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An Innovative Approach to Kinematic Analysis of Multibody Hydraulic Actuation Systems

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ABSTRACT

The paper focuses on the development of an innovative methodology for the direct measurement of the main kinematic variables in multibody hydraulic actuation systems.

The analysis investigates how the motion capture technique has been applied to the experimental determination of position, velocity and acceleration of hydraulically controlled actuation systems for off-highway machines.

A number of earth-moving machines has been taken into account, in particular a mini-excavator articulated arm has been equipped with both a standard mechanical system for position and acceleration measurement (including different accelerometers, linear and angular transducers), and a set of IR markers for motion capture application. First, the hydraulically controlled boom-arm-bucket system has been operated using a control routine reproducing a reference operating condition, in order to define the accuracy of the motion capture system in detecting the kinematic quantities' variations.

At the same time, the hydraulic variables have been also acquired to monitor the behavior during the machine working routine. Thus, the results obtained by the different experimental techniques have been compared, in order to state the reliability of the motion capture technique to predict the fast dynamics of pressure variations through the accurate measurement of mechanical devices' oscillation.

Finally, the paper reports the main results obtained using the data from the motion capture characterization of the dynamic performance of the mini-excavator, with particular attention devoted to the dynamic analysis through lumped and distributed parameter numerical cosimulation.

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INTRODUCTION

The growing concerns for environmental problems drive the development of more fuel efficient and environmentally friendly earth moving machines [1]. Therefore, their design and optimization address the different sub-systems and components of the working machines in order to enhance the efficiency of the entire system [2, 3]. In particular, the analysis of the moving parts becomes fundamental for investigating and optimizing the capabilities of the working machine to accomplish its specific tasks [4, 5, 6, 7]. The accurate measurement of the trajectories of the moving parts with respect to the actuation system provides the designer with an essential information about the performance and efficiency of the machine.

The analysis of the characteristics of the motion is usually carried out by means of sensors able to measure specific quantities that are necessary to describe the performance of the moving body. Main devices adopted for this experimental campaign are linear displacement sensors or angular position transducers that use a wire or magneto-resistive components for detecting the relative motion between two elements.

Indeed, this methodology has demonstrated several drawbacks when carrying out the experimental campaign in the real working field; for example, the accuracy of the sensors can be decreased by the harshness of the test environment or the sensors' set up procedure can result very difficult or take a long time

The recent technology advancement made it possible to employ new methodologies for investigating the motion and trajectories of moving bodies. In particular, the infrared technology found an important application field in the analysis of the motion with an accuracy in the order of the tenth of a millimeter. Among the infrared based systems, the Motion Capture (MoCap) is one of the most widely employed, having the animation movies a particular application that gave it a strong impulse. Indeed, this methodology has been also adopted for the measurement of the human body motion [8] or the study of animal characteristics. Examples of the MoCap application can be found in the area of real-size earth moving machines [9] as well as of test-rig scaled prototypes of machines [10].

In this paper, the Motion Capture technology is used for the measurement of the 3D trajectory of the mini-excavator working device and the acquired data are compared to the values obtained by means of regular motion transducers for linear and angular displacements.

The experimental campaign is carried out on a modified Fiori mini-excavator (MiniDig GR1000 series); first, the internal combustion engine of the machine and the hydraulic control system have been replaced with an electric motor and a fully electronically controlled hydraulic distributor in order to realize a computerized and remote control system. Afterward, a specific working cycle of the actuation cylinders is defined so that the motion of the moving arm, boom and bucket is representative of a standard working routine of the machine. Finally, the trajectory of the moving mini-excavator working device is measured simultaneously by the MoCap system and the regular transducers and the data acquired by both approaches are compared in order to outline the capabilities and accuracy of the infrared technology any given section.

CHARACTERISTICS OF THE MINI-EXCAVATOR

The original mini-excavator, see Figure 1, is powered by a Diesel internal combustion engine and the motion is controlled by a manually operated hydraulic system. The working device can move freely in the three directions by means of the three actuation cylinders, which operate the arm, boom and bucket respectively, and the hydraulic motor for the cabin rotation, see Figure 2.

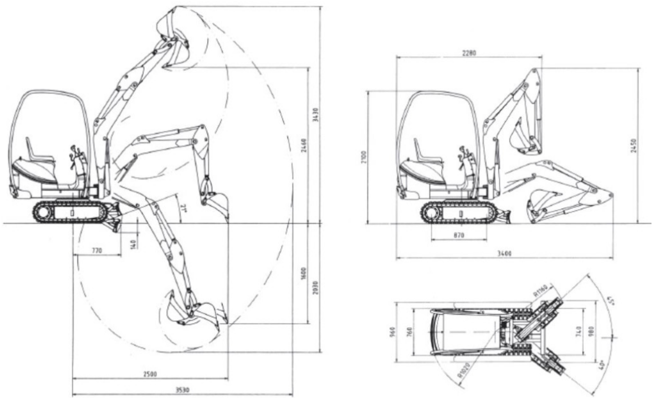


Figure 1. Schematic operating field of the mini-excavator.

Table 1 reports the main technical specifications of the machine.

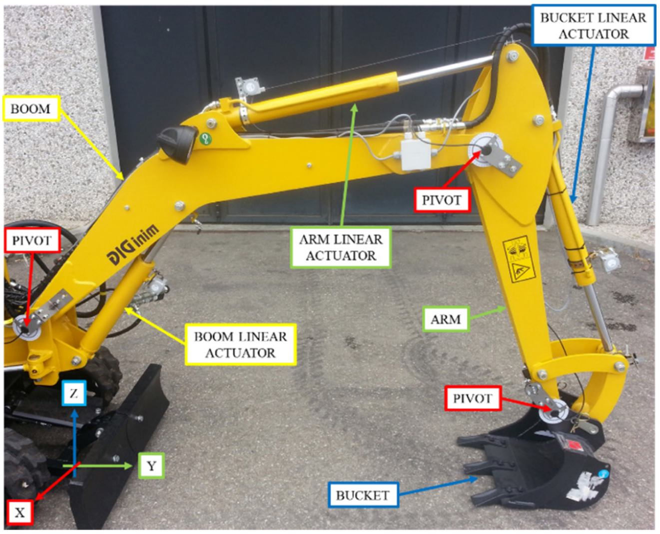


Figure 2. Imagine of the mini-excavator working device and of the actuation hydraulic components for the motion of the arm, boom and bucket.

Table 1. Main characteristics of the mini-excavator internal combustion engine

Engine model	LDW 1003
Displacement	916 cc
Maximum power @ 2200 rpm	13.2 kW
Maximum torque @ 2200rpm	62.5 Nm
Minimum engine speed	900 rpm
Maximum engine speed	2200 rpm
Fuel	Diesel
Dry weight	85 kg

The Diesel engine is a LDW1003 produced by Lombardini with a peak power output of 15 kW at 2500 rpm. The hydraulic power unit includes two external gear uni-directional fixed displacement pumps installed in series and powered by the thermal engine. They are characterized by a displacement of 6.5 cc/ rev each with a total maximum flow rate of 14.3 l/min at 2200 rpm. A number of modifications are carried out to the original machine, in order to make it suitable for indoor testing and to operate it with specific and repeatable working routines.

Table 2. Main characteristics of the new mini-excavator electric motor

Power supply:	400 V 50 Hz
Poles	6
Number of rotations nominal	2500 rpm
Power	15.7 kW
Torque	60 Nm
Maximum supply current	31 A
Efficiency	94.3%
Weight	55 kg

First, the Diesel internal combustion engine is replaced by an aluminum synchronous brushless electric motor with the specification depicted in Table 2.

The motor is characterized by a high power to weight ratio and a low mechanical inertia, thus enabling high acceleration of the rotational speed. The electric motor is powered by an inverter, see Table 3, for the fine tuning of the motor rotational velocity.

An ad-hoc designed two-half elastic joint is adopted for the connection of the motor to the external gear hydraulic pumps, see Figure 3.

Table 3. Datasheet inverter

Motor model	VFS15 4150PL
Rated current normal / heavy load	38.0/33.0 A
Engine power normal / heavy load	18.5/15 kW
Power supply range Class 400V	323-550Vca 50-60Hz
Weight	1.5 Kg

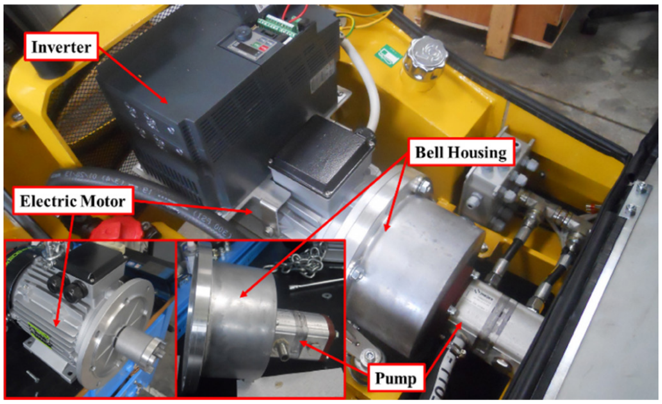
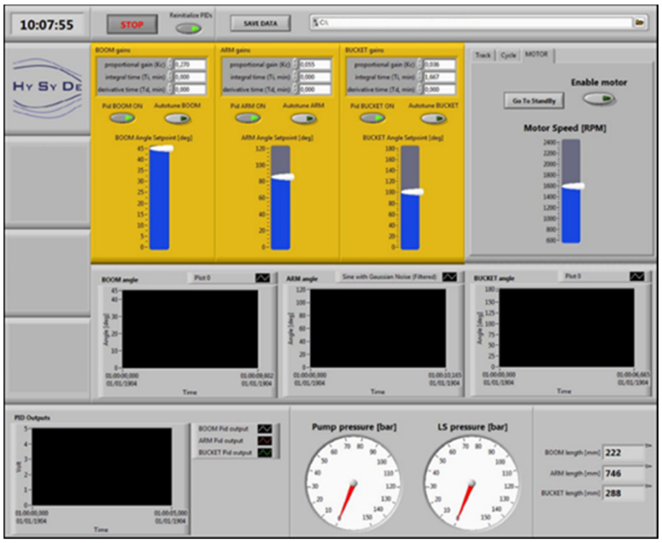


Figure 3. Connection of the motor to the hydraulic external gear pumps with the bell housing.

Afterward, the original hydraulic control distributor of the mini-excavator is fully replaced since the hand operated actuation is not reliable for obtaining identical loops of the same working routine. Thus, the original Bucher HDS11 control block is substituted by a fully electronically operated control block of the same manufacturer. In particular, the electronic actuation is carried out by solenoid proportional valves controlled by the computer via a National Instrument real-time embedded controller (Chassis NI cDAQ-9188, with 256 channels). A LabView interface is created both to acquire the signals of the traditional transducers employed in the experimental campaign and to implement the control algorithms for the electric motor, hydraulic power unit and electro-valves to realize loops of the same working routine, see Figure 4.



BOOM gains: proportional gain (Kc) 0,270; integral time (Ti, min) 0,000; derivative time (Td, min) 0,000
ARM gains: proportional gain (Kc) 0,055; integral time (Ti, min) 0,000; derivative time (Td, min) 0,000
BUCKET gains: proportional gain (Kc) 0,036; integral time (Ti, min) 1,667; derivative time (Td, min) 0,000
BOOM length [mm] 222
ARM length [mm] 746
BUCKET length [mm] 288

Figure 4. On-board electrical panel with 1) the electrical components, 2) NI CompactDAQ, 3) terminal sockets

The new mini-excavator electronic control system is finally placed within an on-board electrical panel, depicted in Figure 5.

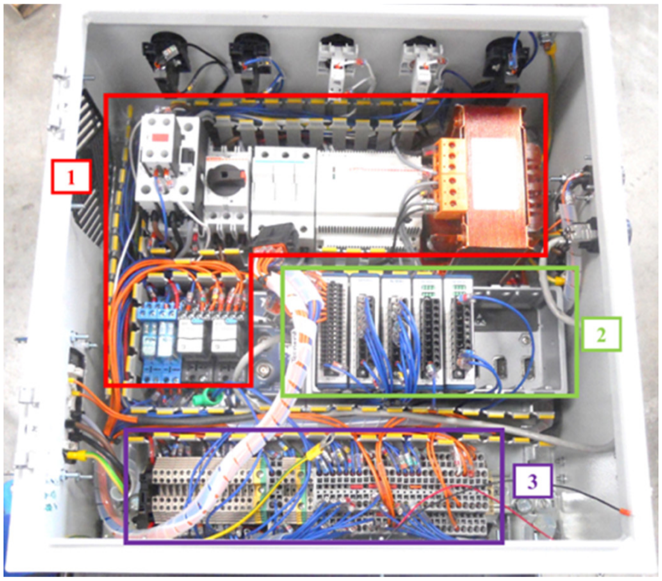


Figure 5. LabView front panel for the mini-excavator working routine control and traditional transducers' data acquisition

Finally, a short time working cycle is defined for the machine working device, see Figure 6.

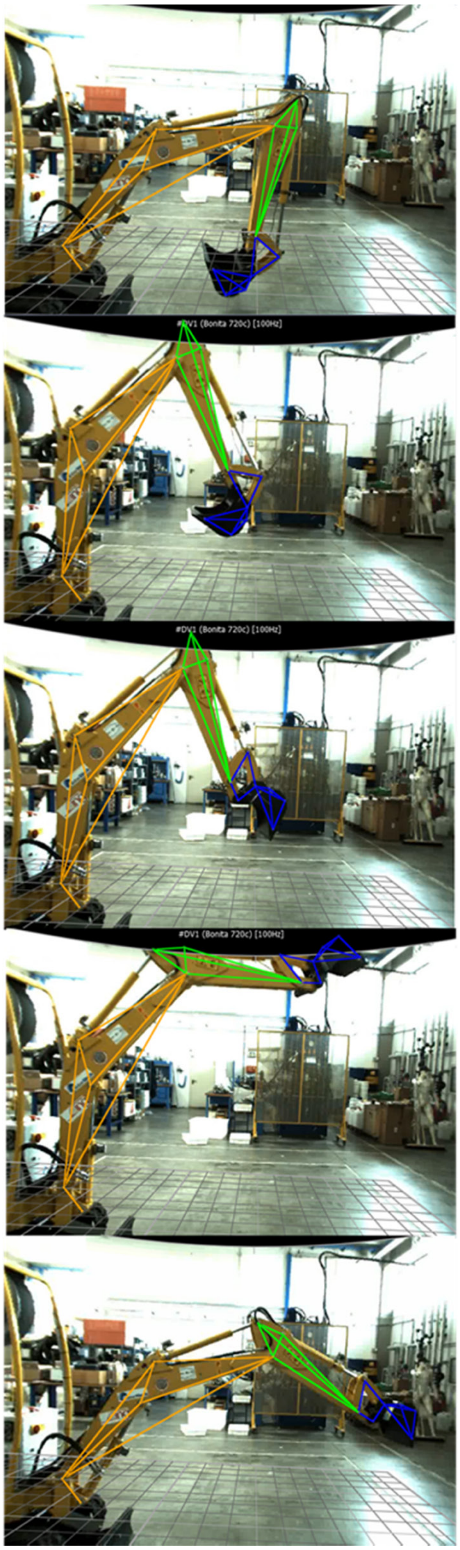


Figure 6. Consecutive images of the main positions reached by the mini-excavator working device during the routine

The selected actuations and the corresponding trajectory of the arm, boom and bucket reproduce the typical working routine a mini-excavator executes when digging.

EXPERIMENTAL SET UP

Main focus of the paper is the analysis of the mini-excavator working device during the digging phase. Therefore, the device is assumed to be working on the same plane and thus, the motion of the cabin rotation is neglected and its position is fixed.

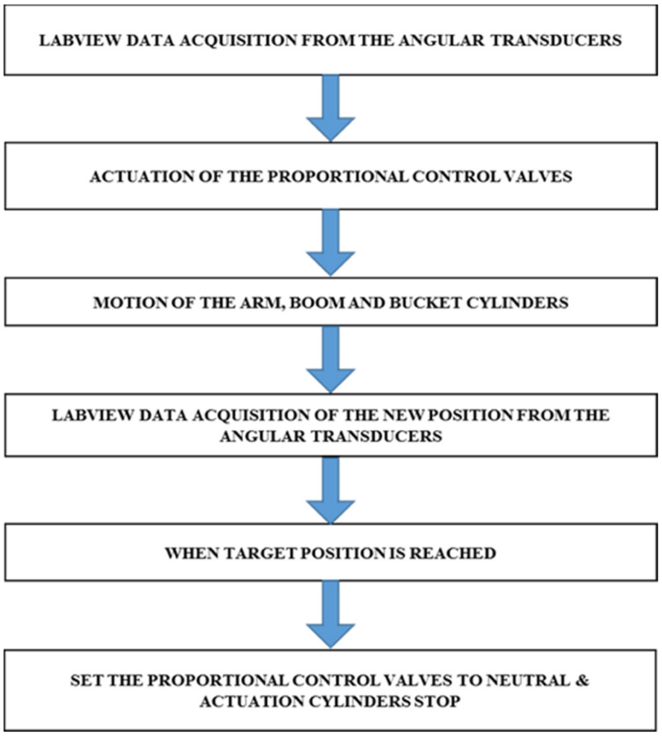


Figure 7. Control and actuation strategy

In order to measure the relative rotation between bucket and boom, bucket and arm and finally arm and the cabin, the angle swept by each joint is detected as well as the stroke of each cylinder is monitored, see Figure 7.

Both traditional transducers and the MoCap system are adopted for the measurement of the mini-excavator working device. In the following, the main specifications of the experimental equipment are detailed.

Traditional Transducers Equipment

Usually, the traditional equipment for the measurement of the machine working device motion includes linear displacement sensors and angular position transducers. In this analysis, wire linear potentiometric transducers (WLPT) are adopted for measuring the stroke of the three cylinders that actuate arm, boom, and bucket. The two ends of each wire sensor are rigidly connected to the barrel and to the piston rod of the cylinder respectively, as it can be seen in Figure 8.

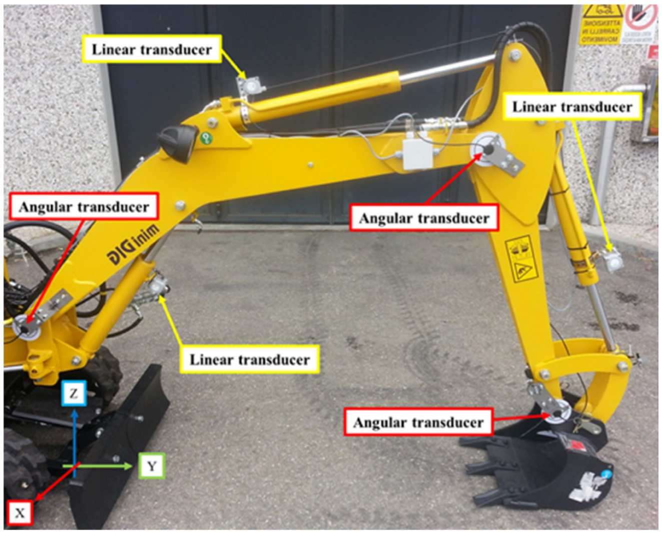


Figure 8. Positions of the traditional angular and linear transducers

The characteristics of the sensors employed for the linear displacement measurement are reported in Table 4.

The relative angular position of the main components of the mini-excavator working device is detected by means of contactless magnetic rotary sensors rigidly connected to each joint of the arm, boom and bucket, see Figure 8. The main specifications of the sensors adopted in the analysis are listed in Table 5

The data from the sensors are collected via the National Instrument real-time embedded controller mentioned in the previous section.

Table 4. Main characteristics of the sensor employed for the linear displacement measurement

	SP3-25	SP3-50
Full stroke range	635 mm	1270 mm
Accuracy (% of f.s.)	0.25 %	0.25 %
Cycle life	500000 cycles	250000 cycles
Input voltage	8-40 VDC	8-40 VDC
Output	4-20 mA	4-20 mA
Repeatability (f.s.)	0.05 %	0.05 %
Electrical connection	1 m multi-conductor cable	

Table 5. Main characteristics of the sensor employed for the angular displacement measurement

	NRH 280 DP
Measurement range	20° – 360°
Resolution	0.025 % of measurement range
Maximum rotation speed	3600 °/sec
Maximum supply current	<25 mA
Supply voltage	9-30VDC
Non-linearity	± 0.4 %

Motion Capture

The Motion capture system records the movement of objects or people and it can be employed in many different applications, such as military, entertainment, sports, medical applications, and for validation of computer vision and robotics.

The system is based on infrared radiation emitted by several devices that are able to detect the radiation reflected by a number of passive markers positioned in the measuring volume. The triangulation of the reflected signals provides the coordinates of each markers and thus the position of the object to which they are rigidly connected. The markers are made of plastic material wrapped by a reflecting film.

In the present analysis four Vicon DV infrared cameras are employed to detect the position of 14 markers placed on the mini-excavator working device. The signals are then post-processed by the NEXUS 1.8.5 software in order to calculate the coordinates of the markers and reconstruct the relative motion of the arm, boom and bucket. The specifications of the MoCap system are listed in Figure 9.

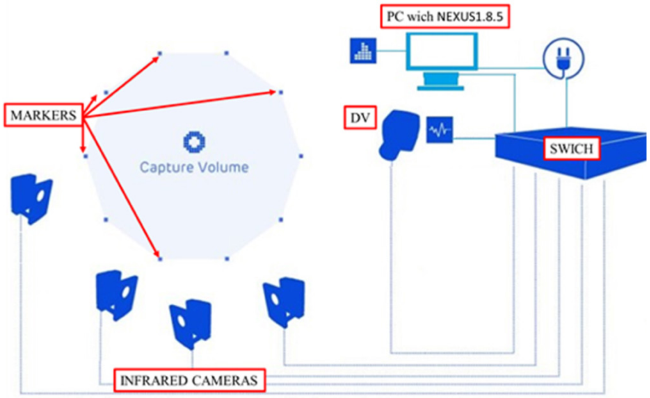


Figure 9. MoCap system

More in detail, the infrared cameras emit radiation with a characteristic wavelength between 780 and 820 nm; by means of a LED strobe light synchronized with the image acquisition frequency it is possible to discretize the marker the reflected radiation is being detected from. By analyzing the reflected radiations on three reference planes, the coordinates of each marker can be calculated. For the tests carried out in the present analysis, the capture volume was characterized by 8 m length, 5 m height and 2 m depth. These values can be significantly increased by employing additional cameras and the capture volume can reach dimensions similar to the full operating field of the mini-excavator.

In order to reconstruct the trajectory of the analyzed object, the markers should be located in specific positions of the body. First, the markers should provide an information covering all the degrees of freedom of the measured object, eventually with a redundancy that depends on the complexity of the measured body or of the expected motion. In addition, each marker should be detected by at least three cameras during its trajectory so that the position is not lost for the period of time the marker remains blacked out, see Figure 10.

An important issue for the MoCap system accuracy is the interference with other light sources and in particular with the sun light. In fact, radiation having the characteristic wavelength similar to the one emitted from the camera would produce a false information for the acquisition system and introduce errors in the measurement. For the present work, the analyses are carried out indoor with no artificial light in the capture volume. When using the system in the open field with the presence of sun light, active markers can be adopted. Thus, the active markers would emit radiation in a particular wavelength and with an intensity that can clip off the interferences from other radiation sources.

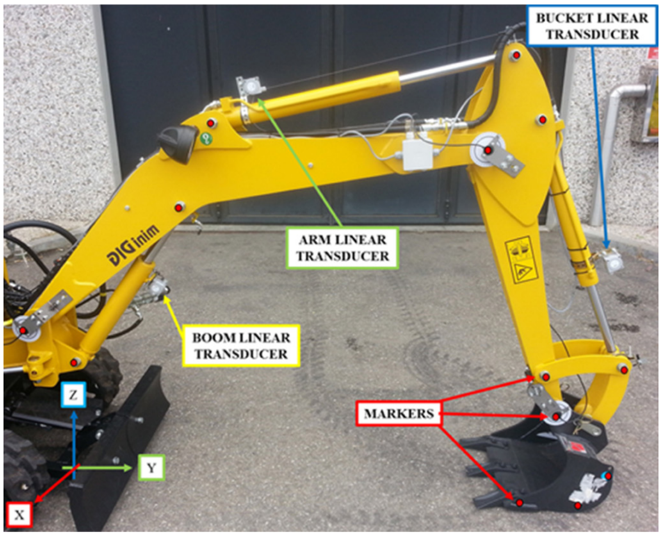


Figure 10. Positions of the MoCap markers with respect to the wire linear transducers' locations

Alternatively, infrared cameras with a more powerful emitted radiation and particular filters for the polarization of the signal can be used when operating under the sun light or with other radiating sources. The preprocessing procedure of the MoCap system includes the calibration phase of the infrared cameras to adjust the focal length of the optics in order to have a clear and distinct image each marker. Similarly, a reference plane has to be defined for all cameras using the positioning instrument equipped with active markers.

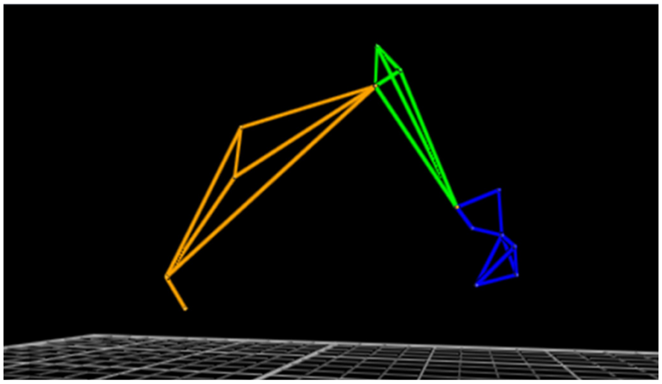


Figure 11. Images of the virtual mini-excavator from the MoCap acquisition system

Finally, each marker is labelled and associated to a specific position of the real mini-excavator working device, in addition rigid bodies representing the geometry of the arm, boom and bucket are created as in Figures 11 - 12. Since for the present analysis the trajectory of the measured component is limited to a plane and the relative motion between the components is a pure rotation, specific constraints are set up in the acquisition system in order to increase the accuracy of the measured values. Overall 14 markers are adopted for the motion detection of the working device and in particular 5 markers are located both on the bucket and the boom and 4 for the arm.

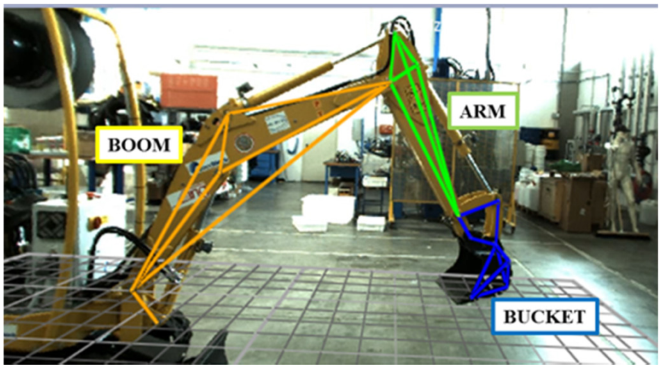
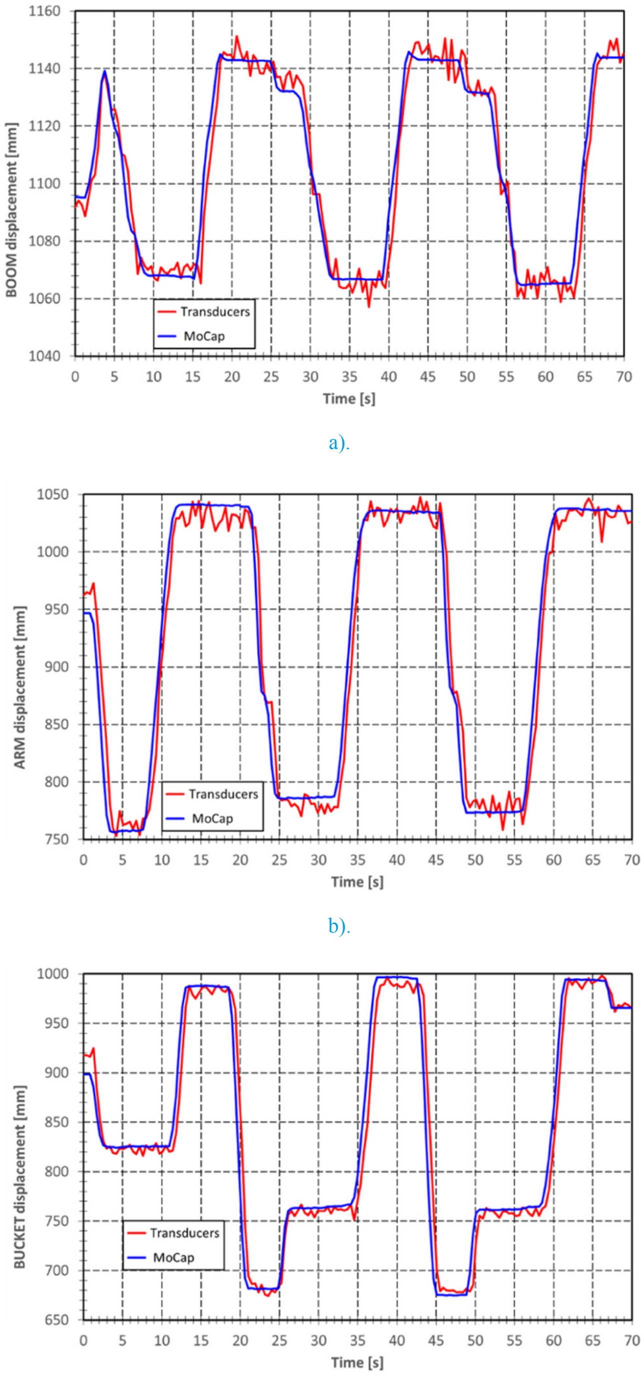


Figure 12. Images of superimposition with the DV camera

RESULTS AND DISCUSSION

The motion of the mini-excavator working device is measured during the digging routine using both the traditional and motion capture approaches. The data from the two adopted systems are acquired with the maximum frequency available, in order to have an accurate profile of the real trajectory. Since the traditional measuring system calculates the relative rotation between the components and the strokes of the three measured cylinders, the data from the MoCap system are post-processed to calculate the same quantities. Figures 13 to 15 show the displacements of the arm, boom and bucket as detected by the wire transducers and calculated by the motion capture system.

It can be noticed that the values measured by the traditional sensors is significantly more sensitive to vibrations than the MoCap results. This behavior is evident not only at the beginning of each working cycle step, when the inertia effects of both the hydraulic actuation and mechanical components could determine real oscillations of the mini-excavator working device, but it characterizes the entire strokes of the cylinders, when likely the inertia effects should be less significant. For the signal of the traditional sensors, no filtering post-processing procedure has been used, since the objective of the work was the comparison of the main capabilities of the two measuring systems. The amplitude of the oscillations observed with the transducers is in the order of few millimeters and within the accuracy. This behavior is enhanced by the vibrations of the mini-excavator working device, which affect the inertia of the inner mechanical system of the wire sensors. Conversely, the inertia effects do not influence the MoCap measurements and only the real working device vibrations can be observed in the relating measurements. In this case, the amplitude of the signal is in the order of few tenths of millimeter (see figure 14). The comparison between the measurements obtained by the two analyzed approaches demonstrate that both of them are able to accurately detect the trajectory of the mini-excavator working device. Nevertheless, some comments can be drawn about the features that differentiate the MoCap system from the traditional transducers.



a).

b).

c).

Figure 13. Comparison of the data from the traditional transducers and the MoCap system in terms of the displacement measurement of a) the boom, b) arm and c) bucket

The infrared motion measurement system is characterized by an overall set up time of the test of approximately three hours, that are mostly due to the capture volume preparation and camera calibration. Similar time has to be elapsed when installing the transducers and the relating acquisition system. The main difference can be outlined when a different object has to be measured in the same capture volume. In fact, for the MoCap system only the markers have to be moved to the other body employing a very short time; on the contrary, the whole set up procedure has to be repeated when using the traditional transducers. Table 6 compares the main proprieties of the two considered systems.

Furthermore, the data are acquired with a frequency of 1 kHz for the sensors and 250 Hz for the MoCap system. These values represent the maximum ones for the adopted equipment. For the MoCap system, infrared cameras with a much higher detection frequency are available and they could be used also for measuring the motion of fast moving objects and shocks due to collisions. The possibility of enduring harsh working environments including collisions makes the MoCap system very useful in detecting the motion of earth moving machines when operating in the real conditions. In fact, if a marker is damaged or lost, the replacement time is minimum as well as its cost. On the contrary, the traditional transducers may encounter more difficulties in the employment on the real field and can be damaged more easily with losses both in terms of time and costs.

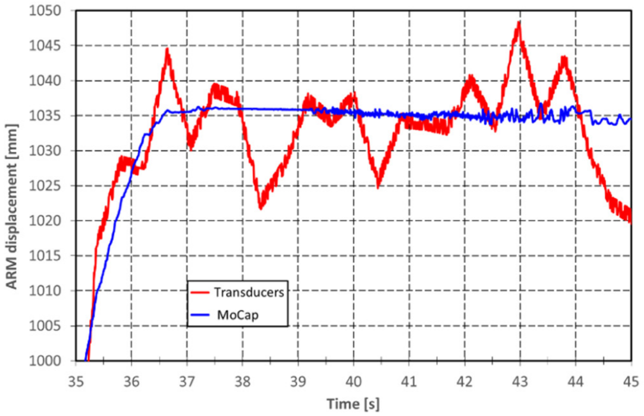


Figure 14. Zoomed view of the arm displacement oscillations, see Figure 13 b)

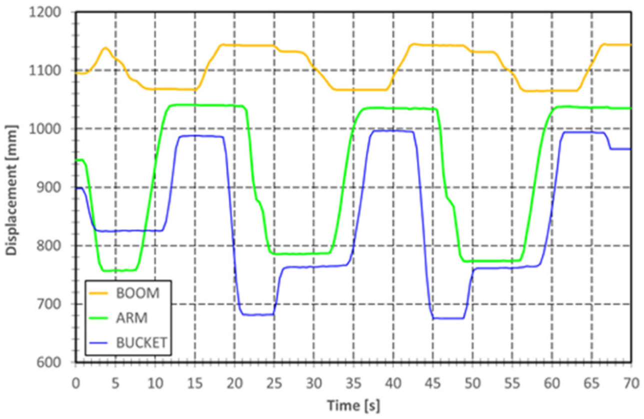


Figure 15. Consecutive displacements of the working device components measured by the MoCap system.

Furthermore, the possibility of shifting among different measured objects makes it possible to compare the behavior of different hydraulic components and their performance in terms of velocity of motion and accuracy in the positioning of the final working tool can be addressed.

Finally, the cost of the two systems is compared and the MoCap equipment is characterized by a remarkably higher cost, i.e. approximately eight times more expensive than the traditional transducers.

Table 6. Main properties of the considered measurement technologies.

	Traditional	MoCap
Accuracy	0.25% f.s. (i.e. 3.125 mm)	± 0.1 mm
Time to preparation system	3 hours	3 hours
Time to change subject	3 hours	5 minutes
maximum displacement measurements	1250 mm	10000 mm
Work environment	Laboratory	Laboratory/work environment
maximum sampling frequency	1 kHz	250 Hz
System cost	~ 5000€	~ 40000€

CONCLUSION

The trajectory of a mini-excavator working device has been measured by means of two different experimental approaches: the traditional linear displacement and angular position transducers and the motion capture system based on the infrared radiation.

The motion of the arm, boom and bucket of the earth moving machine has been measured for a defined working routine representative of the usual digging operation typical of the considered excavator. This measurement is very important for addressing the performance of the whole machine and in particular of the hydraulic control system, while real field operating conditions can be very difficult to account for both traditional displacement sensors and MoCap System. In fact, in harsh working environment they can be easily damaged. For the MoCap system the replacement of the markers can be carried out quite easily and cheaply while replacing a traditional sensor can be time consuming and expensive. While the transducers can interfere with the operation of the machine, the MoCap system has a limitation for the very large operating field as well as for dusty and rainy environments.

The employment of the MoCap system for detecting the trajectory of the mini-excavator working device demonstrated an accuracy similar or higher than the traditional transducer. In addition, the set up time resulted to be practically the same between the adopted measurement approaches, but when changing the object to be measured the motion capture proves to be remarkably more flexible.

Thus, it results a useful tool to investigate the velocity of the motion as well as the accuracy of the positioning of the working tool for different components and hydraulic control systems for the earth moving machine. Nevertheless, the MoCap systems is a useful measuring techniques for R&D purposed, while it cannot replace the traditional sensors in the monitoring of the regular working operations.

REFERENCES

1. Bertini, A., Ceraolo, M., and Lutzemberger, G., “Systematic approach in the hybridization of a hydraulic skid loader” Automation in Construction 58:144-154, 2015, doi:10.1016/j.autcon.2015.07.
2. Nezhadali, V., Frank, B., and Eriksson, L., “Wheel loader operation - Optimal control compared to real drive experience” Control Engineering Practice 48:1-9, 2016, doi:10.1016/j.conengprac.2015.12.
3. Pan, Y., Callejo, A., “Identification, design and kinematic analysis of an earthmoving mechanism” Journal of Terramechanics 66:27-39, 2016, doi:10.1016/j.jterra.2016.03.002.
4. Franzoni, F., Milani, M., and Montorsi, L., "A CFD Multidimensional Approach to Hydraulic Components Design," SAE Technical Paper 2007-01-4196, 2007, doi:10.4271/2007-01-4196.
5. Franzoni, F., Milani, M., and Montorsi, L., "Cavitating Flows in Hydraulic Multidimensional CFD Analysis," *SAE Int. J. Commer. Veh.* 1(1):424-436, 2009, doi:10.4271/2008-01-2678.
6. Bottazzi, D., Franzoni, F., Milani, M., and Montorsi, L., "Metering Characteristics of a Closed Center Load - Sensing Proportional Control Valve," *SAE Int. J. Commer. Veh.* 2(2):66-74, 2010, doi:10.4271/2009-01-2850.
7. Bottazzi, D., Franzoni, F., Milani, M., and Montorsi, L., "Fast Image Processing Applied to Fluid Power Components," SAE Technical Paper 2009-01-2849, 2009, doi:10.4271/2009-01-2849.
8. Bolink, S.A.A.N., Naisas, H., Senden, H. Essers, R. at al., “Validity of an inertial measurement unit to assess pelvic orientation angles during gait, sit–stand transfers and step-up transfers: Comparison with an optoelectronic motion capture system” *Medical Engineering and Physics* 38:225–231, 2016, doi:10.1016/j.medengphy.2015.11.009.
9. Park, S.W., Park, H.S., Kim, J. H., and Hojjat Adeli, “3D displacement measurement model for health monitoring of structures using a motion capture system” *Measurement* 59:352–362, 2015, doi:10.1016/j.measurement.2014.09.063.
10. Kyle, J., and Costello, M., “Comparison of measured and simulated motion of a scaled dragline excavation system” *Mathematical and Computer Modelling* 44:816–833, 2006, doi:10.1016/j.mcm.2006.02.015.