz, T. M.: *Multi-modal user interfaces in teleoperation*, <https://doi.org/10.48550/arXiv.2003.14392>, 2019
- [6] Larsson, J., Broxvall, M., Saffiotti, A. *An evaluation of local autonomy applied to teleoperated vehicles in underground mines*, 2010 IEEE International Conference on Robotics and Automation, Anchorage, AK, USA, <https://doi.org/10.1109/ROBOT.2010.5509276>, 2010
- [7] Hutter, M.; Braungardt, T.; Grigis, F.; Hottiger, G.; Jud, D.; Katz, M. et al. *IBEX – A tele-operation and training device for walking excavators*, International Symposium on Safety, Security, and Rescue Robotics. EPFL, Lausanne, Switzerland, <https://doi.org/10.1109/SSRR.2016.7784276>, 2016
- [8] Hayn, H., Schwarzmann, D. *Control Concept for a Hydraulic Mobile Machine Using a 3D Operating Device*, 2009 Second International Conferences on Advances in Computer-Human Interactions, <http://dx.doi.org/10.1109/ACHI.2009.43>, 2009
- [9] Nuño, E., Basañez, L., Ortega, R. *Passivity-based control for bilateral teleoperation: A tutorial*, Automatica, Volume 47, Issue 3, <https://doi.org/10.1016/j.automatica.2011.01.004>, 2011
- [10] Kallu, K.D., Wang, J., Abbasi, S.J., Lee, M.C. *Estimated Reaction Force-Based Bilateral Control between 3DOF Master and Hydraulic Slave Manipulators for Dismantlement*. Electronics 7, <https://doi.org/10.3390/electronics7100256>, 2018