ASSISTED DRIVING MIDI-EXCAVATOR FOR AUGMENTED PERFORMANCES AND IMPROVED SAFETY

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ABSTRACT

Numerous examples of assisted driving are present in the automotive sector to improve driver comfort and enhance safety. In the Off-Highway vehicles the examples of assisted driving are instead less widespread, although the stresses received by the driver are much higher, due to the more difficult environmental conditions and to the different operations that must be simultaneously controlled.

The purpose of this work is to develop a driving support system, mainly oriented to small-sized excavators, based on a software logic that can support the operator in the execution of predefined functions and paths.

Compared to previous works that dealt with the subject in a theoretical way, the present one starts from a robotic approach, to continue in an extensive simulation activity and conclude with an experimental application.

The case of a 5t Excavator is studied, equipped with 6 degrees of freedom inertial platforms, to dynamically monitor the geometry of the machine.

Keywords: assisted driving, safety, automation, excavator

1. BACKGROUND AND DRIVER NEEDS

There are many types of off-highway vehicles in the world and all of them can perform several different tasks. All these machine needs trained operators for their use, especially for more complex jobs that require constant attention and precision.

In addition to carrying out the specific work, the operator must also pay attention to his own safety and to that of the people around him; this can increase his level of stress.

The main goal of this job is to design, simulate and test logics that can assist the operator during the different working activities in order to both simplify the tasks and increase the safety.

The case study of this paper is a 5 ton excavator: the assisted functions are related to trajectory following tasks to simplify the creation of trenches and slopes with specific inclinations.

The second goal of this job is to perform the assisted operation only with a minimum of onboard sensors without using external equipment or sensors like GPS or Laser.

In this study the excavator is equipped only with 6 degrees of freedom inertial platforms to measure the inclination of the Boom, the Arm, the Bucket and the machine frame.

2. FROM ROBOTIC TO OFF-HIGWAY VEHICLES

An excavator is a typical hydraulic construction machine often used in dangerous and heavy duty working conditions, in adverse weather conditions and in dirty areas where it is not easy to drive the machine by a human operator.

System automation with electrical motors is well studied in the industrial robotics sector. Recently, there has been a growing interest in incorporating concepts from the robotics sector into the control of the hydraulic arms of excavators. In this way, the manual control of each joint would be automated, obtaining much greater performance and operational safety, thanks to the use of assisted systems for the generation of trajectories and joint control.

The excavator operations require coordinated movement of the swing, boom, arm and bucket to control the position of the End Effector (centre of the bucket tip, see figure 1) to obtain the desired trajectory. This can be achieved through the implementation of an automatic control system for the excavation task, which requires the understanding of the kinematics, the dynamics, and the control of the excavator.

Thanks to the large academic and industrial interest in this topic, several authors studied the kinematics of the excavator links [1], [2], the system mechanics and dynamics [5]. [6], and the control algorithms [3], [4], [7].

With respect to the relevant bibliography, in our work we aim to achieve a practical and effective approach that includes kinematic analysis and robust control algorithm development. The result of the theoretical research was tested through software (SIL) and hardware (HIL) in the loop simulations. Going into details, a model-based design approach was applied following these development steps:

- The kinematic and the dynamic models of the arm of the excavator have been deeply studied. This step also included the validation of the model using real data acquired from on-field experiments.
- The mathematics of the inverse kinematics have been derived in closed form to allow the implementation in cost effective ECU (electronic control unit), e.g. with limited computation power.
- A robust closed-loop control algorithm, derived from the implementation of trajectory follower in robotic applications, was finally developed and tested.

In the following sections the above development steps will be described in detail.

3. 5T EXCAVATOR

The hydraulic system of the Excavator analysed is a Load Sensing (LS) system [13] composed of a Variable Displacement Piston Pump with electronic flow control and a flow sharing Main Control Valve (MCV) provided of electrohydraulic commands.

All the HMI devices (joysticks, pedals and display) and the machine ECU are connected through a CANbus network.

The machine is equipped with 6 degrees of freedom inertial platforms (IMU), to dynamically monitor the geometry of the machine.

3.1. Vehicle sensors

Figure 1: 5T Excavator with Inertial Platforms

The sensors used [15] [17] are the following:

- Three single axis IMUs are used to detect the movement of the Boom, Arm and Bucket.
- One dual axes IMU is used to detect the frame movement (roll and pitch) respect to the ground.
- One Hall Effect sensor is used to detect the cabin swing.

The inertial measurement units used have the following characteristics:

Table 1: IMU characteristics

Characteristic	Value
Measurement Range	1 axis 360° / 2 axes ±90°
Absolute Accuracy	± 0.30°
Resolution	0.01°
Repeatability	≤ 0.05°
Dynamic Accuracy	± 0.50°
Hysteresis	≤ 0.05°
Signal	CANbus

The angles measured with the IMUs need to be elaborated in order to be used for kinematics purpose.

3.1.1. Boom Angle (Theta 3)

The Boom angle Theta 3 value is given by the IMU sensor plus an offset to consider the assembling orientation and a real time correction that consider the roll and pitch angles of the machine on the ground:

$$\vartheta_3 = \vartheta_{IMU\_BOOM} + \vartheta_{IMU\_BOOM\_OFFSET} + \vartheta_{IMU\_FRAME} \quad (1)$$

3.1.2. Arm Angle (Theta 4)

The Arm angle Theta 4 value is given by the IMU sensor plus an offset to consider the assembling orientation and a real time correction that consider the roll and pitch angles of the machine on the ground minus the Boom Angle:

$$\vartheta_4 = (\vartheta_{IMU\_ARM} + \vartheta_{IMU\_ARM\_OFFSET} + \vartheta_{IMU\_FRAME}) - \vartheta_3 \quad (2)$$

3.1.3. Bucket Angle (Theta 5)

Typically the Bucket IMU is not fitted directly in the bucket but on the linkage arm (see Figure 2 for details), and the calculation formula has to take into account this geometrical complexity.

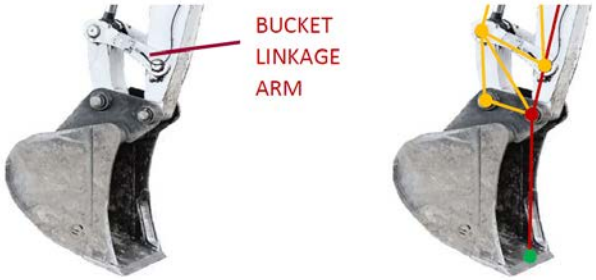

Figure 2: Bucket linkage arm

The angle value of the Bucket linkage Alpha 5 is given by the IMU sensor plus an offset to consider the assembling orientation and a real time correction that consider the roll and pitch angles of the machine on the ground minus the Boom and Arm Angles:

$$\alpha_5 = (\vartheta_{IMU\_BUCKET} + \vartheta_{IMU\_BUCKET\_OFFSET} + \vartheta_{IMU\_FRAME}) - \vartheta_4 - \vartheta_3 \quad (3)$$

The Bucket Theta 5 value is calculated using the linkage angle Alpha 5 with trigonometric approach.

3.1.4. IMU sensors VS Cylinder sensor

To validate the IMU solution, a comparison between the two sensor technologies has been made and in Figure 3 it is possible to notice the difference of the values of the two sensors for a typical working cycle.

The value of the difference of the two signals is normally less than +/- 0.5 degree.

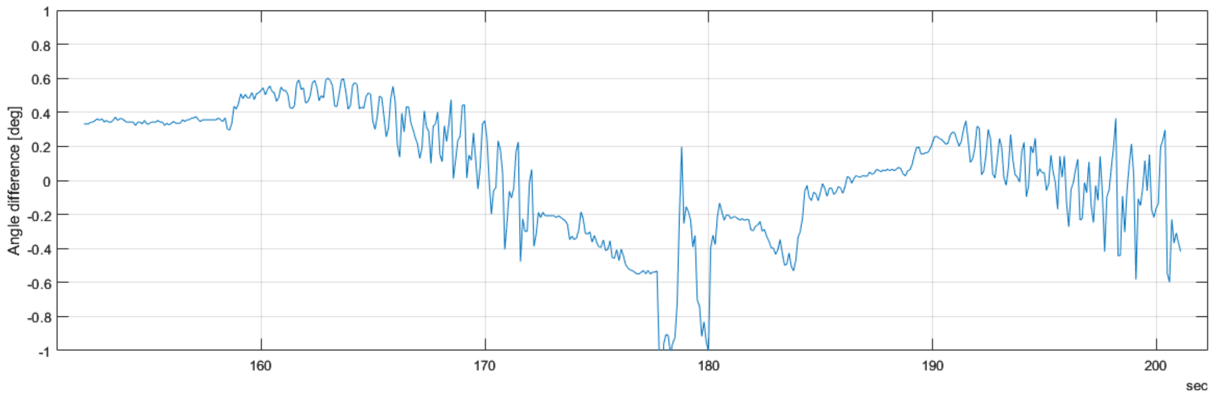

Figure 3: Comparison IMU VS Cylinder sensors

The use of the IMU sensors respect to other solutions like sensors inside the cylinder presents several benefits especially from the assembly and cost point of view.

3.2. Denavit–Hartenberg convention

The kinematic of the machine [10] has been obtained using the Denavit-Hartenberg convention.

The origin of the reference system (O0) is coincident with the centre of rotation of the cabin and positioned at the ground level (see figure 4).

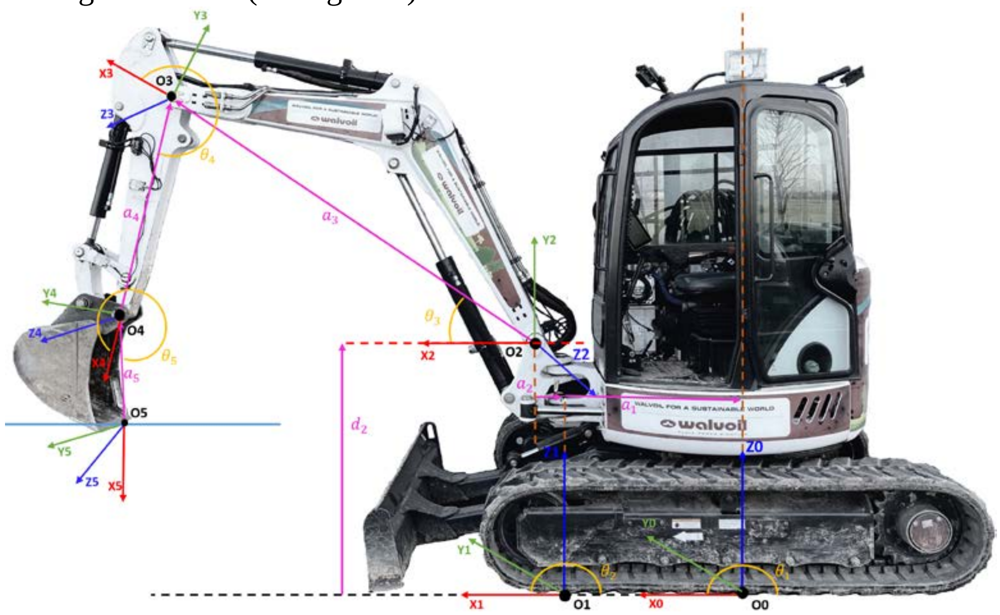

Figure 4: Denavit-Hartenberg reference systems

The Denavit-Hartenberg parameters of the specific excavator are detailed in the following table.

Table 2: Denavit–Hartenberg Parameters

Cylinder parameter	a_i [m]	d_i [m]	α_i [rad]	ϑ_i [rad]
Joint 1, Swing	0.799	0	0	ϑ_1
Joint 2, Boom Swing	0.155	1.155	$\Pi / 2$	ϑ_2
Joint 3, Boom	2.644	0	0	ϑ_3
Joint 4, Arm	1.370	0	0	ϑ_4
Joint 5, Bucket	0.725	0	0	ϑ_5

3.3. Trajectory definition

The operator defines the desired trajectory [14] [16] with the following parameters:

- Starting point; positioning the End Effector in the desired position.
- Inclination angle respect the horizontal and the vertical offset level; with machine HMI.

Algorithm calculate the trajectory up to the ending point where the joints reach them limits.

The geometry of this specific excavator allows a generation of a trajectory with a maximum length of 3000mm.

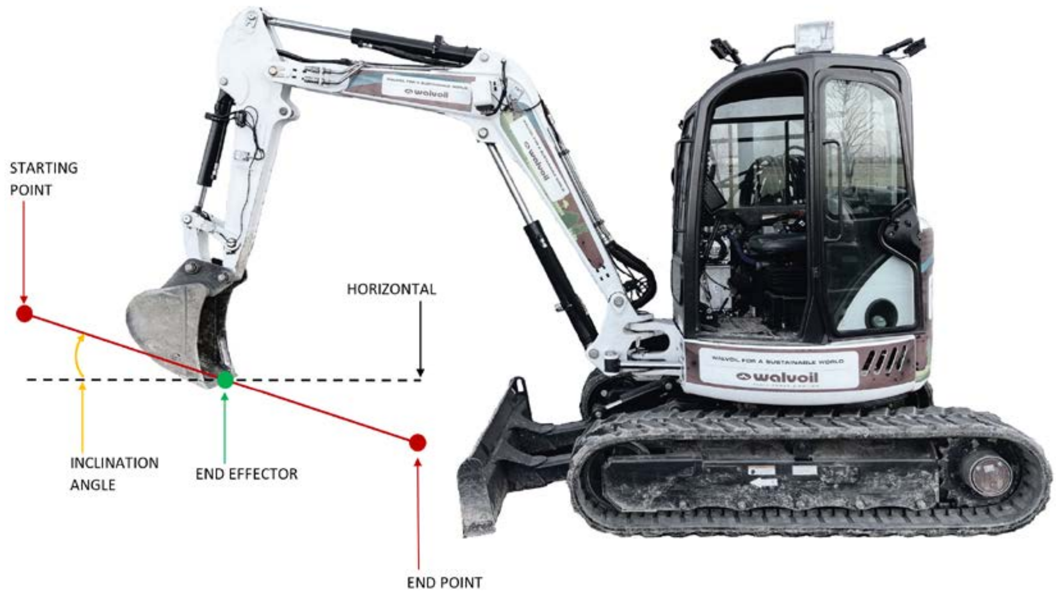

Figure 5: Trajectory generation example

In this paper two specific use cases have been considered:

- Trajectory with -1° of inclination; to simulate the final grading of a trench for pipe laying.
- Trajectory with 45° of inclination; to simulate the creation of an embankment.

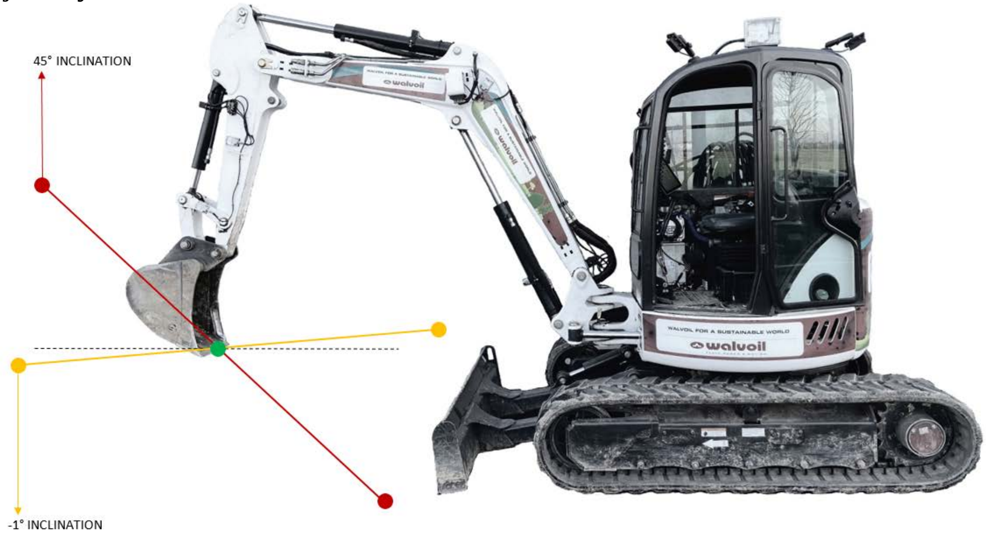

Figure 6: Trajectory used during the testing activities

3.4. Excavator Model

Validation of control algorithm is achieved using a multi-domain vehicle simulation [12].

In MATLAB® environment, a hybrid model can be built comprehensive of: CANbus command signals, hydraulic circuit and mechanical components.

The CANbus messages are converted via lookup-table into control current information, to be transmitted to the electro-hydraulic stage of the Main Control Valve.

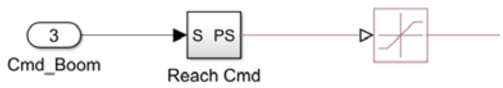

Figure 7: Main Control Valve command

The Proportional Pressure Reducing Valves are modelled with all the characteristics of hysteresis and non-linearity to represent the real conversion from current command to pilot pressure.

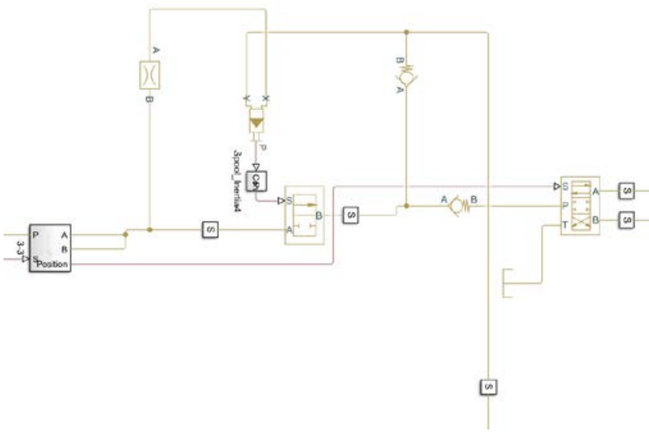

Figure 8: Proportional Pressure Reducing Valves and MCV

The pilot pressure is applied to drive the spools in the desired position. The Load Sensing MCV and the Pump are developed using the hydraulic components in the Simscape Fluids® library.

The purpose of modelling the MCV and its components in every detail (i.e. meter-in and meter-out area, local compensator, etc.) is to have a complete representation of the actuation speeds and any pressure phenomena on the vehicle. Thanks to these it's possible to check the control algorithm.

After verifying the correct functioning of the hydraulic power stage, the complete model of the vehicle, with its inertia, constraints and kinematics, a complete 3D CAD model is drawn (Solidworks®).

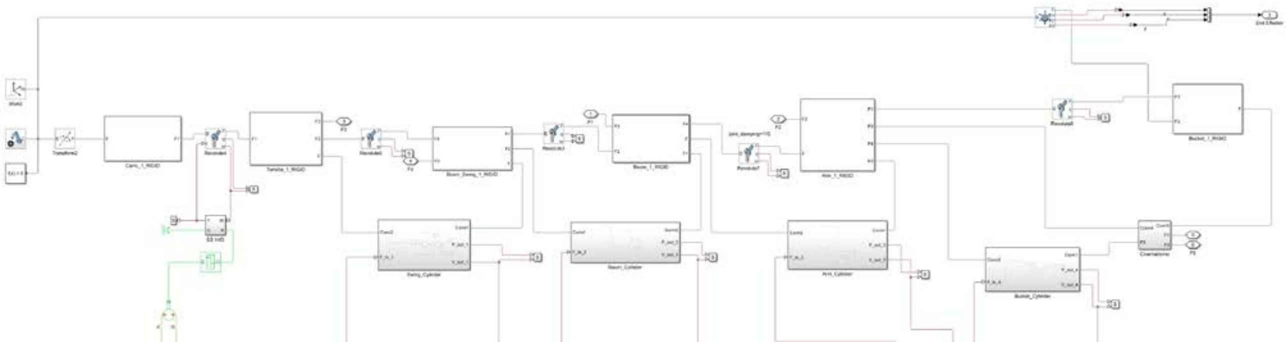

Figure 9: Mechanical System

The mechanical system is imported with a specific Simscape Multibody ® add on.

After export, the hydraulic system can be properly connected to the mechanical one to achieve the overall functionality of the vehicle.

As shown in Figure 9, the outputs of the model are the joints angle and the End Effector cartesian coordinates.

Thanks to the Simscape Multibody ® tool it is also possible to see the 3D model of the machine during the simulation phase.

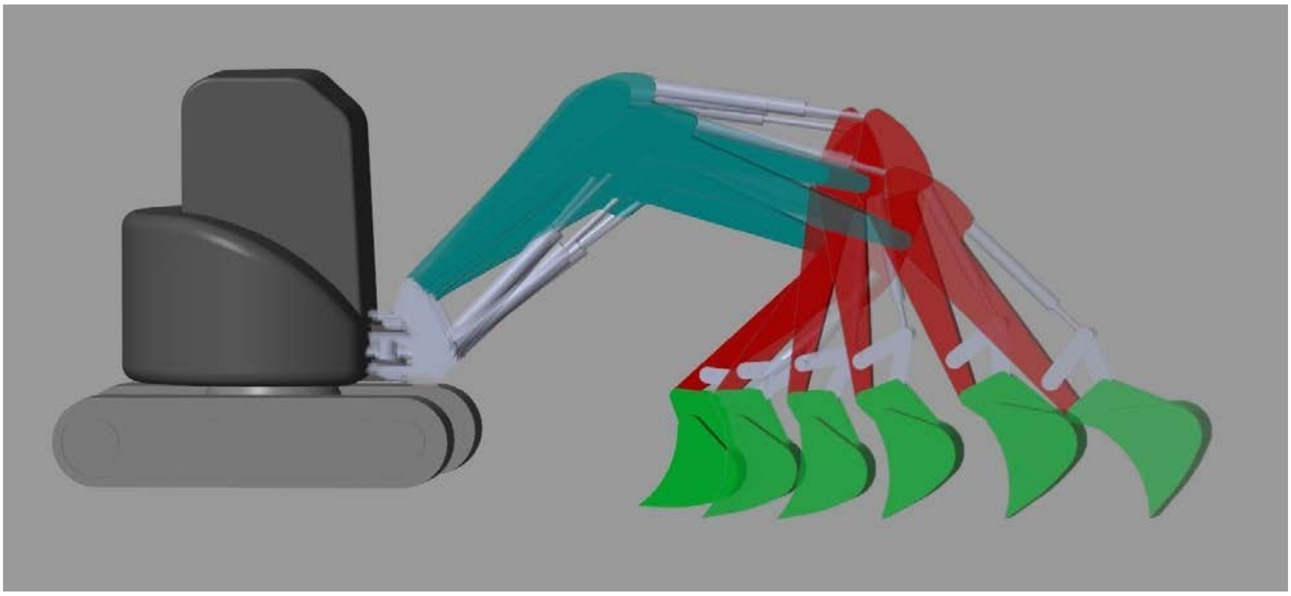

Figure 10: 3D model of the machine

3.5. Control algorithm

The model of the excavator has been inserted in a complete Simulink ® model with the specific control algorithm.

The controller used for tracking the reference position on the three joints is of the Proportional-Derivative (PD) type [8]. The main characteristic of the PD controller is to try to anticipate the position error, compensating the signal propagation delays, and improving the stability characteristics of the controlled system [11]. The equation describing the PD algorithm is

$$u(t) = K_p \cdot e(t) + K_d \cdot \frac{de(t)}{dt} \tag{4}$$

K_p is the proportional gain and K_d is the derivative term. In particular, the derivative term acts by compensating the variation of the joint position error, thus providing an anticipatory correction with respect to the estimate of the future joint position error.

4. SIMULATION RESULTS

First of all, the two defined use cases, trajectory with -1° of inclination and trajectory with 45° of inclination, have been tested in MATLAB Simulink ® environment with the defined control algorithm.

The benefit of simulation is that it is possible to test many control algorithms by varying the main configuration parameters until the optimal ones have been found.

In this way a huge amount of time dedicated to tests on the real machine on the field can be saved.

After the simulation loops, the optimal parameters values have been defined and the results are the following figures.

To evaluate the results of the simulation, the figures 11 and 12 show the trajectory error, defined as the difference between the computed and the simulated trajectory [9], and the joints angle error, defined as the difference between the computed and the simulated joint angle.

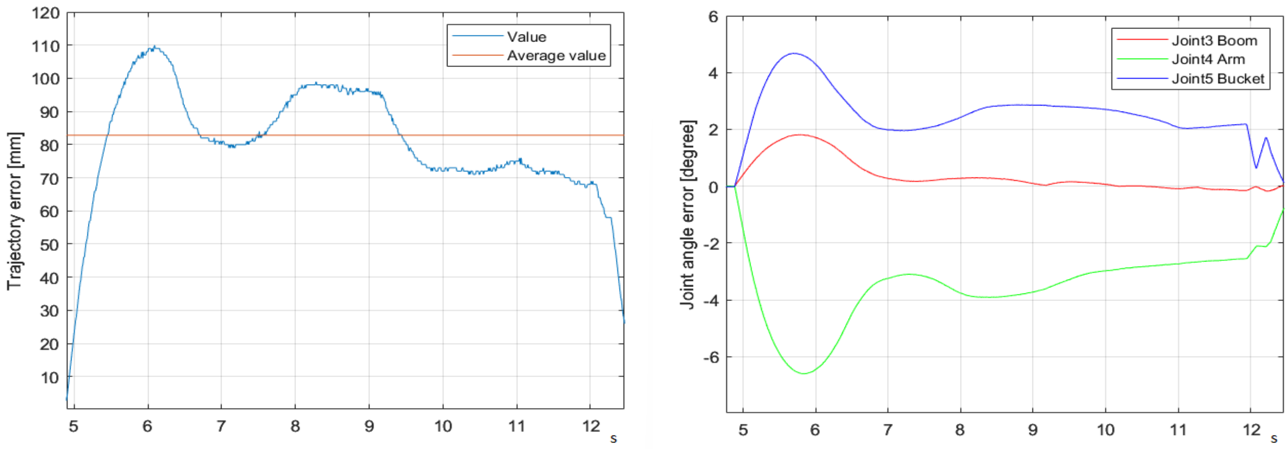

Figure 11: Trajectory and joints errors (-1° inclination)

The trajectory error average is 82.8 mm and the joints angle error is +4.5° / 6.5°.

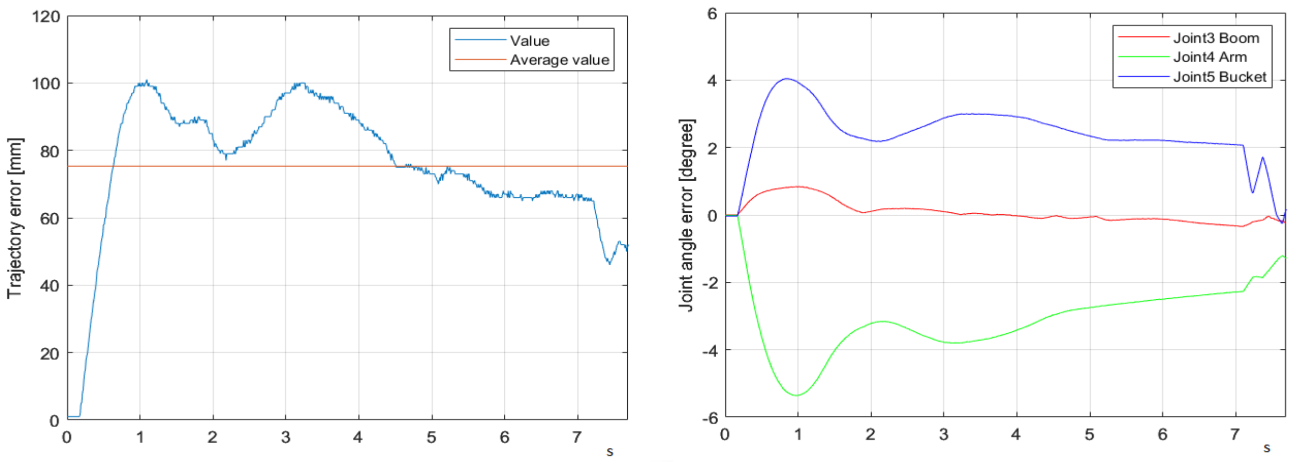

Figure 12: Trajectory and joints errors (45° inclination)

The trajectory error average is 75.3 mm and the joints angle error is +4° / -6°.

5. VEHICLE TEST RESULTS

At this point it is possible to start the real vehicle tests on the field initially with the optimal parameter values defined during the simulation.

After further tuning of the parameters on the machine, the best configuration has been obtained, and the results are in the following figures.

To evaluate the results of the experimental tests, the figures 13 and 14 show the trajectory error, defined as the difference between the computed and the measured trajectory [9], and the joints angle error, defined as the difference between the computed and the measured joint angle.

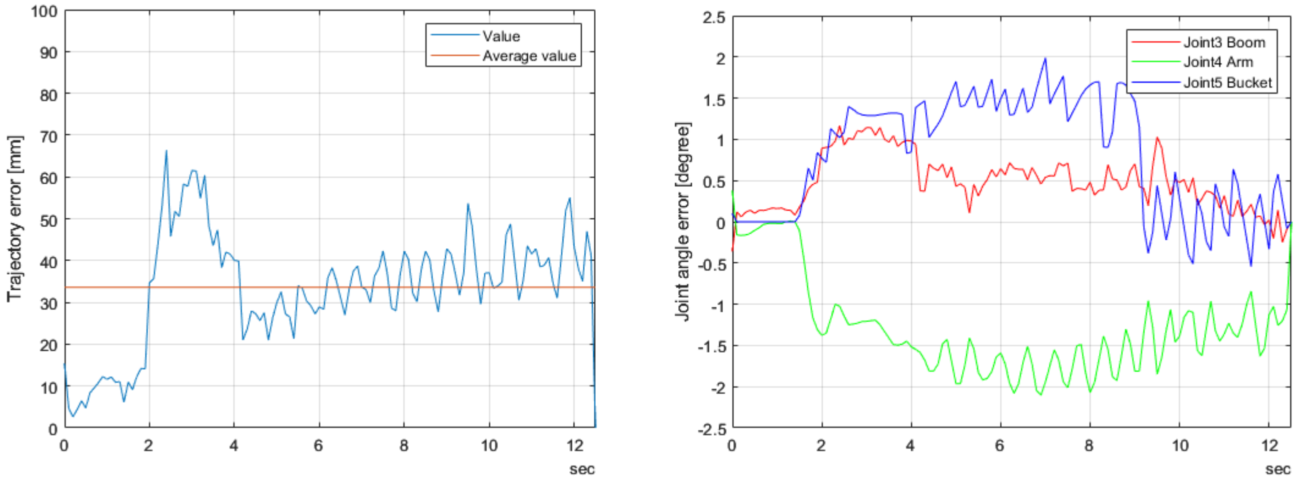

Figure 13: Trajectory and joints errors (-1° inclination)

The trajectory error average is 33.6 mm with a peak due to the initial acceleration phase and the joints angle error is less than ±2°.

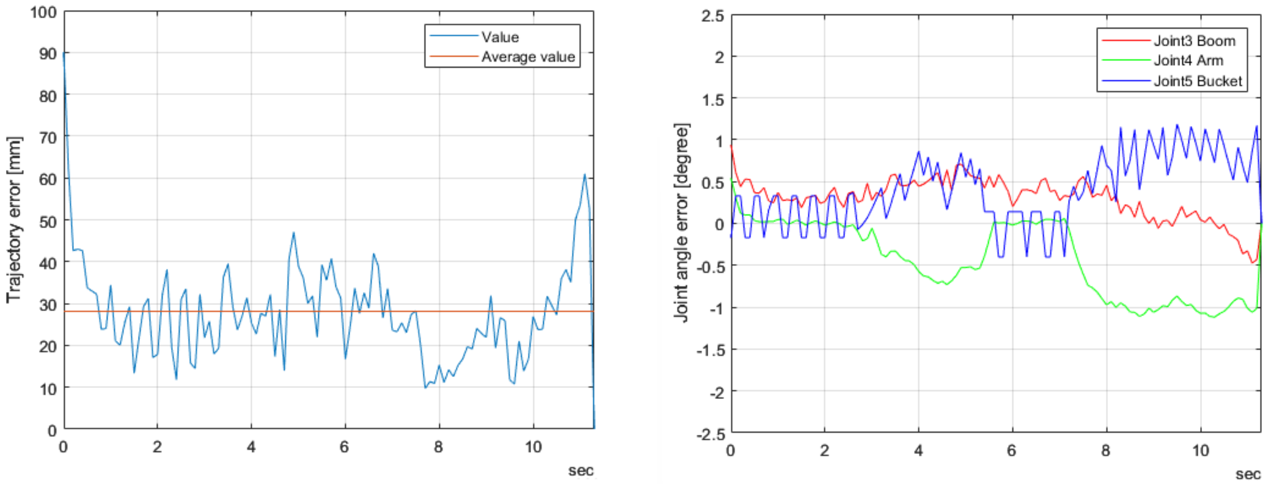

Figure 14: Trajectory and joints errors (45° inclination)

The trajectory error average is 28.1 mm and the joints angle error is less than ±1.5°.

6. CONCLUSION AND OUTLOOK

This paper confirms the benefit of working in simulation before starting any test on the vehicle, this gives the possibility to save resources and obtain an optimal result in a short time.

The main result of this work is the development of a linear trajectory driving system applied to a real excavator.

The experimental result show that the average difference between the theoretical trajectory and the real one is less than 50 mm, in line with the operator expectations.

This result that increases safety and accuracy with a reduced operator stress was achieved adding only a minimum number of sensors to the vehicle without using external equipment or sensors like GPS or Laser.

7. FURTHER DEVELOPMENTS

The next step of the work is to improve the assisted driving functions adding features that increase the safety of the driver, the bystanders, and the vehicles in the working area.

The feature to improve the safety involves the adding of virtual wall that define the safety area where the machine is not allowed to work.

Further development is to define the safety area dynamically by means of a set of cameras that together with AI technology allows to detect and avoid workers or obstacles

NOMENCLATURE

LS	Load Sensing	
ECU	Electronic control unit	
PD	Proportional Derivative	
HMI	Human Machine Interface	
MCV	Main Control Valve	
K_p	Proportional gain	
K_d	Derivative gain	
α_5	Bucket linkage	rad
ϑ_3	Boom Angle	rad
ϑ_4	Arm Angle	rad
ϑ_5	Bucket Angle	rad
ϑ_{IMU_i}	Imu Angle	rad
a_i	Distance between two joints	m
d_i	Distance from ground	m
$e(t)$	Joint position error	rad
IMU	Inertial Measurement Unit	

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