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Coordinated control paradigm for hydraulic excavator with haptic device

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Abstract

The usability of heavy construction equipment is strongly affected by the design of their Human-Machine Interfaces. Lack of confidence with the current input devices is due to their counterintuitive design and the absence of loop feedback between the end effector and human hands. In the last few years, many researchers have been demonstrated that haptic devices, joined with a suitable design of the control levers, could help to face this problem. In this paper, an innovative control logic for hydraulic excavators has been proposed based on the inverse kinematic of the arms of the hydraulic excavator. The aim of this control is to reduce the cognitive effort of the users if compared with the one required by the current control systems. The implementation of this control logic has been based on previous research projects, technical documentations and interviews with experts. The proposed control logic has been evaluated by means of experimental activities with a virtual simulator which test the usability and efficiency of the proposed solution.

Keywords: Usability Evaluation, Virtual Reality, Excavator, Coordinated Control, Human-Machine Interface, Haptic Device

1. Introduction

Over the years, technological progress has increased the possibility to simplify most human activities. In the field of earth-moving machines, for example, new methods have been studied in order to increase productivity (in terms of the amount of work done in the shortest time possible), efficiency (in terms of cost of employees and machines) and safety (in terms of injury risk for the workers due to the dangerous operating environment) [1, 2].

Excavators, used for mechanized construction in industrial and civil fields, mining, farmland transformation, transportation and demolition, are the most common materials handling equipment. Due to the large number of available sizes, their high adaptability to different applications and their high-power density provided by the embedded hydraulic system, excavators are widely used in small, medium and large industries.

Modern manufacturers have started to re-design and produce excavator systems able to keep the traditional functions and operation modalities of their predecessors, but with the integration of new functionalities. These innovative capabilities have the purpose to increase system intelligence, fuel efficiency, reliability, operators comfort and safety as well as to reduce inactivity time and maintenance duration/cost [3, 4, 5]. Consequently, the complexity of such systems has greatly increased in modern ages and a lengthy training period is still required before acquiring the skills of expert operators. Being a skilled user, with the ability to safely control all the movements of the excavator, requires a complete understanding of the machine capabilities and the principles behind its operation (i.e. the control logic). Thousands of hours of practice are needed to be labeled as an expert [6] and these expenditures directly burden costs. This is especially so when new equipment is required or training is needed to perform the necessary tasks [7].

The ambitious idea of reducing the time needed for training novice users has led researchers to develop new interaction paradigms. The idea is to provide a user interface that mimics the movement of the controlled part of the hydraulic arm as much as possible: the goal is to increase the learnability of the system while preserving the overall ergonomics. Finding the correct balance between these two aspects is crucial: intense cognitive and physical loads are required to the operators, whose working days may last more than seven hours. A suitable human-machine interaction can therefore reduce the risk of misunderstandings and errors without affecting the effectiveness of the performed actions [8].

This paper aims at proposing a new system for the coordinated control of a hydraulic excavator by means of a haptic interface. To achieve this goal, an analysis of the current use condition has been made, with the consequent definition of the involved kinematic and dynamic parameters. Thanks to these data, it has been possible to develop two new control schemes based on the motion of the actuated joints: the operator acts directly with the end effector, managing its position or speed, without mentally computing the motion of single links to accomplish the desired tasks. The revolution motion of the cabin, instead, is provided by an auxiliary device.

A validation activity of these devices has been carried out by means of a virtual reality system where typical scenarios for excavators have been reproduced. The physical simulation of the main device has been performed with a programmable haptic device suitable to mimic the motion of the coordinated control. This, unlike most of the works available in literature, can reach extremely high performances for both the rendering of the haptic feedback and the stability of the control. On the other hand, the auxiliary device has been prototyped with an open-source microcontroller board. The final part of this work is characterized by the test phase in which different tasks have been assigned to a panel of users without previous experiences with excavators. During the simulation session, the users have to use both the standard lever and the new novel haptic interface based on the coordinate control schemes input devices. The simulation sessions have been organized to ensure repeatability. The measurement of parameters, such as position, velocity and forces, allowed the devices to be objectively validated, whereas questionnaires allowed the analysis of the subjective aspects of the simulation (i.e. feelings, opinions and suggestions) to be taken into account.

2. State of the Art

It is possible to identify three different groups of controllers for hydraulic excavators based on their automation level [1]. From the bottom level, i.e. systems that perform only simplified parts of the job of earth-moving within a limited number of parameters, the human presence continuously decreases till machines capable to perform the assigned task autonomously. The classification includes also tele-operated systems where the operator is removed from the machine but is still necessary for its control. Modern technology, however, is not able to handle the huge volumes of data required to operate in a completely autonomous way with large machines and complicated functions. This is one of the reasons why several years are still necessary before having a tested solution on the market. The Shared Control Algorithms proposed by [9] could be a viable approach to semi-autonomous solution, however it still lacks in robustness and requires the investigation of several issues (e.g. take-over request). For these reasons, interesting possibilities of development are related to the improvement of the systems currently available in terms of simplification of the operators work and reduction of their cognitive load. Human factor is still required for taking decisions, which will therefore be processed by the control unit in order to perform the required task.

In conventional earth-moving machines, such as excavators, the movement of each degree of freedom is realized thanks to the extension or retraction of hydraulic cylinders. These actuators are manually controlled by proportional or servo valves that direct the oil flow from the pump to a specific cylinder. The user controls the flow rate by acting on four single axis levers or two dual axes joysticks. These devices have an easily identifiable neutral position that maintains constant the pressure in the cylinder and locks the arm in the current position. When the operator acts on a lever, the position of the corresponded spools in the valves change and consequently the position of the respective link: the speed of the link is proportional to the tilt of the lever. When a task implies to reach a target with the end-effector, this way of interaction compels the operator to compute mentally the inverse kinematic of the hydraulic arm. The transformation from the piston space (i.e. the one used to move the arm) to the task space (i.e. the one used to perform the action) requires a lot of mental effort and can be performed automatically only after years of training [10]. In addition, external factors perturb the nominal behavior of the machine, like change of the terrain or rigid obstacle. Consequently, the accuracy and the speed of task execution strictly depend on user experience [11].

Alongside the innovations targeting improvements in the task execution, several solutions have been proposed to mitigate risks for operators. Often, to preserve the operator's safety when the excavator works in dangerous conditions, the use of remote control allows the supervision of all the movements of the hydraulic arm without staying seated inside the cab [12]. However, this usually worsens of the operator's performance in comparison with the direct control due to the lack of a real perception of the terrain, its properties and the relative force feedback [13].

The improvement of the devices is possible when they are capable to handle an input signal as much simplified as possible, and then reprocess it to motion commands for the hydraulic arm. With this approach, also called Master-Slave, the operator interacts directly with the master, which imitates the arms mechanism, to obtain a position or motion variation of the slave. The first step to obtain a good compatibility between the parts is to reproduce the degrees of freedom, the types of joints and the directions of movement [14]. For this reason, the kinematic analysis of the mechanism of the excavator's arm is fundamental in design: a total of four Degrees of Freedom (DOFs) to move the end effector in a 3-dimensional space. For what concern the manipulator, this means, the swing of the cab and the rotation of each link of the arm (boom, stick, bucket) around their joint. A meaningful example is the haptic device with four DOFs developed by K. Dongnam et al. which allows manipulating all the excavator movement with a single hand [15]. The input system, which resembles a stylus, controls the swing and the bucket motions thanks to its left-right tilting and the rotation of the top thumb-wheel while the position of the boom and the stick are defined by a combination of front-rear inclinations and extensions. The latter is calculated by using inverse kinematics equations to let the user simply interact with the end part of the device without taking care of every single joint of the excavator.

By analyzing the digging activities in which hydraulic excavators are used, it is possible to reduce the three-dimensional volume of motion of the end effector in a space with only two dimensions where the rotation of the cab is rarely operated simultaneously with the other degrees of freedom [16]. According to this idea, H. Hayn et al. [14] have split-up on two separate devices the total DOF under control: a rotary knob for the cabin swing and an operating element able to rotate and move in a vertical plane for the control of the translation of the tool centre point and the bucket tilting. Similarly, Ryder C.Winck et al. in [17] have developed a device kinematically similar to the excavator's arm. Excluding the increase of intuitiveness for the operator, this solution has the advantage of controlling the rotations of the hydraulic joints of the boom and the stick proportionally with the links of the device. The additional swing motion is controlled by an ordinary joystick whose interaction pattern is similar to the one currently used.

Kyeong Won Oh et al. [18] proposed a further step to increase the intuitiveness of the control thanks to the kinematic similarity between human and hydraulic arm. According to this research, it is possible to control the slave device by analyzing the rotations of human articulations. A haptic device is used, placed in the horizontal plane on which the three DOFs are controlled by the elbow, wrist and finger of the operator. In [19] instead, the same arm acts as a master device, in this way the position of its joints (shoulder, elbow and wrist) is detected by using suitable sensors embedded on the operator. The tests performed underline strengths and weaknesses experienced by operators both in [18] and [19]. In particular, the absence of a force feedback (or in any case of a mechanical resistance) prevents reaching high precision in control, in addition to a greater tiredness for the operator. For this reason, the hi-tech idea of using human limb as a control device has been rejected by many researchers in favor of devices capable to provide touch and haptic feedbacks. Although the best practice for designing such category of devices is to remove the effect of frictions as much as possible (i.e. the device should be transparent to the user), in this case the interface can be used as information channel about the use and the possible interactions between the end-effector and the environment [20].

Most of the simulations, involving users, allowed subjectively verifying the usefulness and suitability of the designed devices, and all those aspects that need further developments. Analyzing these aspects within the paper published up to now, it allows to discriminate the useful variables and to avoid those that do not provide the desired or interesting results.

Find unbiased metrics to evaluate the suitability of the designed device is crucial, especially when the test environment is virtual. Generally, virtual simulations provide good but subjective indications about those features of the user interface that need further developments. In fact, the simulations with the user are preliminary tests, necessary to record all those parameters that monitor the correct execution. A possible approach considers the identification of a set of tasks easy to perform for both expert and novice users. In this way, repeatability of results is ensured. Examples of this methodology can be found in the tests conducted by Mark D. Elton et al. in [21] where each participant performed simple digging tasks: load on the bucket as much material as possible from a ditch and discharge it to a specific point further away. Of course, a brief explanation and demonstration of how the system works in order to ensure a basic familiarity with the device before making any test are necessary. For example, in [22] all participants had the opportunity to freely try the simulator out for 15 minutes after a short introductory video that explains the purpose of the test and how to use the designed system. It is often helpful to think of a mixed group of participants, men and women of different ages as well as experienced traders and not, in order to have a broader spectrum of feedback as possible. This is the basis of the dual dimension of the acceptability definition provided by Benjamin Osafo-Yeboah in [23]: the practical one and the social one. With novice users, and those less suitable to carry out the tasks, the first type of acceptability is analyzed and it is related to the usefulness and usability; with experienced users, instead, it is considered the social aspect, and then the future assertion possibilities of the designed device. According to similar tests, a set of relevant parameters to track during excavation tasks are selected: total execution time of the programmed task [23, 22], speed of each joint (or of each hydraulic piston) in function of time [19], position in x and y of the end effector (or trajectory of the joints) in function of time [24], force exerted by the operator in the direction of x and y as a function of time [24, 25], environmental force reaction on the bucket as a function of time [24], quantity of soil removed in total or for each excavation operation [17, 21], total fuel consumption in the execution of the operation [17], number of actuator simultaneously used during the operation [25], operating errors due to a motion of the end-effector in the wrong direction [26]. Particularly useful is the repetition of the test by changing the use conditions for the users, such as: the type of control logic, from position to rate [21], the presence of an active force feedback [22] and the type of input system, from the traditional joystick to the haptic device [23]. Leonhard E. Bernold [25] explained how it is possible to quantitatively measure and compare the performance of an operator in controlling an excavator. The duration of the training period plays a crucial role in these measurements.

3. Preliminary study

3.1. Interviews of the users of the excavators

Based on the principles of the user-centered design, interviews and questionnaires to the users are the starting point to guide the development of a new interface. A mixed group of users with different ages and background has been selected. The interviewees, aged between 20 and 60, are divided by the type and dimension of the used excavator and by the level of experience (i.e. expert users with more than 10 years work experience using the same machine and new users). Thanks to this approach, it is possible to cover most of the possible connections of the variables involved.

The pie chart on the right of the Figure 1 shows the most relevant and unexpected data related to the difficulties identified, which were due to the current control configuration: 80% of the operators declared the counter-intuitiveness of the joysticks, especially during the initial phase of the training period, while the remaining identified the main problem in the number of different parts controlled by the single input device. This result can be read as a confirmation of the well-known basic issue in the control of excavators but reveals also that these issues do not depend on the skill or experience level of the users.

The second part of the interview had a different aim, as all the possible improvements were analyzed. Thanks to that, interviewees had to freely think about the experience they had during the testing session, and they were asked to identify which kind of feedback is more helpful to perform the job and in which situations. The outputs, summarized in the bar chart of Figure 1, reveal the necessity to introduce, or in some cases to upgrade, at least one control aid especially to avoid the overload of the arm and the risk of impact with external obstacles. All the opinions lead to the same result as regards the type of feedback that can be used and well interpreted by the users: acoustic danger signal should be avoided in favor of monitors where well-known messages are displayed. More divergent is the opinion regarding the introduction of tactile or vibrational feedback due to the workplace. In actuality, if the user is working in an environment with a high level of vibration of different nature and provenience, the vibrational feedback results to be not effective nor useful. For these reasons, other independent solutions can be introduced in the analysis like wearable components or devices with an adaptable vibration frequency.

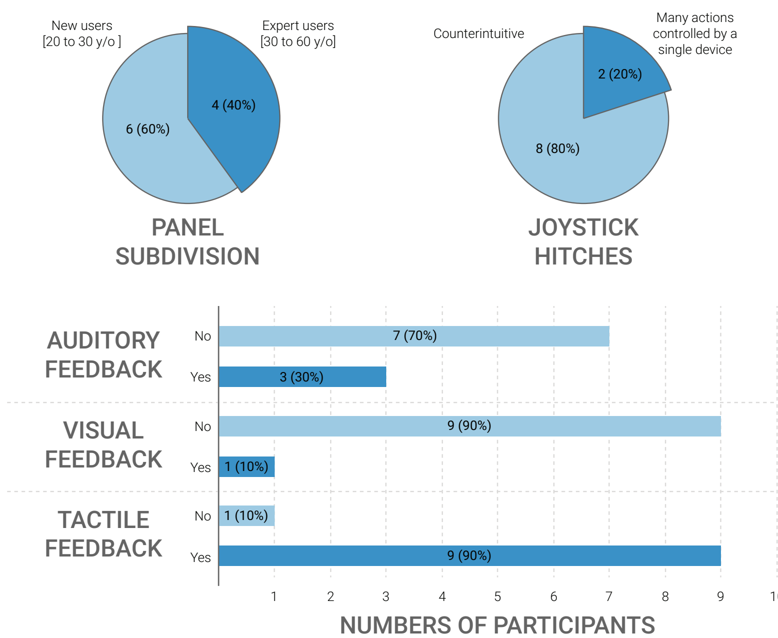


Figure 1: Summary of the results of the interviews

3.2. Device requirements: surroundings and operative environment

The on-site observation is necessary to define other important requirements of the new interface from both the control scheme and the device point of views. At this stage, the system collects all the information regarding the environment in which the proposed solution is supposed to operate. Hence, the internal cockpit of the excavator (i.e. dimensions, available space, user position, view obstacles-free, other instruments, etc.) and the external factor, which influence the correct use of the device (i.e. dust, vibrations, high range of unexpected movements, etc.), have been investigated.

As described in Section 2, the current configuration of the excavator control is mainly based on two dual-axis joysticks, in which the motion of each degree of freedom causes the extension or retraction of a specific hydraulic cylinder. The relationship between the input device and the controlled part can be different according to the standard (or pattern) used but, in any cases, there is no possibility to make them more intuitive: the operator must learn to associate the name labeled to a lever, or its position in relation to the other one, with the backhoe function it controls. In order to reconfigure the setup, it has been necessary to observe the behavior of an actual machine during digging operations:

- the swing motion can be considered as movement independent of the others DOFs;
- the bucket rotation is generally performed when the hydraulic arm has reached the desired configuration;
- boom and stick are moved simultaneously;
- the user works principally by considering the vertical and horizontal displacement of the bucket.

These assumptions allow the design of the control logic to be simplified with relevant advantages concerning the computational cost and the design of the potential physical device. Given a certain swing angle, the motion of the bucket can be visualized in a 2D space as made of two elements of the kinematic chain. In addition, the master and slave parts must work with the same reference system so as to avoid forwarding the computation of the inverse kinematics equations to the user's mind.

3.3. Excavator modeling

For the development of the new excavator control, all the kinematic equations related to the hydraulic arm have been made explicit. Figure 2 shows the reference schema for the kinematic analysis. By using the Denavit-Hartenberg approach, it is possible to move from the task space (i.e. the position of each point of the hydraulic arm in Cartesian space with the origin in O_0) to the joint space (i.e. the rotation angle of each rigid body of the hydraulic arm around the joint axis) and, then to the cylinder space (i.e. the length of each linear actuator).

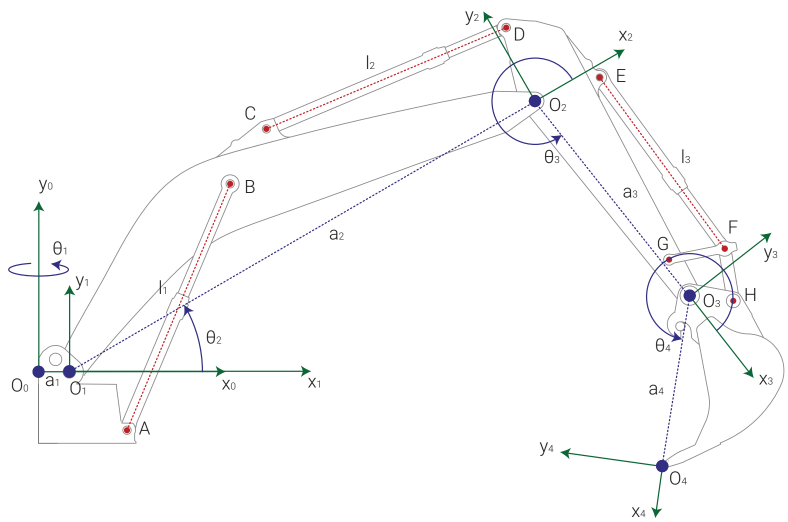


Figure 2: Kinematic schema of the excavator's arm

Since the coordinate control logic allows the operator to act only on the displacements of the end-effector (node O_3 in Figure 2) referred to O_1 joint and the rotation of the bucket with respect to O_3, the kinematic analysis has to be carried out accordingly. As described in Section 3.2, the fourth DOF (θ_0 in Figure 2) has been taken into account separately. The direct control on the boom and sticks joints avoids independent revolutions of the bucket with respect to the other elements of the arm and reduces the number of DOFs which the user can handle together. For this reason, it is not needed to embed the entire kinematic chain in the control scheme and allows reducing the amount of singularity that occur for computing the inverse kinematic of the mechanism.

With these assumptions, it has been possible to split the entire motion of the hydraulic arm into three separated parts:

1. the translation of the stick-bucket link (O_3 in Figure 2) in a vertical plane. The motion of the boom and the stick are considered for the first

DOF. This means that all the DOFs placed upstream (swing motion) and downstream (bucket motion) in the kinematic chain do not affect the way of controlling the target or its own reference system. In fact, the reference system is placed in correspondence of the body-boom link jointly with the cab;

2. the rotation of the bucket (θ_3 in Figure 2) with respect to the position of the stick, that is the last movable link of the hydraulic arm. Its position or rotation change continuously with respect to the global coordinate system (represented by the position of the tracks whose movements are not considered in this analysis), even if it is not directly operated by the user. A new local reference system is set at the stick-bucket link, fixed with the stick itself, to make the control easier. With this procedure, the bucket is independent of the other movable links;
3. the revolution of the cab (θ_0 in Figure 2), that is directly connected with the ground system. Its motion is responsible for the lateral transition of the bucket (i.e. the swing), and it is the only joint whose axis of revolution is orientated in the vertical plane.

The goal of the inverse kinematic is to find the value of the rotations (time by time) to be given to θ_1 and θ_2 in order to ensure the position X-Y of O_3 with respect to O_1 origin specified by the user. From these equations, the set of points reachable by the hydraulic arm of the end-effector (i.e. the working volume) can be derived (Figure 3).

Simplified dynamic equations are also introduced in the analysis to better simulate the behavior of the hydraulic arm. This has been used with different purposes with respect to previous studies [27]: starting from the definition of the hydraulic features of the machine it is derived the force exerted by each piston on the related joint and consequently the movement speeds of each link. This information is then used to compute in real time which is the maximum speed reachable by the controlled target accordingly with the current kinematic configuration of the arm and thus limiting the movement of the users during the interaction with the interface [28]. It is important to underline that the early testing activities, developed in this paper with non-expert users, do not consider any interaction between the bucket and the environment. Simulating the dynamics of the machine is thus not required to ensure a good quality of the coordinated control. In addition, there are intrinsic features of the hydraulic arm which support this simplification like the high forces exerted by the pistons which make the inertia of each link

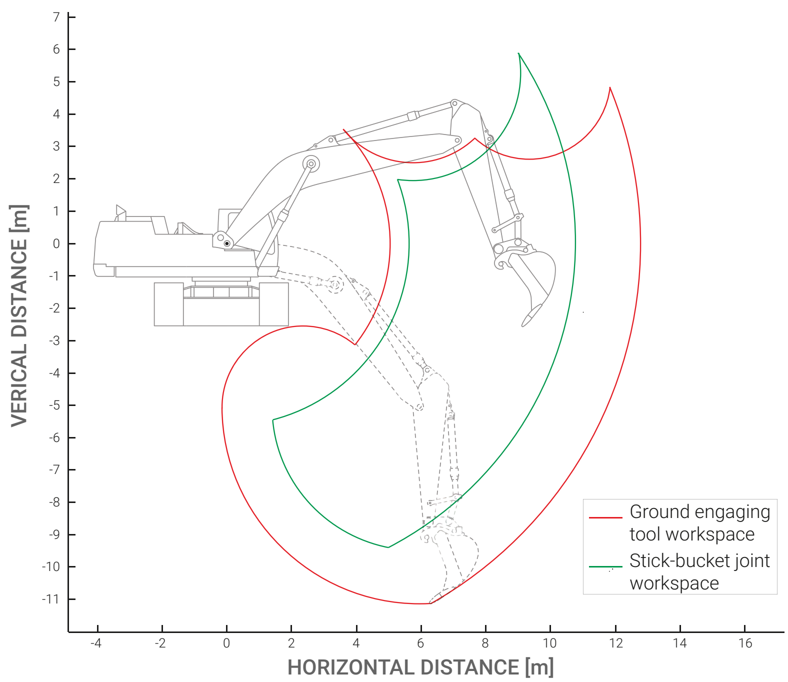


Figure 3: 2D representation of the excavator workspace. The volume can be obtained by rotating each 2D projection around the cabin vertical axis

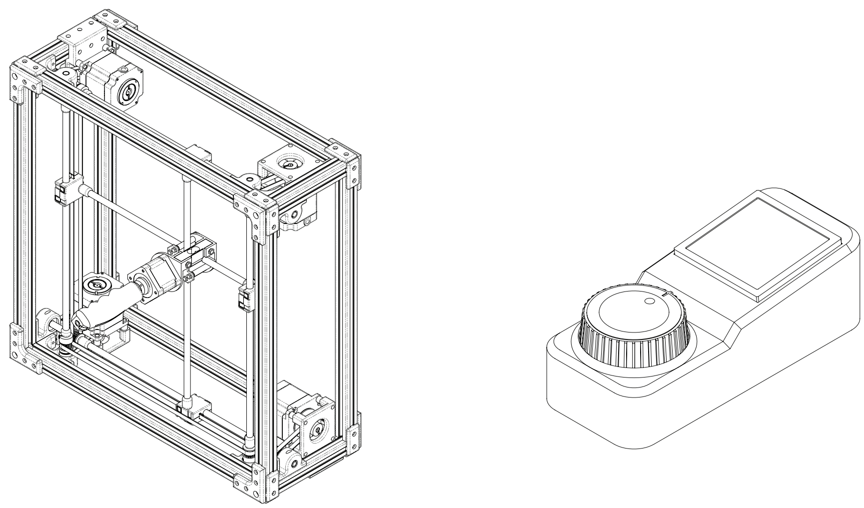
negligible during the movement of the kinematic chain itself [29, 30].

The use of the dynamic equations has not to be considered as a means of a complete simulation of the excavator behavior during its use. The introduction of force feedbacks on the input devices should be carefully calibrated in order to find a balance between fatigue and signals. Simulating all the aspects related to the hydraulic arm and its working environment, like the load of the bucket, may affect the prolonged use of the controller by tiring seriously the user's arm.

4. Proposed coordinated control paradigm

Grounding on the outcomes of the preliminary study (Section 3), it has been possible to define and conceive a new control logic for the four main DoF of the excavator hydraulic arm, based on the paradigm of the coordinated control. In the following sections, it will be detailed for each of the three subsystems previously identified, i.e. target translation (Section 4.1), bucket rotation (Section 4.2) and cabin revolution (Section 4.3).

In order to introduce the new control scheme, a complete redesign of the human-machine interface is also required. One of the most suitable solutions is presented in Figure 4 with a conceptual representation of the two completely new devices: the main one (Figure 4a) is an interface to directly control the translation and rotation of the bucket while the auxiliary one (Figure 4b) is used to control only the swing of the cabin and to display relevant information regarding the use. Even if their definition is not relevant for the objective of this paper, the presentation of their main features provides a better understanding of the new principles introduced with the control logic.



(a) Main device

(b) Support device

Figure 4: Concept of the devices that can be integrated with the proposed coordinated control logic: a Cartesian structure for the main one where the handle can move in a vertical plane and rotate around it axis thanks to sliding bars and motors (a); a rotating knob for the support to ensure the fine control of the cab (b)

The Cartesian movement of the handle for the control of the target is obtained by means of two perpendicular sliding bars which can operate simultaneously thanks to four independent motors (two for each slider). These transmit the motion to the movable components by means of pulleys and are grounded onto the external frame. All the sensors required for the identification of the user interaction and the measurement of its magnitude are placed inside the basement. Here, the handle is joined with the frame, keeping it free to rotate around its longitudinal axis. This type of design has been developed in order to meet the following requirements: (i) build with sufficient strength to withstand the forces and vibration exerted by the operator or transmitted from the machine; (ii) create sufficient force feedbacks distinguishable from those provided by the machine itself; (iii) have small but efficient workspace for the implementation of different control methods without affecting the ergonomics; (iv) have intuitive orientation with respect to the controlled parts; (v) configured to not limit mechanically the user's movement or actions but to prevent any lags; (vi) designed to reduce all the mechanical plays which can affect its smooth motion with low inertia; (vii) designed to be as less invasive as possible to avoid dangerous limitations of the operators field of view.

Different is the approach used for the development of the support device. Here the disc knob can rotate around the vertical axis and, accordingly with the type of control, it has its own mechanical resistance or a motor to prevent too rapid rotations. This device is also used to make adjustments on the entire control as well as to check the correct use of the interfaces.

4.1. Target control

The main interface should be a haptic device in order to provide the user with a force feedback during its use. Generally, there are two ways to control haptic manipulators [31]: admittance or impedance control. The former measures the forces that the user exerts on it and reacts with motion. In other words, the manipulator acts as a mechanical admittance which accepts force inputs and yields motion outputs. With the impedance control, the user moves the device, and the device will react with a force. In other words, the manipulator acts as a mechanical impedance which accepts motion inputs and yields force output.

Admittance controlled devices can generate very high stiffness, because there is no stability issue when simulating hard surfaces. The inner motor loop deletes the real mass and most of the frictions of the mechanical device. On the other hand, simulating free air motion is hard because the virtual mass cannot be null in order to avoid infinite acceleration. Thanks to these properties, the admittance approach has been chosen to develop the control scheme of the target. When the operator acts on the device, his input force is measured for both directions of movement, vertical and horizontal, by the load cells embedded in the handle support. This allows considering the DOFs of the system separately and where a single mass interacts with the environment. The admittance model is thus used by the excavator control unit to calculate the desired position and/or velocity of the end effector depending on the chosen control type, position or rate. Later, through inverse kinematic and dynamic equations, length variations and relative speeds for the hydraulic pistons of boom and stick are found out. These are necessary for the proportional valves that change the pressure in the system and cause a variation in motion. At this point, the information follows the reverse path and from the sensors embedded on the arm goes to the device controller. These sensors can be of different types, angular for the measurement of the arm rotation or linear for the measurement of the length of the pistons. With the data coming from the sensors and the direct kinematic equations, if necessary, the real position and velocity of the end effector are determined. At this point the new position of the handle is firstly calculated, by taking in consideration the device workspace and the chosen excavator control type, and then reached by acting on the motor for the haptic feedback.

Two different information loops are provided in the control logic, both necessary for the evaluation of the end effector and handle errors between the real and the desired position. A correct interpretation of these data allows for a better understanding of the use condition of the excavator and the design of a correct force feedback for the user. In other words, if the error of the end effector increases step by step, it means that the motion of the hydraulic arm is prevented due to the external environment. On the other hand, if the device error increases the desired inertia, damping or stiffness of the admittance equation require some adjustments.

On the basis of the work done by E. C. Poulton in [32] only two types of control scheme have been developed for the motion of the boom and the stick. Indeed, position and rate control have been proven to be superior to higher order control such as acceleration control. The latter is usually less intuitive, unstable and does not provide the user with fine command. With position control, the operator directly acts on the end effector position; the transfer function is a constant gain for each axis (i.e. a zero-order transfer function). The equation that relates the input signal I with the output O at n^{th} time step is (G_p is the constant gain):

$$O(n) = G_P \cdot I(n) \tag{1}$$

With rate control, where the transfer function from human input to the movement of the end effector is a single integrator for each axis (i.e. first order transfer function), the user manages the velocity of movements of the end-effector. In this case, the equation that relates the input signal I with the output O at n^{th} time step is (G_v is the constant gain and T is the sampling period):

$$O(n) = O(n-1) + G_v \cdot I(n-1) \cdot T \tag{2}$$

Much work has been done to evaluate the difference, in terms of performance, between the position control and rate control. From an isomorphic point of view [33], the first one can be considered more direct than the second one and this is due to the direct correspondence between input and output in its descriptive equation (1-to-G_P). For this reason, less mental effort is required to generate the end-effector movements, and the device becomes more intuitive for the operator.

However, position control has some conceivable disadvantages related to rate control: (a) all human movements, whether voluntary or involuntary, are transferred to the end effector. This is in contrast with the low pass filtering effect introduced by the integral function in a rate control scheme, where the high frequency involuntary noises are suppressed; (b) the movements of the end effector are less smooth than rate control where, by definition, its velocity is controlled; (c) the maintenance of a constant velocity for the end effector is more difficult than rate control because the user shall move the device with a steady speed; (d) to ensure the reachability of all points of the workspace of the end effector, the device workspace in position control should be very small. Therefore, a fine control is not guaranteed, and the user movements can be very large, causing a rapid fatigue on upper arms.

Changing the control scheme does not affect only the way the device moves the end effector with respect to similar input forces, but also its workspace. With the position control, in fact, the shape of the handle working area resembles the 2D shape of the stick-bucket link, while with rate control it is obtained with a rectangular profile. Since both control logic should be implemented on the same device, the reachability limits of the handle are obtained mechanically by exerting an opposite and equal reaction on the user hand. Thanks to that, the operator has also the possibility to change the dimension of the device workspace accordingly with his needs. By reducing it, the user has the possibility to perform the same operations on the bucket, with respect to a higher dimension of the working area, but with less movement of his arm and therefore with a minor risk of fatigue for the upper limb or unattainable points of the device workspace. At the same time, a reduced movement of the human arm may cause a worsening in terms of precision on the controlled part, mainly for what concerns the position control where the target movement is already widely scaled if compared to the handle displacement.

4.2. Bucket control

For the control of the bucket revolution, a different approach is used: it was performed thanks to the rotation of the main device handle. Due to physical limitations of the user in the wrist articulation, it is not possible to use a position control in this case, since the end effector can perform a 165 degrees rotation. The only available approach is the rate algorithm in which the rotation angle of the handle, measured between the zero position and the actual position, corresponds to an angular speed of the bucket in the same direction. Obviously, the largest the rotation is, the higher will be the angular velocity reached by the bucket.

Another issue comes from the use of the device during the end effector translation. Naturally, the user changes the absolute wrist angle, and this depends on the hand position with respect to the shoulder. To avoid involuntary movements of the bucket, the controller of the handle rotations is not always active, and the human operator chooses when to turn it on or off (e.g. by capacitive button). When it is done, the current handle angle is set as zero and each change is computed accordingly. With this controller, it is possible to lock the bucket rotation without necessarily looking for the neutral position. The actuation of the handle DOF is not needed, because of the control principle described so far. No force feedback is necessary for this switchable rate control, neither to feel the neutral position where the bucket movements are stopped. Moreover, the handle shall move freely while bucket rotation is not enabled in order to meet the natural movements of the users hand.

4.3. Swing control

The control of the swing motion of the excavator cab is performed by means of a rotary knob. Both position and rate control logic are made available in order to evaluate differences between the two logics (see Section 5). With the first control type the knob rotational angle, measured between the neutral position and the actual one, is related with the angular speed of the main body of the excavator. The direction of rotation for the master and slave part corresponds in order to improve the intuitiveness of the device. With the rate control type, instead, the absolute rotational angle of the knob is linked to the absolute angular position of the excavator main body.

The implementation of rate control algorithm will require the knob to have specific (mechanical) limitations to avoid rapid rotations (not feasible for the excavator) and blocks its movements when the user does not act on the knob itself.

5. Evaluation tests

A test campaign is necessary to validate the proposed control logics from the usability perspective. All the tests performed are compliant with the definition of *usability* provided in ISO 9241 [34]. A comparison between the old-fashion control system (i.e. joystick configuration) and the one proposed in this paper is the goal of the tests. Their aim was not to assess the operators skill with earth-moving machines during the operation, as it has been done by Bernold in [25], but to compare the ability of the two input systems to facilitate the learning. The tests of the ergonomic aspects can be divided, in its turn, into two sections: the intuitive design (input action related to joint angles) and the control aspect (joystick in rate and a haptic device in position and rate). In [35], Fitts et al. describe the three phases of the learning process as cognitive, associative and autonomous. In the first phase, the operator will constantly have to think a lot, observe and copy actions. During the second phase no further instructions are needed, the focus of the user is now placed on performing the actions at his best. In the final stage, the operator no longer needs to think about the movements because they become more natural. In this way, the control and the actions are smooth and accompanied by integrated patterns. Thanks to these tests, which involve the psycho-motor skills of excavation, it is possible to investigate the input layout at an early stage of the learning process.

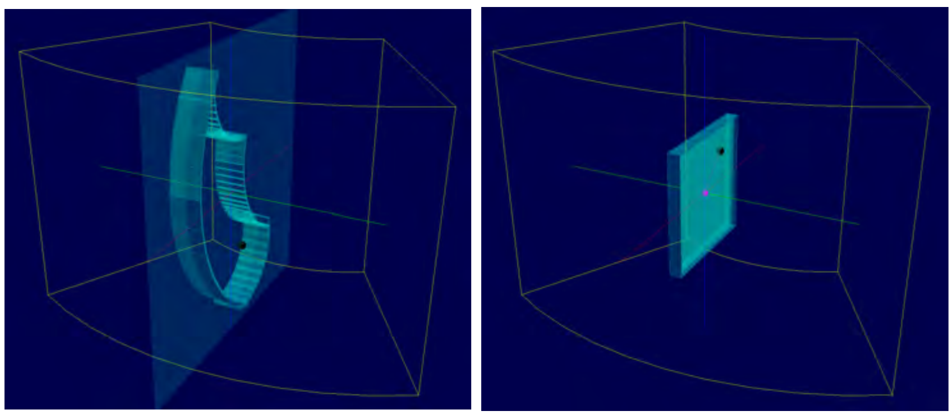
A description of the experiment set-up is necessary in order to understand the results of the test procedure. In the following section, the virtual simulation, equipment, tasks, procedure and data are described.

5.1. Simulator

Building the physical prototype of the device and testing within real operating environments is expensive and high risky. In this study, a virtual simulator is used to validate the new device design and its control logic from the users point of view. The virtual scene simulates the kinematic and the behavior of the device, the hydraulic excavator as well as the surrounding in which it is supposed to operate (Figure 5).

Figure 5: Virtual Reality environment implemented for the tests

The HapticMaster device has been adopted to simulate the controller of the hydraulic arm: an admittance-controlled device which measures the input force exerted by the user on the end effector and, according to the haptic model, it reacts with a displacement. More detailed characteristics and performances of the device are described in [36]. The dimensions of its workspace (80 liters with the shape of a partial hollow cylinder) and the three DOFs (base rotation, arm up/down, arm in/out) are suitable for the simulation of the main device. In order to mimic the concept previously presented, two working volumes have been rendered within the HapticMaster. As shown in Figure 6, for the position control, these consist in 22 prisms and 2 spheres suitably oriented and sized for the reconstruction of the front-down and rear-top limits respectively, and, for the rate control, in 4 rectangular prisms aligned with the reference system. The use of this type of solution is justified by the limited number of shapes deployed by HapticMaster API and rendered as virtual haptic objects. Two lateral planes with high stiffness are then generated to constraint the extra degree of freedom (i.e. the base rotation) that is not used by the control logic. Also, the behavior of the device is changed according to the type of selected control and human-machine interaction. In position, for instance, the device is locked to the actual position when the user releases the handle while dynamic viscosity effects are adjusted in real-time to regulate the exerted input forces as well as to make the user aware of the movements of the hydraulic arm. With rate control, instead, a spring effect is introduced to help the user identifying the neutral position of the device (i.e. when the bucket speed is set as zero) and to automatically move the handle back to the origin when there is no interaction between the user and the machine. A snippet about the implementation of these two controls with the Haptic Master is provided in the Listing 1.



(a) Position control

(b) Rate control

Figure 6: Render of the haptic boundaries of the HapticMaster working volume according to the two control logics.

Since the HapticMaster does not handle the rotation of the end-effector (i.e. the DOF needed to activate the bucket rotation, θ_3 in Figure 2), a physical handle has been attached on the end-effector of the HapticMaster and interfaced to the whole system through an Arduino board [37]. This uses a potentiometer to measure the absolute rotation of the handle and a capacitive sensor for the activation of the related DOF. The same controller board manages the operation of the support device which embeds a wide rotating knob to ensure a correct grip of the user and LCD panels for visualizing the degree of its rotation.

The functional schema of the virtual simulator is depicted in Figure 7. Here, all the main flows of information provided to the user during the use of the simulator with the coordinated control configuration are described by using arrows. The three main actors (i.e. Haptic Master, Arduino board and the graphics engine) are highlighted as three dashed boxes, connected to each other by means of serial communication channels, which have to perform specific functions to transform the different input signals.

Listing 1: Snippet of the position and rate control implemented in C++

```
if (_controlChangedToPosition() == true)
{
    _defineWorkVolumePosition();
    _setPositionEffects();
    _setNeutralDampingEffect();
    P_EE = _calculatePosEE(P_T);
    _moveEE(P_EE);
    ControlType = "position";
}
else if (_controlChangedToRate() == true)
{
    _defineWorkVolumeRate();
    _setRateEffects();
    _moveToOrigin_EE();
    ControlType = "rate";
}

if (ControlType == "position")
{
    if (F_measured > 0)
    {
        P_EE = _calculatePos_EE(F_measured)
        P_T = _calculatePos_T(P_EE)
        _armInverseKinematic(P_T)
        if (_isInsideWorkVolume_EE(P_EE) == true && ...
             _isInsideWorkVolume_T(P_T) == true && ...
             _isWithoutObtacles(P_T) == true)
        {
            V_EE = _calculateSpeed_EE(P_EE, P_EEold)
            if (V_EE <= _calculateMaxSpeed(P_EEold))
              _setNeutralDampingEffect()
            else
            {
                _increaseDampingEffect();
                P_EE = _calculateMaxPos_EE(P_EE);
                P_T = _calculatePos_T(P_EE);
                _armInverseKinematic(P_T);
            }
            _move_T(P_T);
            _move_EE(P_EE);
            P_EEold = P_EE;
        }
    }
    else
      _lockPosEE()
}
else if (ControlType == "rate")
{
    if (F_measured > 0)
    {
    P_EE = _calculatePos_EE(F_measured)
        P_T = _calculatePos_T(P_EE);
        _armInverseKinematic(P_T);
        if (_isInsideWorkVolume_EE(P_EE) == true)
        {
            _moveEE(P_EE);
            if (_isWithoutObtacles(P_T) == true)
                _moveT(P_T);
        }
    }
    else
        _moveToOrigin_EE();
}
```

The real-time computation of the kinematic and dynamic equations is performed by the integrated CPU of the Haptic Master which ensures high performances and, at the same time, reduce the computational effort of the graphics engine. This latter is only used to decode all the data coming from

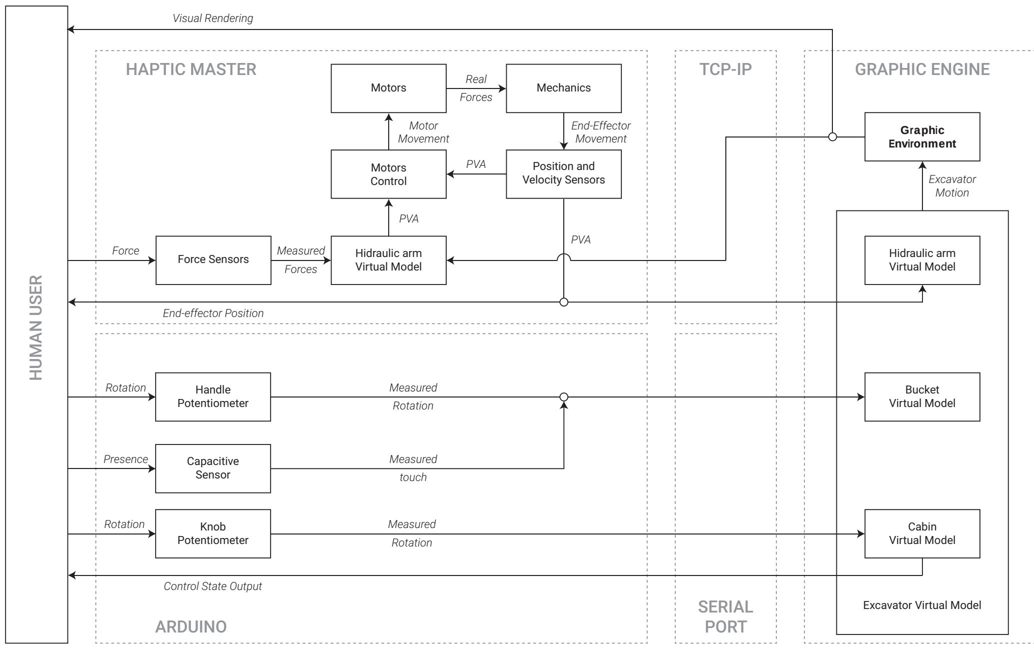


Figure 7: Functional schema of the implemented virtual simulator.

the devices and correctly rendering the virtual scene to be displayed to the user. Since all the tasks are executed without any interaction between the hydraulic arm and the external environment no loop-back data related to the terrain deformation have been implemented. Indeed, the terrain has been simplified as a rigid body and all the collisions are detected thanks to the physics module provided with the game engine. These data are then used to render similar rigid haptic feedbacks on the Haptic Master and to thus to limit the movement of the users on a restricted portion of the working volume. No additional feedbacks regarding such type of collision, or for the haptic rendering of the bucket load, has been added within the simulation. These, in fact, requires an appropriate calibration to be performed with different tests in order to prevent the risk of fatigue for the user's upper limbs and confusional haptic signals.

5.2. Equipment

The structure of the virtual simulator is composed of an external frame, which is made with aluminum profiles to support the seat and the hardware devices, and the seat, which is mounted on a power sliding support to ensure a correct posture to the user. Two different configurations of the simulator have been adopted: one equipped with joysticks (Figure 8a) and another one that includes the proposed interface (Figure 8b).

The simulation of the joystick control is performed by using a pair of joysticks placed on appropriate supports in front of the user. The simulation of the coordinated control, instead, is carried out by placing the HapticMaster on the right side of the users and the support device in front of them on the other side.

(a) (b)

Figure 8: The configurations used for the tests with the joysticks on the left and with the proposed interface on the right.

Since the perception of the depth is fundamental to increase the realism of virtual environments, the virtual scene has been rendered through a 3D projector to allow the users to efficiently perform the prescribed tasks. In fact, it is difficult to get proper hand-eye coordination, especially during the joystick use: in this case, the boom and the stick are moved independently, so it is necessary to notice the distance in the third dimension.

A video camera has been used to capture simultaneously the user, the input devices and the projected virtual environment to verify, after the test, the correct execution of the tasks.

5.3. Task

It is generally hard to get an objective and systematic evaluation of the usability performance of new human machine interfaces. The tasks, the users are asked to perform, are crucial for a successful test campaign. In this work, the assignment concerns to best follow one by one three prescribed trajectories with the three different configurations of the simulator. These are designed in three dimensions and rendered in the virtual scene by means of colored linear paths (Figure 9). Due to the definition of the task and the dimension of the excavator end-effector compared with the paths, a sphere-shaped target is placed within the bucket and used to guide the users. Its dimension is critical because it corresponds to the maximum error allowed to the user during the execution of the test.

Figure 9: 3D visualization of the paths used during the tests inside the virtual environment. The background of the picture has been modified in order to highlight the shape of the paths and the excavator itself (the sphere-shaped target is also visible inside the bucket)

The three different paths, with an increasing degree of difficulty are always assigned in a specific order:

1. *bucket movement* (yellow line in Figure 9): it consists of three straight lines, two horizontals and one oblique, that the user has to cover by closing the excavators arm or, in other words, by moving the target towards itself. For the execution of the task, the only two DOFs involved are the rotations of the boom and stick links. In this case, the user

interacts with the HapticMaster (Figure 8b), or with the vertical axis of the joysticks (Figure 8a), to move the excavator's end-effector in the vertical plane.

2. *bucket orientation* (light blue line in Figure 9): it consists of two semi-circles and a vertical straight line at the end that the user must cover by closing the excavators arm. In this case, the three DOFs involved are the rotations of the boom, the stick and the bucket. Compared with the previous task, the user must also use and activate the rotation joint of the knob or the horizontal axis of the right joystick in order to reproduce a digging motion. To facilitate the correct perception of the task, the rotation of the bucket is not applied simultaneously to the target movement and the path line change color when it is required to operate that DOF.
3. *full movement* (green line in Figure 9): it is developed on a circular arc centered with the rotation axis of the cab in order to compulsorily involve the swing motion in the simulation. Moreover, three different changes of course are added so that the user must cover them by using the other links of the hydraulic arm. In this case, since all the four DOFs are involved (i.e. boom, stick, bucket and swing), a three dimensional motion of the target is required. This path scenario is the most complex among those proposed, and the user has to move simultaneously the main body of the excavator and the end-effector to reproduce digging operations where some obstacles are present along the desired trajectory.

5.4. Operative procedure

Fifteen users with no experience in the control of earth-moving machines were involved. They were 14 men and 1 woman aged between 21 and 27 years. This age group was made up of students and it has been selected to be congruent with the average age at which users start using excavators. These values are also justified in [4], where more than two hundred operators were investigated and classified according to the age and the level of experience. No expert operators have been included in this testing activity since their higher confidence in using joysticks may affect the comparative evaluation with the proposed control logic. This latter was designed to reduce the learning time, and it is therefore measured only with beginners in order to include their immediate performances without significant training.

At the beginning of the session, the participants were briefed on the purpose of the study and asked to fill the pre-test questionnaire out. Then, they were provided with a detailed explanation of the test procedure and on the operation principles of the input devices. The users were given the opportunity to freely use the simulator for ten minutes to become familiar with each control, i.e. joystick (JOY), Haptic Master in position (HM_{pos}) and Haptic Master in rate (HM_{rate}). All participants were informed that the experiment was video recorded for further analysis (Figure 10). Each user performed a total of 9 different tasks (3 for each path). In fact, each of the three paths was followed by mixing all the three available controls. Table 1 shows the configuration of the three patterns: the IDs will be the labels the authors follow in the rest of this paper.

Figure 10: Image of a user during the execution of the task with the coordinated control

The sequence of the tests was also randomly varied to prevent a possible learning effect. Upon completion of the tasks, participants were asked to complete a post-test questionnaire. Overall, a single session lasted maximum one hour.

5.5. Collected data

The survey is divided into three parts to be completed at different times: before, during and after the test. The pre-test interview is necessary to collect

ID	Device	Control	Kinematic
JOY	Joysticks	Rate	Forward
HM_{pos}	HapticMaster	Coordinated Control in position	Inverse
HM_{rate}	HapticMaster	Coordinated Control in rate	Inverse

Table 1: Description of the three experimental patterns and relative ID

basic information of the user, his previous experience with simulator games and haptic device, and his expectations from the test after receiving the basic information. During the test, participants were asked to think aloud in order to collect their feelings about the simulator, their mental process and the possible problems identified. The post-test interview consists of a multiple-choice questionnaire to target all the possible answers and facilitate the collection procedures. The surveys ranged over many topics, including, but not limited to, the initial training utility, the comparison between the current and the new device, the users feelings with the solutions proposed, in terms of control logic, intuitiveness and comfort, and some possible improvements.

On the other hand, some parameters have been also measured while the tests run. The Cartesian position of the end effector is calculated directly from the virtual application as the distance between O_0 (Figure 2) and the target. This is provided as function of the time step in order to directly compute the velocity of the movements. These data are necessary for the evaluation of the users precision and efficiency. In addition, by knowing the real location of the paths, it is possible to estimate the errors committed. Another index, useful for the evaluation of the performance, is the completion time. It is measured automatically for each task until the user does not stop following the path. Thanks to the use of kinematic equations, all the relative joints angles of the excavator's arm are known. In this way, it is possible to find out another parameter which helps to objectively interpret the users control ability: the number of actuators simultaneously used. This is intrinsically related to the previous data; indeed, the hypothesis is: the greater is the number of links used, the better is the control level achieved. However, this evaluation must be weighted on the errors: the parameter is less relevant if the operator moves the links in the wrong direction, increasing the error, compared to the situation where the number of links is smaller but moved in the correct way.

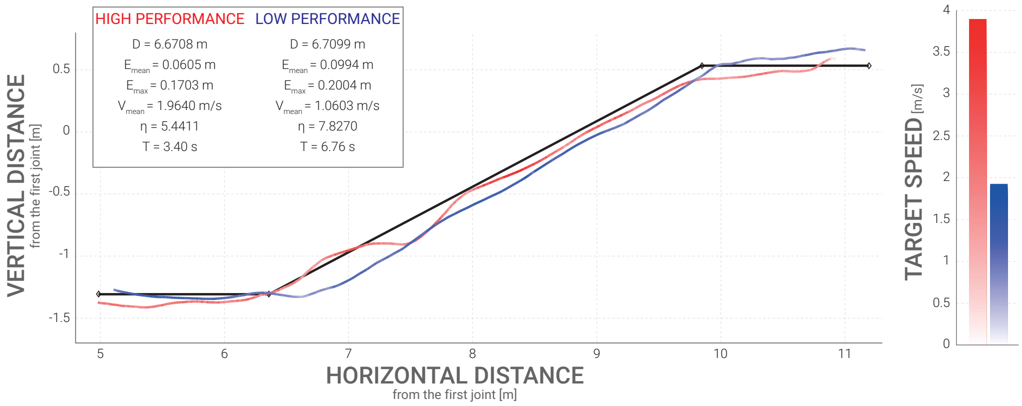
With the parameters presented above, the achieved performance by the users during the tests has been analyzed. However, the aim of the test was also to evaluate the proposed solution from a design perspective: the measured force, the force feedback and the measured Position-Velocity-Acceleration (PVA) vector of the end-effector are also collected. The first and the last ones are directly provided by the HapticMaster embedded sensors, while the feedback perceived by the user is computed from the values of the mass, the damping and the stiffness of the virtual model (Figure 6). Even the orientation angle of each joystick has been taken into account in this data collection. This measurement takes into account different aspects of the users confidence level, such as: the rapidity to move from one position to another or from one actuator to another, and the percentage of the maximum available stroke used.

6. Test results

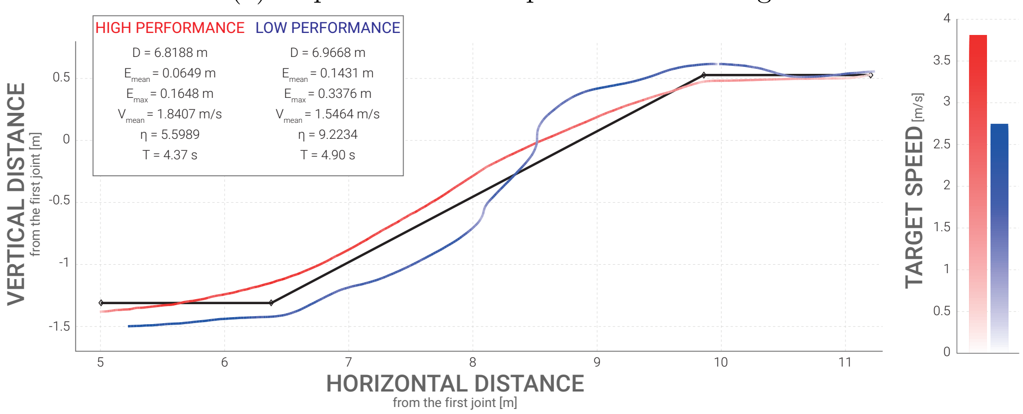
It is necessary to make some observations about the results, which will be shown in the subsequent sections. As detailed in Section 5, both subjective (i.e. questionnaire answers) and objective (i.e. measurements) parameters are recorded. In the following section, the results are presented of both the questionnaires and the measured performance.

6.1. Objective performances

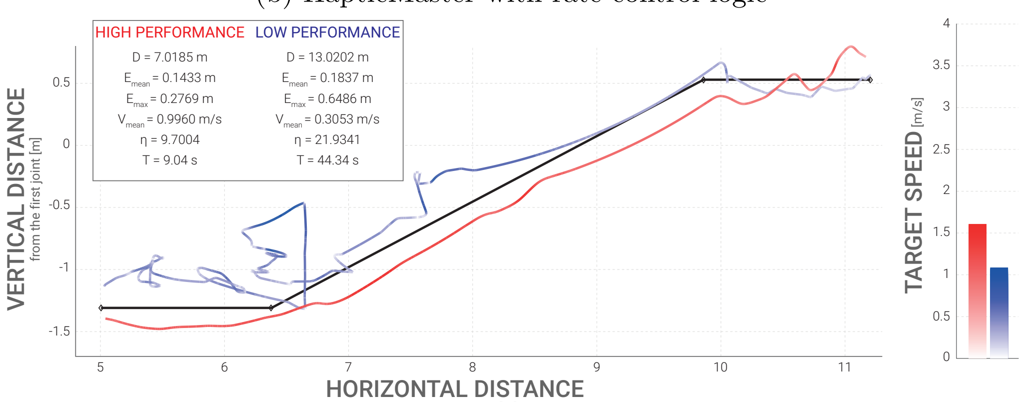
Several considerations can be derived from the analysis and the evaluation of the data collected during the experimental activity. An intuitive way to present these outcomes is by means of bi-dimensional or three-dimensional graphs where the trajectory of the target is illustrated with respect to the desired path. An example of this is Figure 11 where results of the three different control logic (i.e. HM_{pos} in Figure 11a, HM_{rate} in Figure 11b and JOY in Figure 11c) during the execution of the first path are presented. Here the black line represents the desired trajectory while the red and the blue lines depict the best and the worst user respectively, measured accordingly with the performance parameter described in Equation 3. The color intensity of the lines is an indicator of the instantaneous speed value of the target, which is calculated with respect to the maximum achievable speed of the hydraulic arm in the current kinematic configuration.



(a) HapticMaster with position control logic



(b) HapticMaster with rate control logic



(c) Joysticks

Figure 11: Best (red lines) and worst (blue lines) test results of the first path for each of the three simulator configurations. Black line is the desired trajectory.

It is evident the great difficulty encountered by the users during the execution of the task with the *JOY* configuration. Even the best experienced user performed the first part of the path proceeding with a trial and error approach due to his difficulty in remembering which levers, or their combination, are required for the initial bucket movement. This issue stands out with higher importance by looking at the blue line of the same graph where the operator, in the final part of the path, has completely lost the control of the excavator's arm. A similar behavior is visible on the graphs of all the other tests performed with joystick control, either at the beginning or at the end of the path and with different magnitude. When the coordinated control was used, the performances of the users were much closer to one another. Systematic errors on the trajectory position have been identified on the low-performance tests, clear sign that the users did not notice the mistake committed and they continued to move the target along the path believing to be in the right position. The majority of users, on the other hand, were more adept at identifying the positioning error and thanks to this control configuration they were able to act promptly and properly.

Another issue, emerging from the graphs and from the analysis of the exported data, is the unintentional activation of those degrees of freedom of the excavator's arm that are not necessary for the completion of the task. This error has occurred to all the users performing the *JOY* condition with a mean incidence rate of about 21% for the bucket motion and of 5.5% for the swing motion. The behavior can be explained as follow: the user does not have in his mind the relationship between the joystick axes and the joints, and also he has a very bad motion perception of the levers. In this specific case, this means that the user slightly moves the levers in the horizontal direction. An error of this kind becomes very dangerous especially for the rotation of the bucket where, unlike with the swing motion, it is very difficult to detect whether the other joints are in motion. Conversely, the latter problems have been greatly reduced by using the coordinated control (Figure 11a and Figure 11b). This means that all the users have been able to correct the error as soon as they noticed.

Equivalent charts for the remaining two paths lead us to similar consideration. The second path, for example, has been designed to facilitate the *JOY* configuration with respect to the coordinated control, since the bends of the desired trajectory can be covered with the target by activating one joint at a time. This improvement can be significantly noticed in the low error rate of the *JOY* for the first two sections of the path, even if the user's uncertainty is still present and well suggested by the lower speed in approaching the target. Some problems come out due to the final part of the path, where the target is moved vertically and the user has to change the rotation direction of the joints. As in the previous path, this sudden reconfiguration to the levers input system is not always performed in the correct manner and it often caused a target motion very far from the desired one.

With the third and most complex path among those proposed, a strong relationship between the task execution time and the average error emerges. Using the joysticks configuration (JOY), the users can be clearly distinguished into two groups: those who have followed the path more precisely and those who have adopted a more rapid approach. The first group is able to maintain a lower average error, but it never dropped below 80 seconds (that is almost three times the average time got with the coordinated control configuration). The second group, instead, have doubled the average and maximum error by covering a distance up to 1.68 times greater than the ideal one. As regards the haptic input system, a first consideration can be made comparing the position with the rate control. For the first time there is a turnaround in the performance evaluation and more than half of the participants achieved better results with rate control. Once the users understand the logic behind the control, they can perform the same task with less movement of their own arm and so intervene more rapidly in redressing errors. This fact occurs in path 3, not only because it is the last in chronological order to be accomplished, but also because the user must interact with the knob to control the swing: in this way all the excavator joints are controlled by the same logic (i.e. rate).

Due to the large number of variables analyzed in the tests, to compare and summarize the performance of the user along a specific path the metric η is defined as follow:

$$\eta = \frac{D_r}{D_i} + \frac{E_{mean,r}}{E_{mean,i}} + \frac{E_{max,r}}{E_{max,i}} + \frac{V_{mean,i}}{V_{mean,r}} \text{ where } \eta \geq 4 \qquad (3)$$

where D_r is the real distance covered by the target, D_i is the length of the desired trajectory, $E_{mean,r}$ is the average error calculated as the minimum distance between the real and the desired path, $E_{mean,i}$ is the average error allowed during the simulation (i.e. half radius of the target sphere), $E_{max,r}$ is the maximum error committed by the user, $E_{max,i}$ is the maximum error allowed (i.e. the radius of the target sphere), $V_{mean,r}$ is the average speed maintained by the user, $V_{mean,i}$ is the theoretical average speed calculated

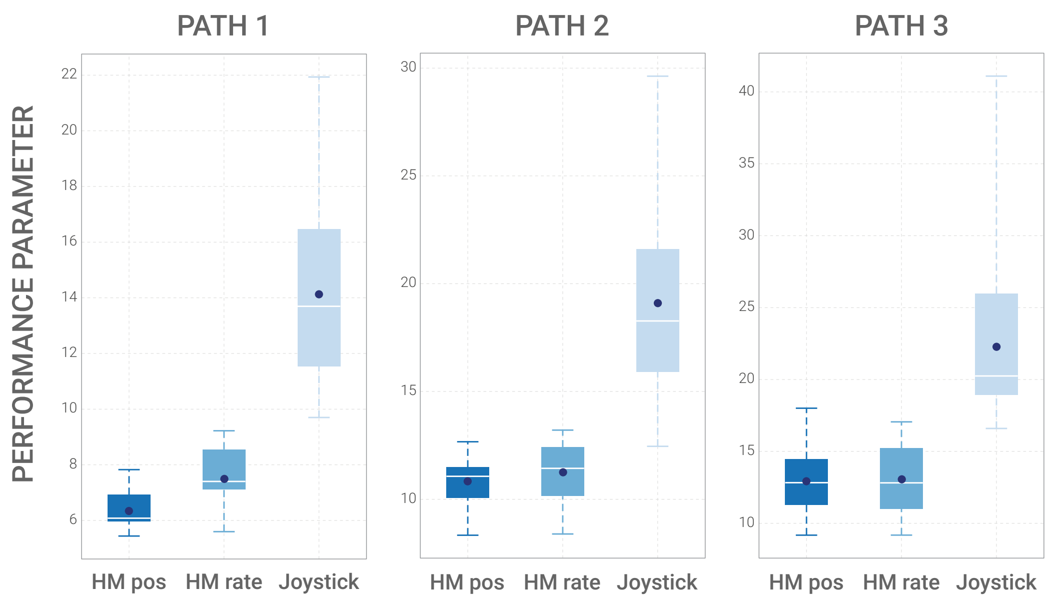


Figure 12: Boxplots of η parameter for each path and control logic

as the mean of the maximum speed reached by the hydraulic arm for each route point. The higher is the value of the η parameter the lower is the level of performance achieved by the user.

Figure 12 reports boxplot of η parameter statistics of each control logic and for all the three paths. This is an aggregated and adimensional metric which simultaneously measure four relevant aspects of the task (individually defined in Table 2): the distance, the mean and maximum error and the mean speed (or the time). It can be noticed a significant reduction of the η value during the transition from joystick to coordinated control, much more stressed with the Haptic Master in position and with the initial paths. All the users reached a performance at least 38.0% higher, with peaks of 74.5%, when they operated the hydraulic arm with the haptic device. The reduced distance of η values in the second and third path can be caused by the activation of the bucket and the cabin revolution, operated with the rotation of the handle and the knob, respectively, in coordinated control condition and with the lateral movement of the levers in joystick condition. The rotation of the handle, and the related capacitive sensor used for the activation of the DOF, requires a longer training to be correctly operated if compared with its planar movement: the user needs to activate the sensor first, and then rotate the handle in the right direction. Many of the participants have chosen to follow slowly the path due to the sensitivity of the haptic device in the wrist action. Similarly, the knob rotation has been operated by the users with less confidence than the other device movements which implied a low angular speed of the excavator cabin. Overall and despite some design limitations, the analysis of the performance states that both the proposed control logic outnumber the traditional one.

Thanks to the data recorded in Table 2 additional considerations related to each aspect of the task has been derived: (i) the average completion time is the greater improvement introduced by the coordinated control; (ii) the mean and maximum distance errors do not show any statistically relevant difference between HM_{pos} and HM_{rate} conditions; (iii) HM_{pos} condition is much more intuitive with respect to HM_{rate}; (iv) HM_{rate} condition requires more training time but can achieve the same, or even better, performances of HM_{pos}.

Parameter	**Path**	$\boldsymbol{JOY}$	$\boldsymbol{HM_{pos}}$	$\boldsymbol{HM_{rate}}$
Time [s]	1	19.9	5.6 (-72.0%)	6.8 (-65,9%)
	2	31.0	6.1 (-80.3%)	8.0 (74.2%)
	3	74.2	30.2 (-59.3%)	35.0 (-52.8%)
Distance [mm]	1	8.5e3	6.8e3 (-20%)	6.9e3 (-18.8%)
	2	17.7e3	15.9e3 (-10.2%)	15.1e3 (-14.7%)
	3	42.7e3	38.9e3 (-8.9%)	36.8e3 (-13.8%)
Mean Distance Error [mm]	1	128	58 (-54.7%)	76 (-40.6%)
	2	215	145 (-32.6%)	155 (-27.9%)
	3	285	175 (-38.6%)	160 (-43.9%)
Max Distance Error [mm]	1	400	180 (-55.0%)	210 (-47.5%)
	2	800	450 (-43.8%)	410 (-48.8%)
	3	1020	570 (-44.1%)	530 (-48.0%)

Table 2: Average values of the test parameters for each experimental path and control configuration. The percentage values express the variation of the coordinated conditions with respect to the joystick of the same path

6.2. Post-test questionnaire

Fundamental for the completion of this research is the final questionnaire filled out by all the testers. This allows us to gather subjective feelings perceived by the user during the tests, which can not be measured. The first data emerged from the questionnaires are related to the comparison among JOY, HM_{rate} and HM_{pos} controls. Four main topics have been investigated: (i) the control intuitiveness, and therefore the ability to obtain the desired movement without thinking too much; (ii) the user-friendless of the device, and therefore the absence of over-complicated control procedures that would impair or slow down the learning; (iii) the comfort of the input systems, and therefore the fatigue sensation felt by the user on the upper arm during the use; (iv) the mental fatigue, caused by learning to use the current control logic effectively. Users have rated each of the aspects assigning a score from one (the worst) to five (the better). Figure 13 depicts and summarizes the results for each item.

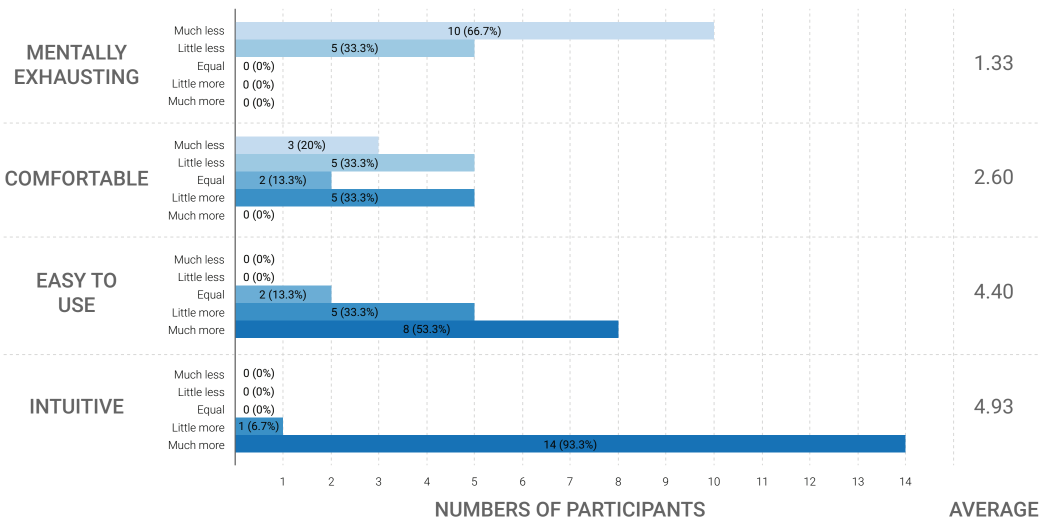


Figure 13: Results of the user's usability evaluation of the joysticks control in comparison to the coordinated control

The first clue suggesting that the goal of the research presented in this paper has been reached can be inferred from "easy to use" and "intuitive" metrics. In fact, their average scores are comparable. Noticeable results are related to the comparison between the current control logic of the swing motion and the bucket rotation (i.e. the lateral movement of the left and right joystick respectively) with the one designed (i.e. the rotation of the knob and the handle respectively). All users have noticed an improvement in intuitiveness thanks to the use of the handle but not in the use of the knob. The main problems are related to the stiffness and dimension of the knob itself, which prevent a smooth movement and a correct grip. The scores are encouraging also for what concerns the *ease of use* aspect (average score of 4.4); this is due to the control mode governing the bucket and cab rotation. The 73% of the participants felt greater confidence with the position control than with the rate one. This can be easily explained by the fact that the master and the slave have the same type of control reference, and therefore the relationship between them is easily understandable. The rate control is more difficult, since the position of the master corresponds to the speed in the slave with the same Cartesian reference system. As proof of this, there is the user request for further information and explanations during the training phase and the feeling of two participants to lose the bucket control. Despite this negative aspect, it is a great improvement if compared with the conventional control, in which 87% of users, under special circumstances, is no longer able to remember the correct joystick movements for the completion of the path. The results obtained can be considered as a consequence of the less logical relationship between the device and the target. For a future real-world application, the rate control will be able to offer the best compromise between the ease in control and ergonomics: the user can perform the same tasks of the position control but with shorter movements of his hand and, with the addition of arm supports, he feels less fatigue. Different is the opinion regarding the *comfort* aspect: the proposed layouts do not present substantial differences compared to the traditional one from this point of view (average score of 2.6). The reasons are two: (i) Although the position of the arm is not ergonomic, no armrests were provided; (ii) wide movements (20-30 cm) were required to the user to accomplish the movements, especially in the position control logic.

Another interesting parameter is the user evaluation of the training phase conducted at the beginning of the test. All participants but one have considered as sufficient the instructions provided and the available time in order to understand the working principles of the input devices. This is significant to distinguish the user's comprehension of the device functions (as a link between the hand motion and the hydraulic arm movement) from his confidence regarding the use. In fact, in the transition between the joystick and the coordinated control, all the users have noticed a marked reduction of the time necessary to achieve a better self-confidence in use. Two-thirds of the sample have never even reached a sufficient confidence level with the use of the joystick, proving the poor results obtained in the execution of tasks. This is the opposite what happened with the coordinated control, in which all the participants understood how to operate the device immediately or after a short time. In support of this trend, there is the evaluation of the time required by the users to perform the training phase. They were all allowed a maximum of 10 minutes with each device but, while no one used all of them with the coordinated control, for many participants it was insufficient with the traditional one.

With the last section of the questionnaire, new development possibilities for the haptic system have been investigated. Five users out of fifteen have felt the need for increasing the rate if the force feedback in order to improve the precision of the movements, the control performance and the feelings about the use condition of the hydraulic arm. This should not be considered as a disadvantage of the haptic control, because only with this type of system it is possible to introduce useful feedback (especially tactile and/or vibrational) for the user. Thanks to the presence of motors and sensors mounted on the master and slave part, it is possible to predict many dangerous situations during the digging operation, and therefore inform the user in time in order to prevent it from happening. However, the majority of the users suggestions concern the handle and knob design and comfort. The main problems relate to the difficulty in activating the capacitive sensor and understanding its functionality, the difficulty in using the knob for the swing motion and the fatigue of the arm in operating the coordinated control.

7. Conclusions

This paper presents the development and testing of a new control paradigm for excavators. The comparison with the traditional input system, based on joysticks for controlling each degree of freedom of the hydraulic arm, has disclosed a considerable improvement of intuitiveness and learnability. Thanks to this, it is possible for inexperienced users to operate efficiently large and powerful machines, without an excessive initial training. The development of these ideas would have not been possible without the support of the users involved in the execution of tests, whose degrees of knowledge and skills were strongly different, enabling the assessment of the new input systems from different points of views.

Two control logics for the hydraulic arm, both based on the coordinated paradigm, have been developed with different potentials and possibilities of use in the execution of excavation tasks: (i) position and (ii) rate control. The first control type has been preferred by most of the users due to its simplicity and easiness to understand. Thanks to the use of a position reference, useful haptic feedback is added in order to transmit, in an efficient and effective way, all the necessary use condition messages to the users (e.g. contact with an external rigid body, bucket movements through areas with different density, the presence of some obstacle, etc.). On the other hand, the need to make large movements and the high scaling ratio between device and excavator workspace, can early stress the users arm and then increase his frustration. Rate control, instead, is more complex to understand but it ensures a greater efficiency about the user movements. By reducing the dimension of the device workspace, it is possible for the operator to make fewer movements of the upper arm without affecting the control capability of the device with respect to the previous control. The drawback is the increased difficulty to introduce additional haptic effects to the one that brings the device to the zero position. The risk is to create too much resistance in the movement of the input system or to get the user biased. In this case it is preferred to use very light vibrational signals and, eventually, video messages.

One of the major benefits of the proposed solution is related to the high efficiency of the input system used for the simulation of the new control logic. Its specifications and technologies made it possible to reproduce very realistic effects on the users hand as well as to rapidly change the configuration of the haptic effects accordingly to the use. It was preferred to other commercial haptic devices because it develops higher force and avoid annoying mechanical play or lack of match between the device and bucket movements.

All users have noticed a great increase in intuitiveness of the bucket rotation control if compared with the lateral movement of the joystick. The advantage is a better understanding of the handle operating mode in order to rotate the bucket in the right direction. However, users have experienced difficulties in the use of handle rotation trigger: when the sensor is released, the controller resets the zero position, previously defined, and locks the rotation of the bucket. This is the best way to reduce the wrist movements and to increase the safety of the system. No one has found necessary the introduction of actuators, and thus feedback, even in this degree of freedom. The system must be free of resistance to ensure a free motion of the handle, when not active, and any feedback could create user confusion if added to those already defined for its planar movement.

The knob used to control the swing has been evaluated by the users in a more divergent manner, mainly for what concerns the design and the possibility to introduce force feedback. Half of the users considered the knob as a better solution with respect to the joystick because it also leverages the implementation of a position control for the cab rotation. However, to improve the control, this input system should have a motor which avoids excessive rotation speed and delay. The remaining of the participants, instead, has encountered more difficulties in its use for the following reasons: high friction resistance, too small size that prevents a correct grip and the absence of signals to understand the rotation rate.

The subjective and objective results presented in Section 6 point out the fulfillment, for the new control paradigm, of all the features initially obtained from the preliminary analysis. Thanks to the performance parameters, it is evident the improvement introduced by the coordinated control which has halved the total execution time and the number of errors with respect to the joystick condition. In all cases, the use of the haptic device has ensured a better execution of the task and, even if most of the users have preferred the position control, often the best results were obtained with the rate one.

In the future, further refining of the control logic algorithms will be implemented to increase its effectiveness and reliability. The hints provided by the users during the questionnaires will be taken into account to improve usability aspects. The re-design of the excavator interfaces is also an opportunity to introduce new type of feedback for the users who still mainly rely on the sight (i.e. what it is seen outside the cabin and what is displayed on the internal cockpit) and hearing (i.e. the sound coming from the engine and the impact with the external environment). If actuated, the new device can provide haptic sensations on the human hand/arm that correspond to well identifiable use condition. This solution can lead to the development of different control algorithms that can be used according to the performed task.

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Appendix A. Collected data

Appendix A.1. Performance results

Table A.3 shows the performance parameters (η) computed for each configuration, paths and user.

Table A.3: Performance parameters evaluated per user and test

User	Path 1 JOY	Path 1 HM_{pos}	Path 1 HM_{rate}	Path 2 JOY	Path 2 HM_{pos}	Path 2 HM_{rate}	Path 3 JOY	Path 3 HM_{pos}	Path 3 HM_{rate}
1	21,9341	5,5974	7,1346	21,4895	10,0625	8,3897	21,3949	14,4725	14,1233
2	17,7896	5,5579	9,2234	12,4562	12,0599	9,4498	20,2163	9,6916	10,4883
3	9,7004	6,0137	7,3906	29,6261	8,3323	11,4472	18,9230	11,8256	12,7311
4	10,2702	6,1221	5,5989	17,6149	9,9200	10,3302	25,9731	12,9640	10,5008
5	14,7224	7,7065	7,4148	12,6039	12,6681	10,1465	17,0627	12,3077	14,3735
6	13,8523	6,9238	6,0293	22,9822	11,1667	10,9636	17,4157	16,1622	15,2051
7	16,4734	6,0331	6,8689	17,7069	12,0117	13,2079	20,8568	18,0042	16,9527
8	10,1202	5,4411	8,5545	14,6650	10,9631	12,9589	16,5953	11,2736	15,3463
9	11,5350	6,1564	7,1204	18,8351	11,2418	12,6411	19,4179	16,1246	17,0545
10	13,5382	7,8270	8,5665	24,0012	10,1679	12,0662	26,5806	12,7432	12,8945
11	18,0280	6,3639	7,2659	16,5621	10,5182	11,4227	41,0997	12,9079	11,1387
12	11,5412	5,9703	7,5308	15,9196	11,4787	12,4127	20,2742	9,4794	10,9931
13	14,7379	6,0438	7,4600	21,6052	11,1946	12,4026	18,9438	14,1041	11,8299
14	13,4063	7,0729	8,6485	21,2769	9,8940	9,7909	27,1694	9,1753	9,1787
15	12,1593	6,8715	6,5716	20,4862	10,1168	9,9432	31,2934	10,3716	9,8767

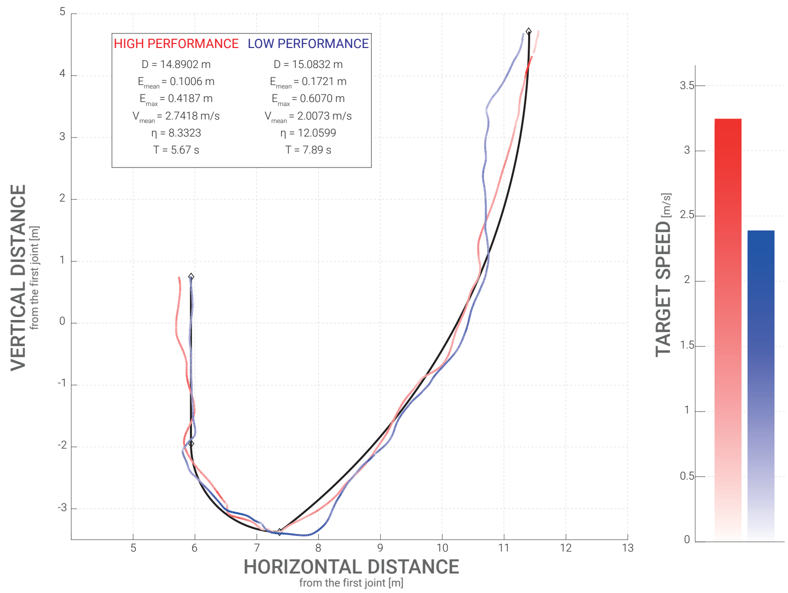

Figure A.14: Second path - Haptic Master with position control logic

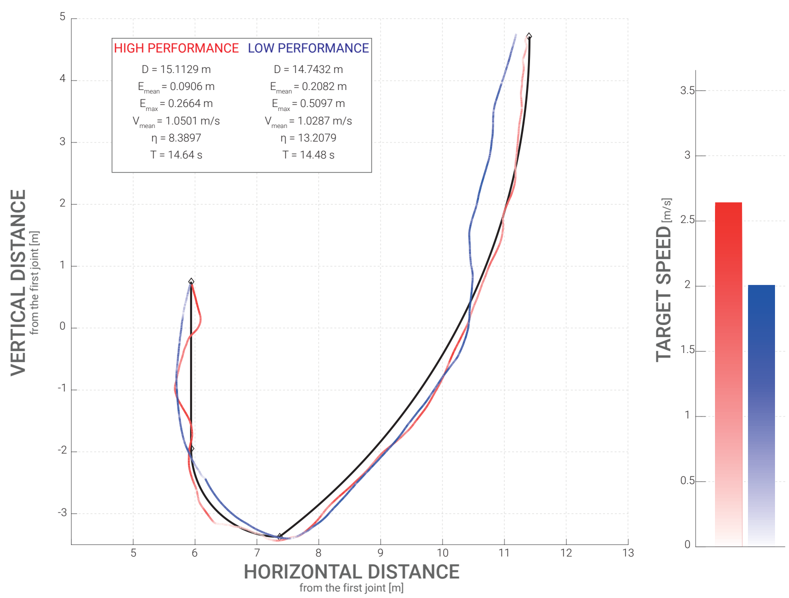

Figure A.15: Second path - Haptic Master with rate control logic

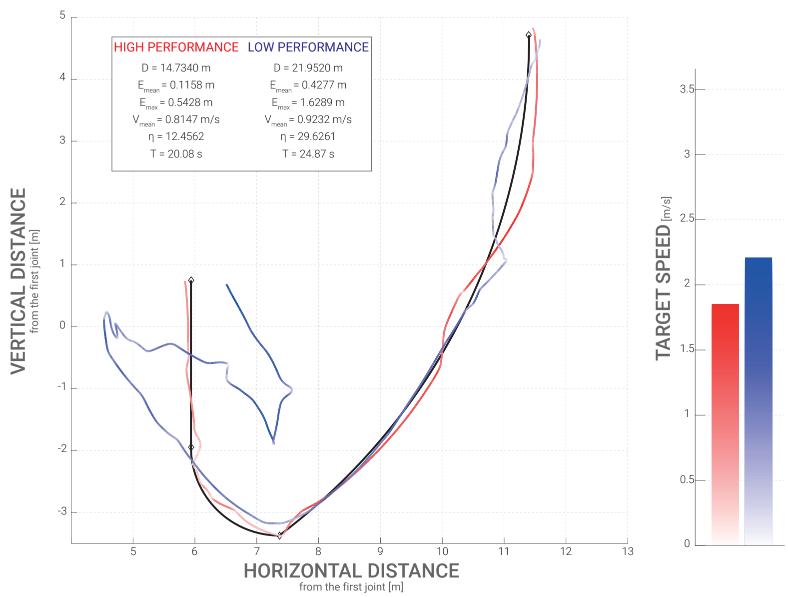

Figure A.16: Second path - Joystick control logic

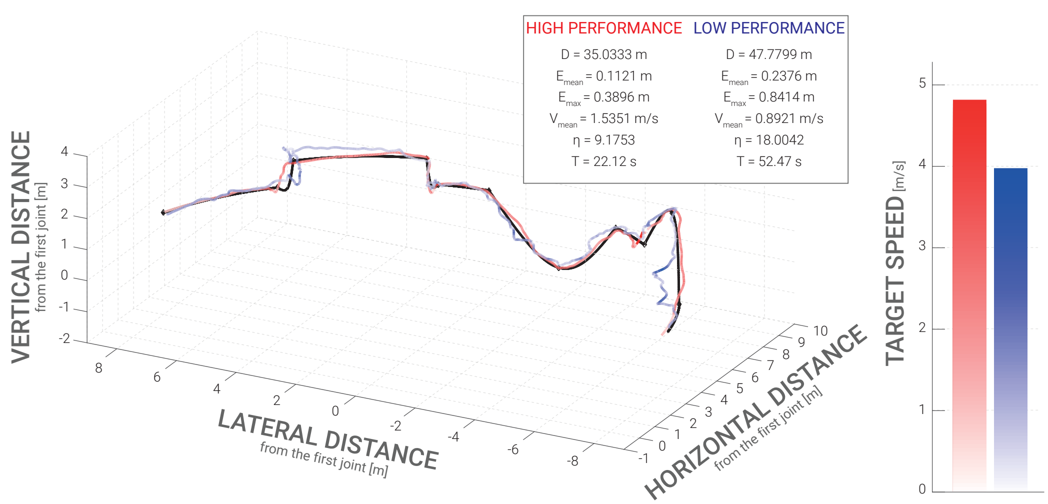

Figure A.17: Third path - Haptic Master with position control logic

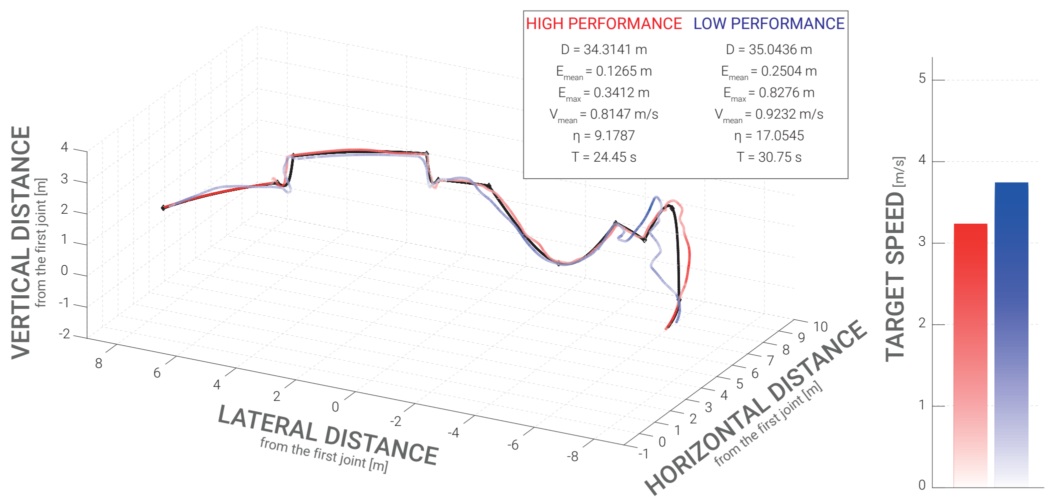

Figure A.18: Third path - Haptic Master with rate control logic

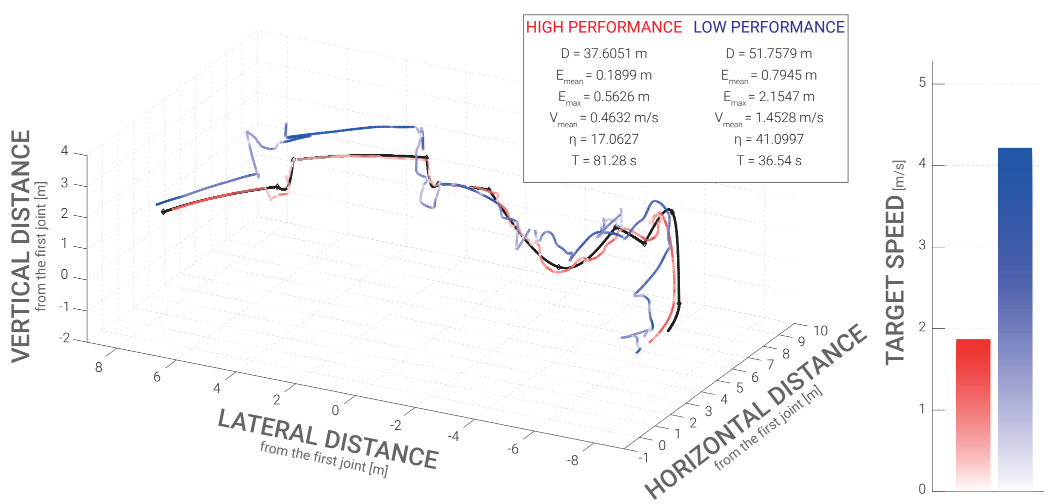

Figure A.19: Third path - Joystick control logic