Tampere University

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HYDRAULIC ROBOTIC LONG-REACH MANIPULATOR ANALYSIS FOR HIGH PERFORMANCE

Kinematic analysis

Master's Thesis
Faculty of Engineering and
Natural Sciences
Professor Jouni Mattila
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ABSTRACT

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Nowadays, autonomous robots for all different purposes are the state-of-the-art technology, all companies across the industry are implementing all kind of autonomous machines to control and computerize the industrial systems and processes, making errors virtually impossible and, despite all the first investment, the transition pays off in the mid and long-term because of all the time and resources saved.
This new industrial phase, which is a current tendency commonly known as Industry 4.0[1], focuses on interconnectivity, automation, machine learning, and real-time data.
The same trend applies to vehicles or mobile machines (for industrial or non-industrial purposes), the use of fossil fuels is decreasing whereas the implementation of automation and systems of artificial intelligence is strongly increasing day by day.

Heavy-duty hydraulically driven mobile working machines (for mining, construction, forestry, and material handling purposes) are also in constant development for increasing efficiency and performance because of the higher requirements set by the constant growth of this sector. As a result, working machines are increasingly expected to become more precise, and robotics like towards autonomous operation.

This thesis studies the design requirements and sizing for each hydraulic actuator system of the case of study, a long-reach manipulator 4x4 Haulotte HA16 RTJ PRO which is available at the University of Tampere (Hervanta Campus). This hydraulic articulated boom, originally manually driven, is being redesigned into a servo-hydraulic system maintaining the original diesel motor source and taking into account its limited power.

The general work consists of requirements of development, hydraulic engineering designs, component selection, modeling, and simulations towards a new prototyped system meeting the set requirements. During the making of this thesis, the component selection was already done and the scope of the study relies on the kinematic and hydraulic analysis for the vehicle.

Also, this thesis has pursued another objective, which is the compilation of technical data (such as the boom dimensions, original hydraulics, or technical information about the main components) among the different reports about the Haulotte, trying to achieve that the upcoming students or researchers can get clearer ideas and the maximum possible information about the case of study reading this document.

The goals are got from a theoretical viewpoint through equations and hypotheses considered throughout the study, therefore, the results obtained must be taken as approximations. The reason is the coronavirus pandemic, which forced the university and the laboratories to close since the beginning of the semester and some parameters or variables taken may not always coincide with the reality because were taken from a 3D model from the original Haulotte website.

Keywords: Wheeled Mobile Robot, Mobile platform, Hydraulics, Automation, Kinematics, Haulotte, HA16 RTJ PRO, Boom, Articulating boom lift, 4WSD

[1] https://www.twi-global.com/what-we-do/research-and-technology/technologies/industry-4-0

PREFACE

First of all, I would like to express my gratitude to my home university, the UPC (*Universitat Politècnica de Catalunya*), for allowing me to study and develop my master's thesis abroad, as an exchange master's engineering student in the beautiful country of Finland.

Also, I am extremely grateful to Professor Jouni Mattila for offering me an interesting master's topic to study and develop, besides providing me all the information and tools needed. Furthermore, I would like to thank the Tampere University, specially the student's services office, for all the help and attention received during this coronavirus pandemic that forced to close the university.

This year has not been easy to anyone, but I feel very lucky to have enjoyed Finland, to have met awesome people and to have been able to learn and to develop and deliver my thesis even with this adverse exceptionally world situation.

16th of September 2020

Alex Diaz Raez

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LIST OF SYMBOLS AND ABBREVIATIONS

2WDS/2WD	Two-wheel drive and steering/ Two-wheel drive
4WDS/4WD	Four-wheel drive and steering, also known as 4x4/ Four-wheel drive
CP	Control point
COR	Center of rotation
LPM	Liter per minute, volumetric flow rate unit of a hydraulic fluid
RPM	Revolutions per minute
SI system	International System of Units
URL	Uniform Resource Locator

A	Flow area
bar	Metric unit of pressure, 1 bar equals precisely 100 000 Pa
c	cylinder length
cc	Non-SI abbreviation of a cubic centimeter (SI unit symbol: cm^3)
Dm	Motor displacement
Dp	Pump displacement
H	Height
i	Gear ratio
L	Length
n	rotational speed (in RPM)
nm	rotational speed of a motor (in RPM)
np	rotational speed for a pump (in RPM)
Ø	Diameter of the piston
Q	Flow rate of a hydraulic fluid
Qp	Flow rate supplied by a pump
r	Radius
u	angular wheels velocity
v	Forward velocity
v_{pcyl}	Velocity of the hydraulic piston cylinder
w	Rate of rotation
x	X axis coordinates
y	Y axis coordinates
θ	Heading direction
φ	Steering angle

1. INTRODUCTION

The Haulotte HA16 RTJ PRO[2] is a Diesel 4x4 articulating boom for rough terrain, a multipurpose lift capable of reaching 16m of height above ground which can be extremely useful for many purposes. The Tampere University (Hervanta Campus) has one of these vehicles in the Mobile laboratory for hydraulic and electronic researching. This vehicle (specially, a modified version from the original one) is the subject of study along this document.

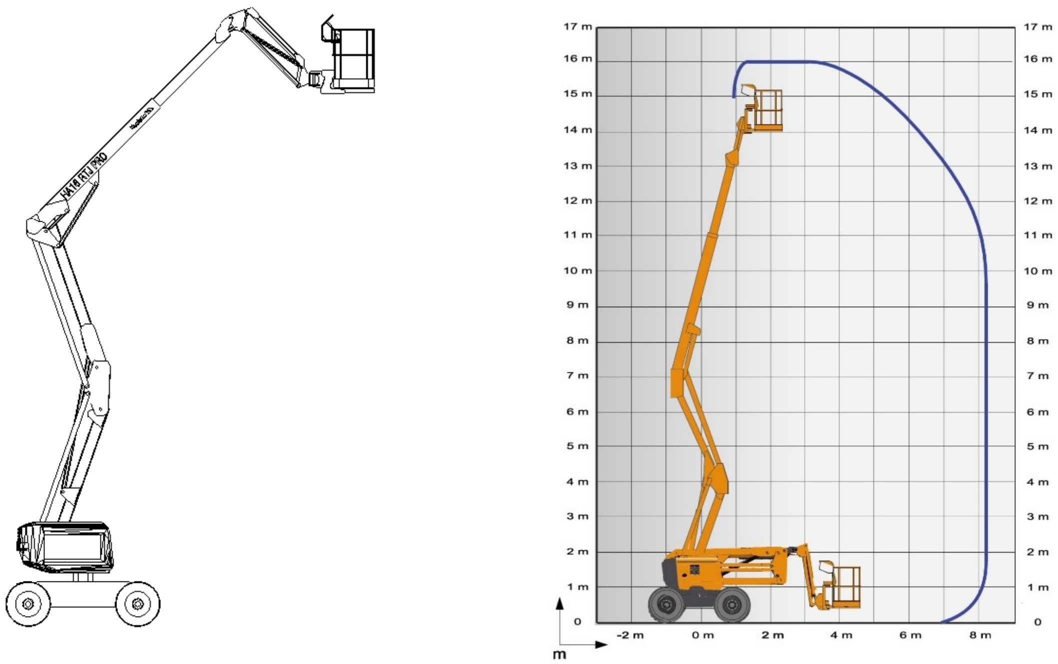

Figure 1. *Profile of the Haulotte HA16 RTJ PRO. Figure from [13]*

Its modifications have been carried out in the year 2018 by the Automation and Hydraulic Engineering research department. The main goal of its modifications is readapting the multipurpose lift to make it completely autonomous in some point.

At the moment, the modifications have been done for the pump control system, the steering system, and the hydraulic system (which is the system that is going to be explained, analyzed, and discussed along this thesis).

The hydraulic system can be operated in its original set up and in modified set up.

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[2] https://www.haulotte.co.uk/product/ha16-rtj-pro

Along this document is considered only the modified hydraulic set up in order to simulate the theoretical hydraulics for each actuator, however the original valve block is discussed in 2.6 to comprehend the differences with the new hydraulics installed.

2. MAIN COMPONENTS

The main components of the Haulotte HA16 RTJ PRO are divided into the power supply elements, the hydraulic actuators, the original valve systems, and the new hydraulic systems.

2.1 Power supply

Power supply is formed by two main parts:

- Diesel engine
- Main hydraulic pump

Hydraulic tank has a capacity of 76 liters. Also, there is an emergency pump in case of fuel shortage which is not taken into account along the thesis, because the idea is to study and design the hydraulic system of the Haulotte in normal operation, not in emergency or specific cases.

2.2 Diesel engine

The Diesel engine provides the energy for all the Hydraulic system by means of the main hydraulic pump which is connected directly to the engine.

The diesel engine and the pump are located under the left side cover.

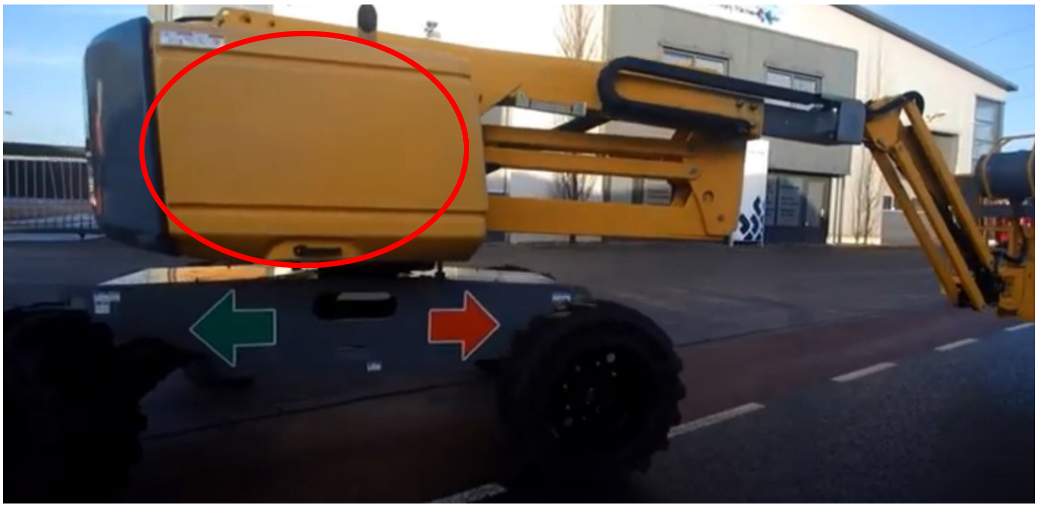

Figure 2. *Location of the Engine and the pump in the HA16 RTJ PRO*

The main specifications of the diesel engine are shown in Table 1, just below:

Table 1. *Main specifications of the diesel engine [7]*

Model	Kubota V 1505 E2B – 26,5 kW
Power	Continuous @3000 rpm: 21,7 kW
	Net int. @3000 rpm: 25,0 kW
	Gross int. @3000 rpm: 26,5 kW
Rotational speed	Min: 900 rpm
	Max: 3200 rpm
Displacement	1495 cm^3
Weight	110,0 Kg

The performance curve of the Kubota V 1505 E2B engine is shown in the figure below:

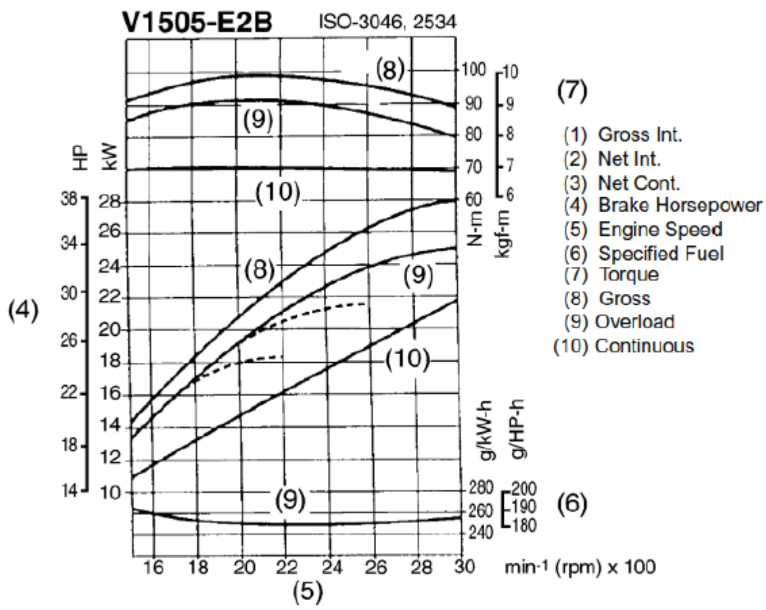

Figure 3. *Performance curve of the diesel engine. Figure from [7]*

In Figure 3 the power output in continuous operation (10) linearly relates to rotational speed in the horizontal axis (5).

For the fuel supply hydraulic line is necessary a mini injection pump (model Bosch MD, implemented already in the Haulotte) to maintain the requested engine speed and not surpassing the limited maximum rotational speed.

2.3 Main pump

One hydraulic pump provides the supply flow to all hydraulic actuators, composed by the mobile platform and the boom (all the different hydraulic cylinders are shown in Boom assembly, 3.2.1).

This hydraulic pump is a variable displacement axial piston pump that can supply 63 L/min of flow rate *Qp* at its maximum rotational speed *np*, as shown in (Eq. 1). (The hydraulic oil used is the 80W90 63[14]).

The location of this element is just next to the engine, under the left side cover, as indicates Figure 2.

The supply pressure by the main pump is limited to 210 bars, and its displacement *Dp* is limited to 21 cm^3.

(Eq. 1) $Qp = \frac{np \cdot Dp}{1000} = \frac{3000 \cdot 21}{1000} = 63\ LPM$

The main specifications of the pump are shown in Table 2, just below:

Table 2. *Main specifications of the main pump*

Model	Bosch Rexroth AL A10V O 28DFR/52R-VSC10N00-SO 97
Type	Variable displacement axial piston pump
Max. displacement	Limited to 21 cm^3
Max. flow	63 L/min (LPM) at 3000 rpm
Max. pressure	Limited to 210 bars
Max. rotational speed	3000 rpm
Control system	Pressure and flow control
Load sense adjustment	22 bars

For identifying the pump, is found the manufacturer's plate attached in the left side cover of the Haulotte [3].

Figure 4. *Manufacturer's plate of the main pump. Figure from [2]*

In the plate, Figure 4, is found the component number (CNR) which relates to the manufacturer (Bosch Rexroth) and from its catalogue it is possible to find the match of the pump by means of the different numbers shown (Model number MNR and Serial number SN).

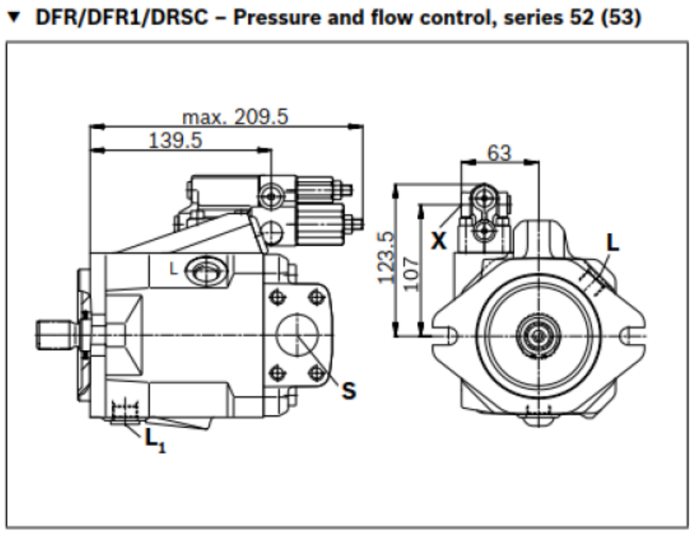

Figure 5. *Measurements of the main pump*

In Figure 5 are shown two control valves for adjusting the pump's angle (the 13th element in Figure 6) and control the pump displacement. The lower valve can limit the pressure decreasing the pump angle when pressure reaches the limit.

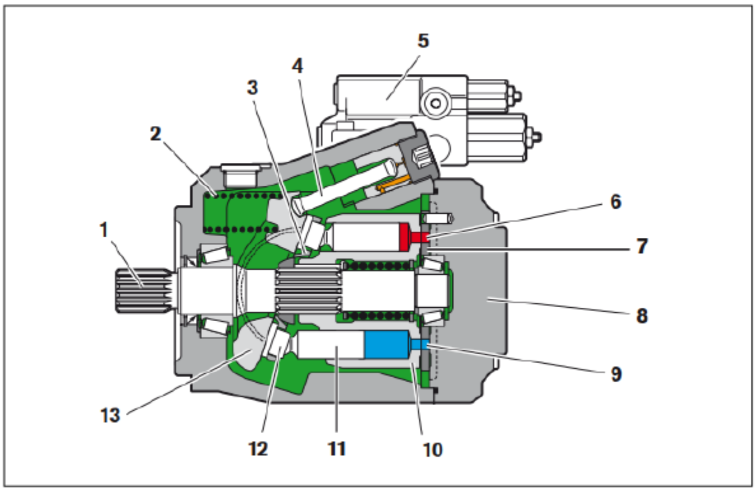

Fig. 2: Assembly of the A10VO

1	Drive shaft	**6**	High-pressure side	**11**	Piston
2	Spring	**7**	Control plate	**12**	Slipper pad
3	Retaining plate	**8**	Port plate	**13**	Swashplate
4	Stroke piston	**9**	Suction side		
5	Control valve	**10**	Cylinder		

Figure 6. *Assembly of the main pump*

2.4 Hydraulic actuators

There are three categories of hydraulics actuators in the vehicle:

- Travel motors or driving actuators: There are 4 motors, one per each wheel.
- Steering actuators or steering cylinders: There are 2 cylinders, one per each pair of wheels (Ackermann steering), only used in 2WD mode of the Haulotte. In this thesis is only discussed the 4WD mode, therefore the steering cylinders are not going to be considered in the hydraulic simulation in next chapters.
- Boom actuators: There are 6 cylinders for operating the boom and 2 motors for turning the base and the basket.

2.5 Travel motors

There are four travel motors for moving the vehicle, each one for each wheel of the mobile platform in the Haulotte. This fact makes possible to control the vehicle with four-wheel drive (4WD)

The travel motor is shown in Figure 7, with its main specifications in Table 3 .

Figure 7. *Travel motor for each wheel*

Table 3. *Main specifications of the travel motor*

Model	Danfoss OMS 100cc
Displacement	Fixed 100cm^3
Travel reducer gear ratio	i=17,7
Max rotational speed	Cont. 750 rpm (Int. 900 rpm)
Max torque	Cont. 305 Nm (Int. 390 Nm)
Max output	Cont. 18,0 kW (Int. 22,5 kW)
Max pressure drop	Cont. 210 bar (Int. 275 bars)
Max oil flow	Cont. 75 L/min (Int. 90 L/min)

The performance curve of this model is shown in the following figure:

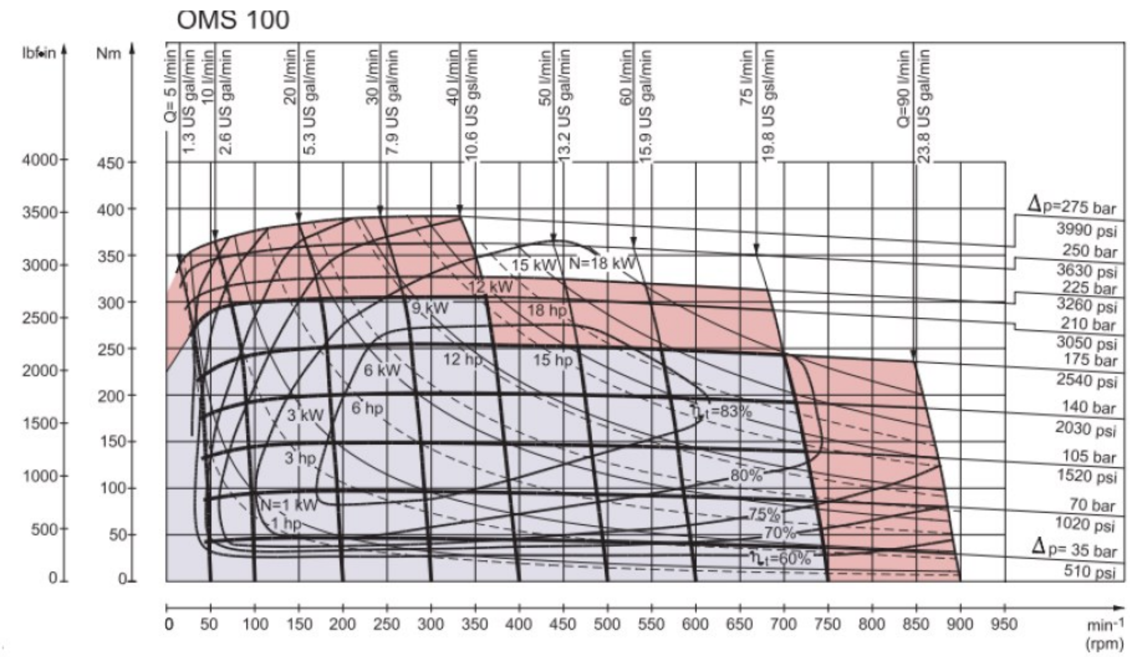

Figure 8. *Perfomance curve of the travel motor.(Figure from the OMS100 Data Sheet, page 14).*

The blue areas are for continuous operation (the operation that is going to be considered in this thesis), and the red areas are for intermittent operation (Manufacturer recommends to work in the red areas only if the operation time working in these areas are less than the 10% of the total operation time).

2.6 Original valve systems

The main pump (shown in 2.3) is capable of supplying the hydraulic power for the actuators, however, to control the actuators properly the original hydraulics of the Haulotte use different valve systems divided in five valve blocks:

- PVG valve block: Controls flow to the drive manifold.
- Drive manifold: Controls the driving mode.
- Movement manifold: Controls the flow to most of the boom actuators, also to the steering block and the ON/OFF block.
- Steering block: Controls the mode of steering.
- ON/OFF block: Controls the flow of a few actuators in the top of the boom.

The PVG valve block, the drive manifold and the steering block are not going to be deeply discussed in this thesis. The purpose of the vehicle is to be used autonomously and in a constant setup of 4WD (maximum speed of 1,4 Km/h).

This thesis focuses especially on the boom actuators; thus, the movement manifold and the ON/OFF block are going to be detailed.

These two valve blocks, that make up the original boom control system, are at the location shown below:

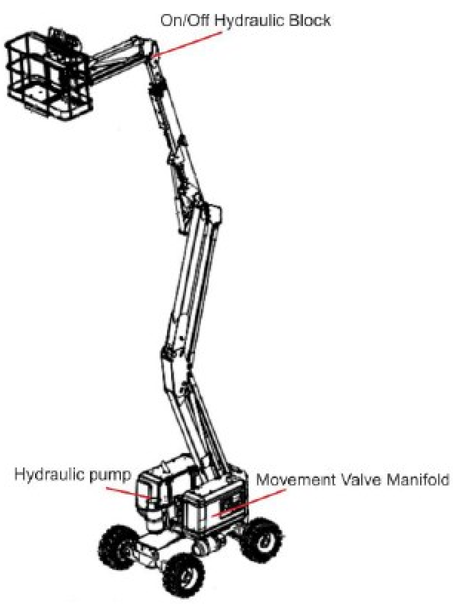

Figure 9. *Location of the original valve blocks and the main pump.Figure from [3]*

Is important to highlight that these two blocks are only found in the original Haulotte set up, which are introduced and explained in this section, nevertheless the current hydraulic configuration is explained in 2.7 and is the setup discussed and analyzed along the following chapters of this thesis.

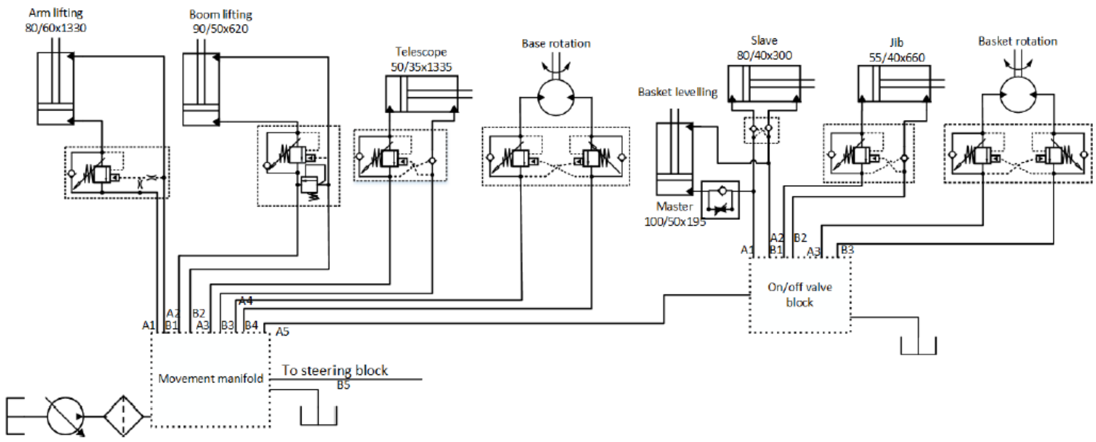

Figure 10. *Original hydraulic valve blocks for the boom system. Figure from [2]*

2.6.1 Movement manifold

The movement manifold is the main hydraulic block for controlling the operations of the boom, it can supply the right amount of flow to the right requested actuator.

It consists of pressure operated valves, electrically operated direction valves and electrically operated proportional valves.

The components of the movement manifold are below, in Table 4.

Table 4. *Movement manifold components summary. Table from [2]*

Component	Qty	Definition
PWN operated 2/2 proportional valve	5	Control the amount of flow to the actuators. The valve is more open when more speed is requested.
Pressure operated 2/2 proportional valve	5	Compensate the load pressure and restrict the maximum flow to different actuators
ON/OFF 3/2 electro valve	8	Select the direction of the flow to the right actuator.

PWN proportional valves work in series with the ON/OFF valves, as can be seen in the hydraulic schematic of the movement manifold

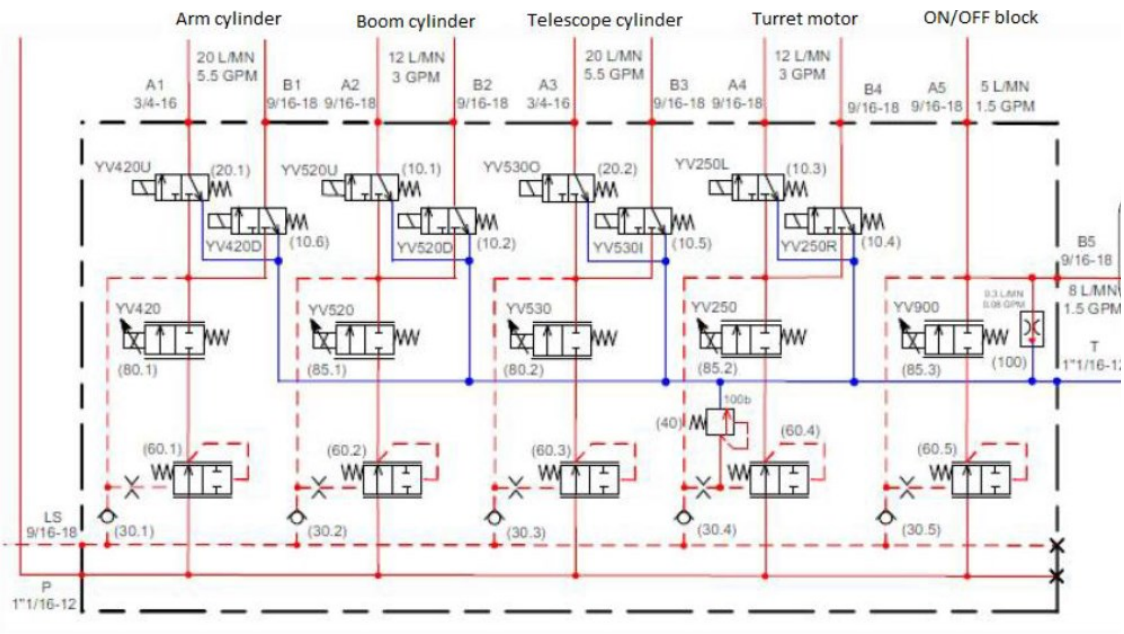

Figure 11. *Movement manifold hydraulic scheme*

The different connections are shown in Table 5.

Table 5. *Movement manifold original connections*

Connection	**Definition**	**Max. flow**
A1 3/4-16 and B1 9/16-18	Arm lifting cylinder connection	20 LPM
A2 9/16-18 and B2 9/16-18	Boom lifting cylinder connection	12 LPM
A3 3/4-16 and B3 9/16-18	Telescope cylinder connection	20 LPM
A4 9/16-18 and B4 9/16-18	Base motor connection	12 LPM
A5 9/16-18	ON/OFF block connection	5 LPM
B5 9/16-18	Steering block connection	8 LPM
T 1''1/16-12	Tank drain line	
P 1''1/16-12	Pressure supply line	
LS 9/16-18	Load sense line to the PVG block	

The movement manifold is in the left side of the base.

2.6.2 ON/OFF hydraulic block

The ON/OFF block controls the basket level compensation, the jib structure, and the rotation of the basket.

It consists of ON/OFF electro valves. The flow to this block comes from the movement manifold block as shown in the hydraulic schematic in Figure 12.

The components are in Table 6 and the connections in 0.

Table 6. *ON/OFF block components summary. Figure from [2]*

Component	Qty	Definition
ON/OFF 3/2 electro valve	3	Select the direction of the flow to the right actuator (jib and basket in this block).
Pressure relief valve	3	Hold the back pressure for the basket levelling cylinder

The hydraulic schematics of this block is shown below:

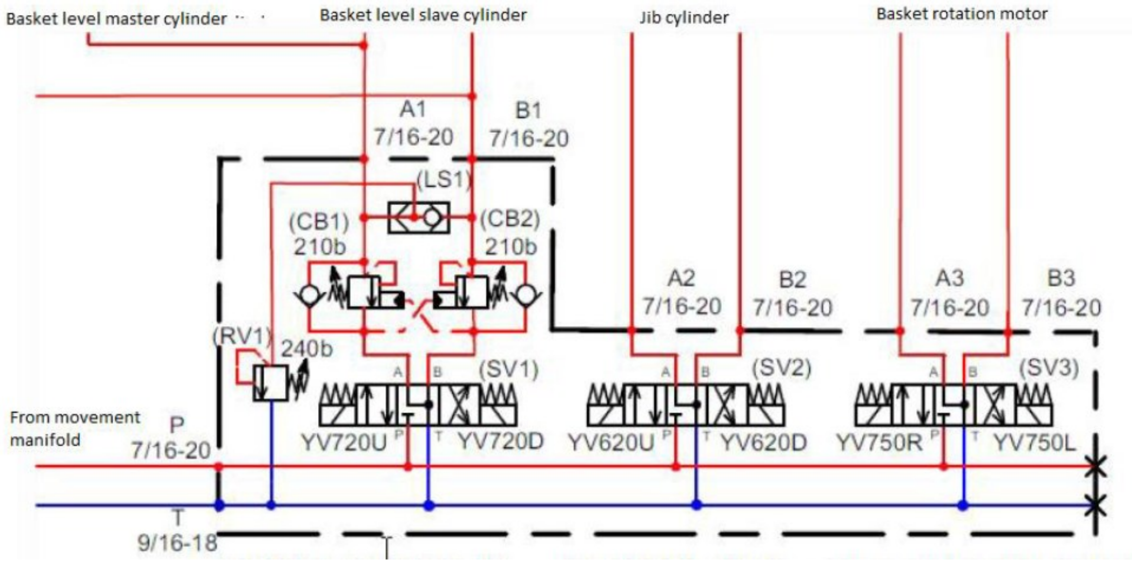

Figure 12. *ON/OFF block hydraulic scheme. Figure from [2]*

Table 7. *ON/OFF block original connections*

Connection	Definition
A1 7/16-20 and B1 7/16-20	Basket leveling cylinders (two cylinders which are operating in parallel)
A2 7/16-20 and B2 7/16-20	Jib cylinder connection
A3 7/16-20 and B3 7/16-20	Basket rotation motor connection
T 9/16-18	Tank drain line
P 7/16-20	Pressure supply line from the movement manifold

The location of the ON/OFF block is in the end of the upper boom, right before the jib joint.

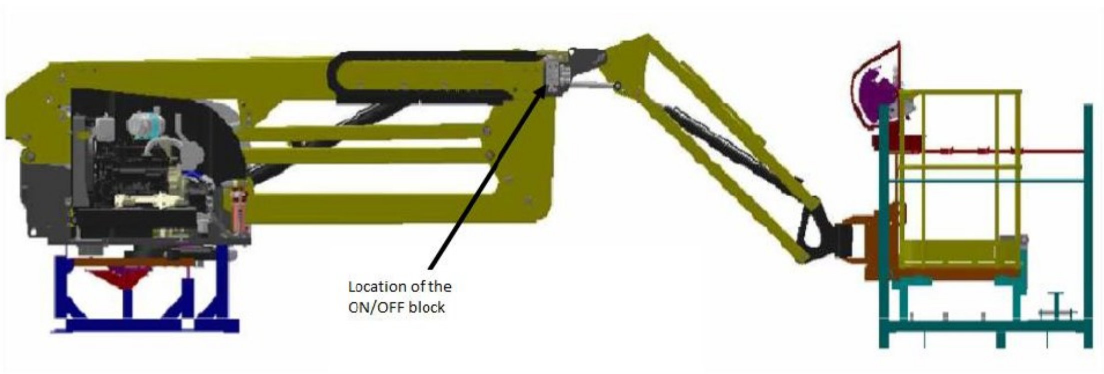

Figure 13. *Location of the ON/OFF block. Figure from [2]*

2.7 New hydraulics

The new hydraulic controlling system is easier than the original one based on valve blocks.

The two boom manifolds (Movement manifold and ON/OFF hydraulic block) are replaced with servo valves for each actuator.

In this new system, the master leveling basket cylinder does not have any function, otherwise the slave basket leveling cylinder is treated as the rest of the other actuators.

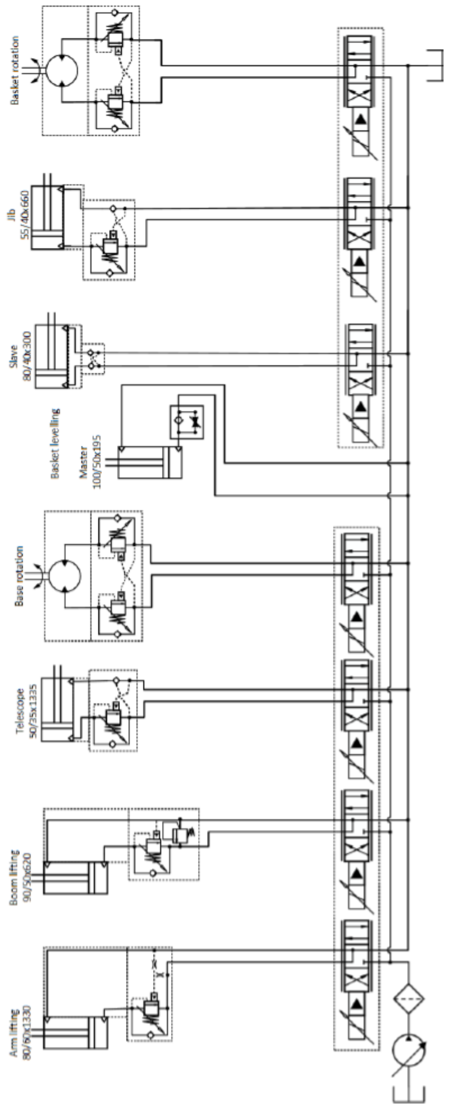

Figure 14. *New hydraulic configuration of the boom's actuators*

From a practical point of view, the original valve system is intended to stay in the Haulotte as a parallel system to maintain the option to use it later. Is possible to switch from movement manifold to the different servo valves of the new concept using three-way valves while the original hoses are still being used to connect the different actuators.

2.7.1 HST

For the hydrostatic transmission (HST) the main new modification is to separate the control for every wheel motor.

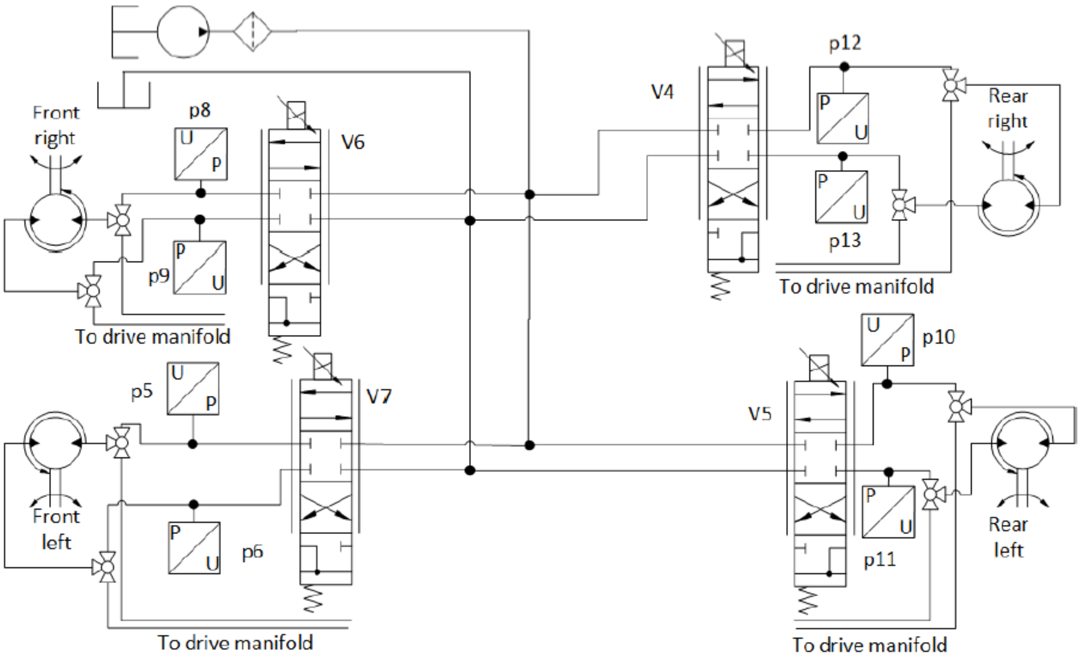

Figure 15. *New HST configuration. Figure from [2]*

The components are in Table 8, just below.

Table 8. *HST components*

Component	Qty	Definition
Bosch-Rexroth WREPH 6 Servo valves	4	24 LPM nominal flow
IMF PA3521 pressure sensors	4	Pressure range 0 to 250 bar

The travel motors are the same as in the original configuration.

The old system is connected by means of the three-way valves, just in case the original configuration is needed someday.

3. THEORETICAL FOUNDATION AND MECHANICAL DEFINITIONS

To review the hydraulic actuators of the Haulotte is important to introduce the theoretical foundation about the mechanics and kinematics of the mobile platform and the boom system.

3.1 Kinematics of steering structures

The wheeled mobile robots are theoretically divided in omnidirectional and non-holonomic categories.

- Omnidirectional robots are capable of driving sideways, in other words, can drive in any direction by means of three or four independently driven Mecanum wheels [10].

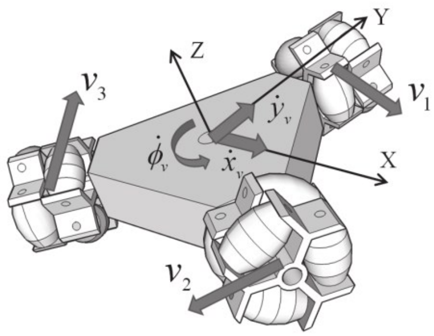

Figure 16. *Omnidirectional robot with three Mecanum type wheels. Figure from [12]*

- Non-holonomic robots cannot drive in a perpendicular direction to their driver heels, the best example is the car which needs a minimum amount of space for maneuver for parking in a place between other cars.

The mobile platform of the Haulotte HA16 RTJ PRO can reach any (*θ,x,y*) configuration in a plane with no obstacles, as a non-holonomic wheeled mobile robot which is subject to a constrained center of rotation (from now on, named as COR) with differential drive-properties, this prevents the mobile from moving directly sideways.

The differential-drive mobile consists of two wheels rotating about the same axis; each wheel is independently driven but are always depending on the respective kinematics.

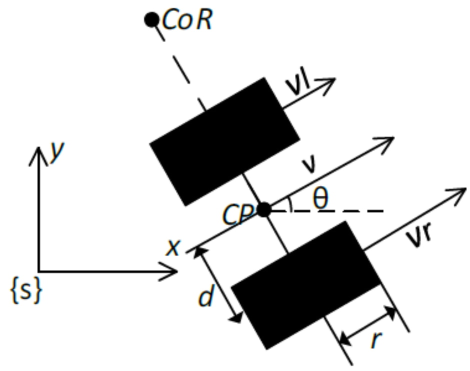

Figure 17. *Front wheel-steered vehicles kinematics*

3.1.1 Two-wheel Drive and Steering (2WDS)

In 2WDS systems, the engine powers two wheels, either in the front or in the back, and have to do two jobs, driving and steering. For front wheel-steered vehicles, the steering is based in the bicycle model, the COR is located perpendicular with respect to the rear wheel's axle and the vehicle rotates about this point.

When the vehicle turns, because of the mechanical shaft between both wheels, the steering angle of the inner wheel have a larger value than the steering angle of the outer wheel, in other words, one wheel is turning more than the other one. This system is known as Ackermann steering and avoids the need for tires to slip sideways when the vehicle is following a curve in the path.

Due to this differential drive, the different angular velocities u_L and u_R, for left and right wheel can be calculated through the lineal velocity *v* of the control point (located in the bisector of the wheels axle), the rate of the heading , the distance d between the center of the wheel and the CP and the radius r.

The equations are the following:

(Eq. 2) $$\begin{bmatrix} u_L \\ u_R \end{bmatrix} = \begin{bmatrix} \frac{v-\dot{\theta}d}{r} \\ \frac{v+\dot{\theta}d}{r} \end{bmatrix}$$

The configuration of 2WDS is defined and can be written as ***q***=*(θ,x,y,φ),*where *θ* is the heading direction of the vehicle, (*x,y*) are the coordinates of the midpoint located between the pair of rear wheels and φ is the steering angle of the vehicle, and it is represented as a virtual wheel located at the midpoint between the pair of front wheels[6] .

The COR is changing along the path, but for each time differential the center of rotation is identical for all wheels.

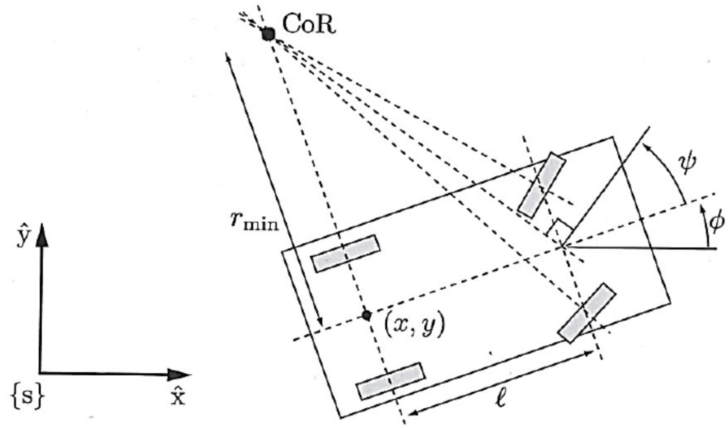

Figure 18. *Kinematics of a car steered using Ackermann Steering. Figure from [6]*

The simplified kinematics for this steering structure can be presented as:

(Eq. 3)
$$\dot{\boldsymbol{q}} = \begin{bmatrix} \dot{\theta} \\ \dot{x} \\ \dot{y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \frac{tan\,\varphi}{L} & 0 \\ cos\,\theta & 0 \\ sin\,\theta & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} v \\ w \end{bmatrix}$$

The Velocity v and w are the control inputs, the forward velocity of the vehicle at its reference point (*x,y*), and the angular speed of the virtual middle wheel's steering angle φ, respectively. The distance *L* is the distance between the reference point or control point (CP) and the axis joining the centers of the two front wheels [6]. Using geometry, it is possible to find the steering angles for right and left wheel, φ_R and φ_L respectively. The mathematical expressions are the following:

(Eq. 4)
$$\varphi_R = \begin{cases} \text{arctan2}\left(\frac{\dot{\theta}\cdot L}{v + \dot{\theta}\cdot d}\right), & \dot{\theta} > 0 \\ \text{arctan2}\left(\frac{\dot{\theta}\cdot L}{v + \dot{\theta}\cdot d}\right), & \dot{\theta} < 0 \end{cases}$$

(Eq. 5)
$$\varphi_L = \begin{cases} \text{arctan2}\left(\frac{\dot{\theta}\cdot L}{v - \dot{\theta}\cdot d}\right), & \dot{\theta} > 0 \\ \text{arctan2}\left(\frac{\dot{\theta}\cdot L}{v + \dot{\theta}\cdot d}\right), & \dot{\theta} < 0 \end{cases}$$

3.1.2 Four-wheel Drive and Steering (4WDS)

Some vehicles, such as the Haulotte, use the Four-Wheel Drive and Steering system due to its high maneuverability characteristics.

Figure 19. The *HA16 RTJ PRO general view*

Conceptually there are two types of different 4WDS:

- Independently steered wheels (or 4WIS).
- Mechanically coupled steered wheels: Easy to control because of the relative distances between the vehicle's mass center and the wheels. It is the Haulotte configuration.

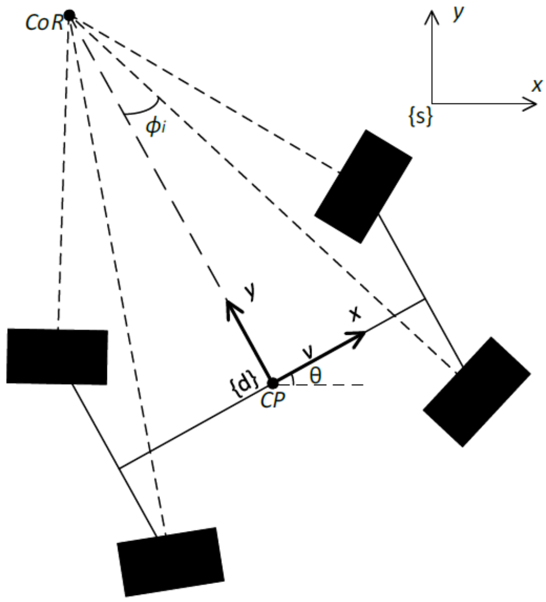

Figure 20. *4WDS kinematic with contrained COR. Figure from [1]*

The position of the COR for 4WDS is apparently more complicated than in 2WDS but there is a simplified way to locate it, by constraining a control point (CP) in the middle of the longitudinal axis of the vehicle, then the COR is along its perpendicular and is joining the CP.

The rear wheel steering angles are symmetrically mirrored regarding the front ones; therefore, this way of definition restricts the maneuverability but is a good approach. The kinematics of the pair of wheels now are constrained as a 2WDS model, therefore, to define the steering angle for left and right wheels it is possible to use (Eq. 4) and (Eq. 5). Notice that the distance L now is the distance between the CP and the axle that joins the centers of the front wheels [1].

In this thesis, for the analysis of the kinematics and hydraulics of the Haulotte, which is the subject of study, its only analyzed using the 4WD/4WDS driving mode, the reasons are discussed in other sections.

3.2 Kinematics of crane architectures

The kinematics of the different parts of a crane is a rather complicated issue because of all the closed structures involved.

To develop and obtain the different kinematics of each part, is important to simplify the geometry of the crane.

Considering a crane or boom as multiple planar mechanisms, kinematic analysis can be performed analytically by means of the projection of vector loop equations for every closed structure.

Every vector loop equation provides the position of vectors for every mechanism. Each equation when is derived from time provide velocities and, when is derived again, provide accelerations [11].

3.2.1 Boom assembly

The boom consists of seven main parts: base (or turret), bottom arm, top arm, upper boom, telescope, jib, and basket.

The position of each part is shown in the following figure.

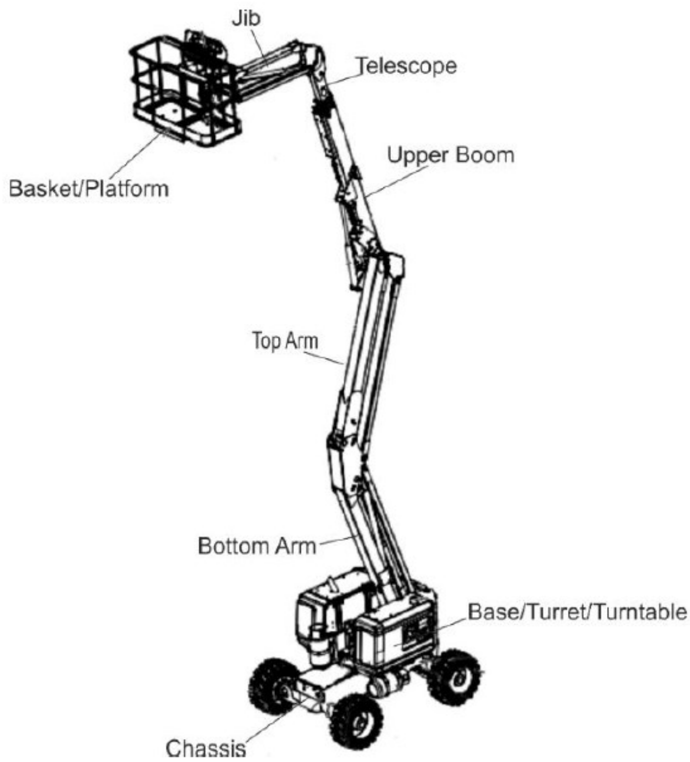

Figure 21. *Parts of the HA16RTJ PRO*

For actuating the boom is needed 8 hydraulic actuators, as it is mentioned in 2.4.

- 2 Hydraulic motors: For the base and for the basket rotation.
- 6 Hydraulic cylinders: For the arm lifting, the boom lifting, the telescope, for levelling the basket (master and slave cylinders) and for the jib.

The position of each hydraulic actuator is shown in the following figure.

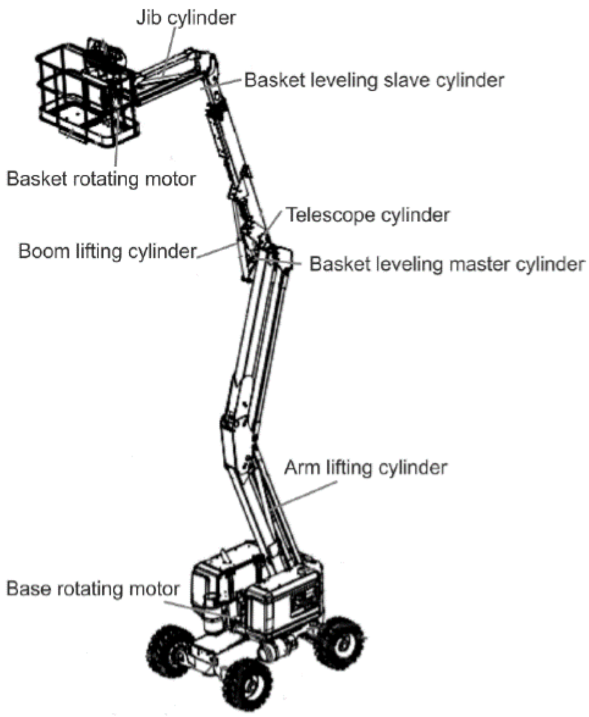

Figure 22. *Actuators of the HA16 RTJ PRO (Boom and base)*

The boom can be divided into the lower boom (corresponding to the arms) and the upper boom as two independent mechanisms in order to obtain independent kinematics and hydraulic simulations, because the Haulotte can move, if its needed, only the upper boom structure maintaining the lower boom in the rest or initial position, or maybe the situation reversed.

The base rotating motor will be discussed independently from the lower or upper boom.

3.2.2 Lower boom

The lower boom is formed by a bottom and a top arm, there is a middle part working as a joint between them and all bars together form a scissor like structure when the cylinder, which is connected to both arms, is actuating, both arms gain angle and therefore the top arm's end gets higher.

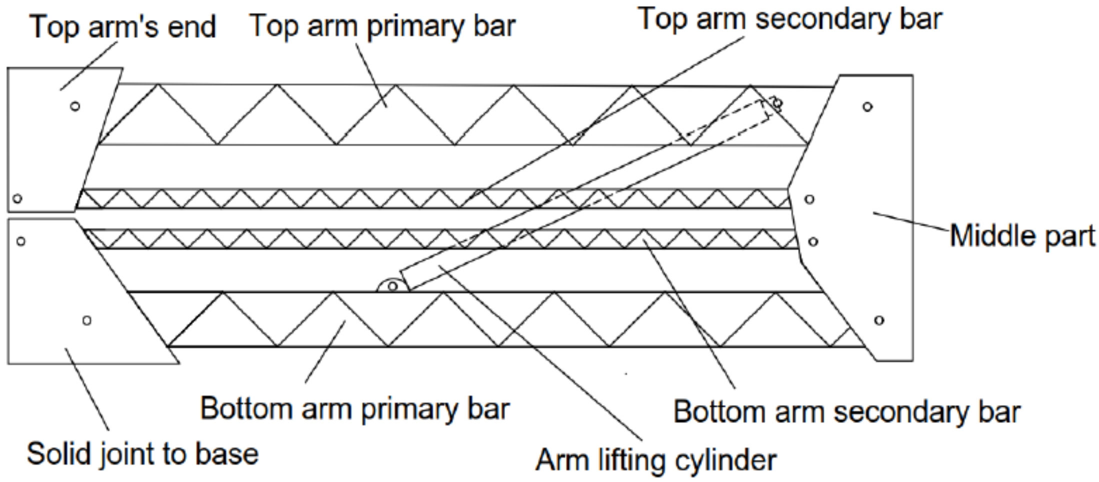

Figure 23. *Lower boom definition. Figure from [3]*

Each bar (bottom and top) has two parallel bars to stiffen the scissor like structure but are not considered for obtaining for obtaining the kinematics in next chapters.

3.2.3 Upper boom

The upper boom is the upper structure that relates to horizontal offset to the top arm's end.

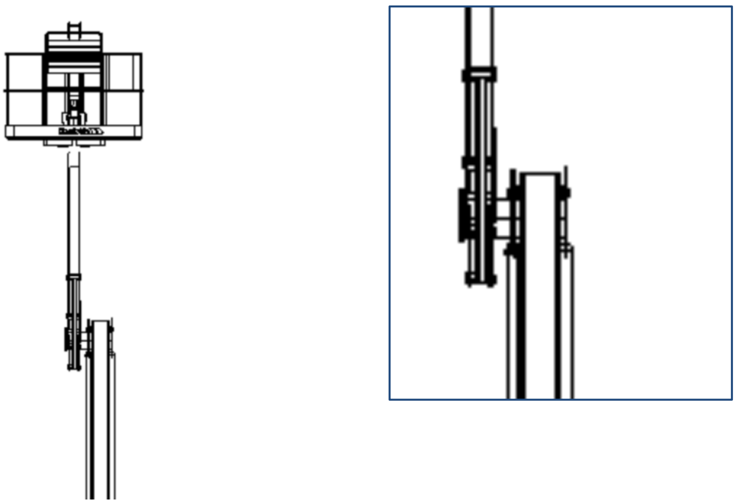

Figure 24. *Horizontal offset between the lower and upper boom*

As it can be seen in the following picture, the basket levelling master cylinder and the boom lifting cylinder are between the upper boom and the lower boom, just located in the horizontal offset of the top arm's end.

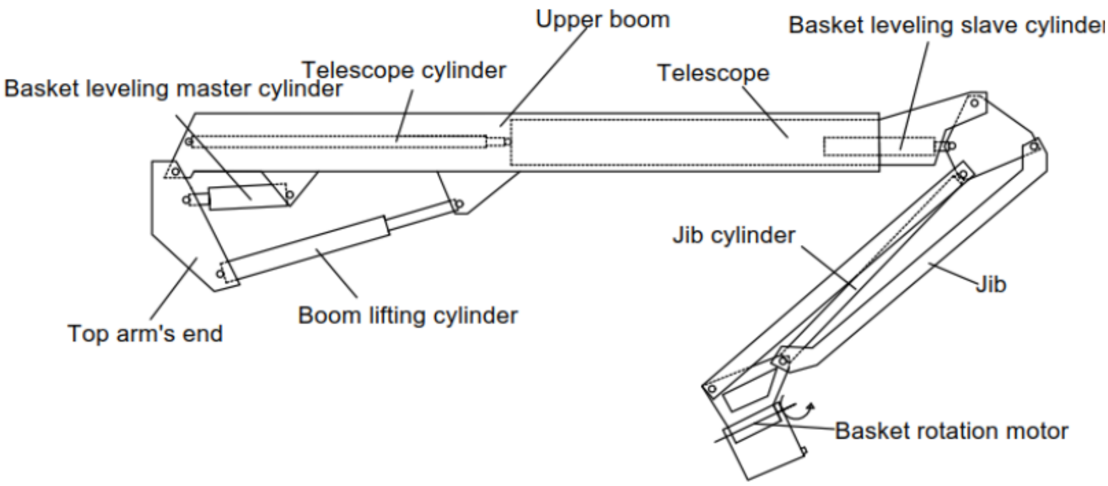

Figure 25. *Upper boom definition. Figure from [3]*

The telescope cylinder and the telescope part itself are inside the upper boom, and the basket leveling cylinder is inside the telescope.

After the telescope part there is the basket leveling slave cylinder and the jib joint, after it follows the jib, a closed structure composed of two parallel bars, the inner (formed by two parallel inner bars to stiffen this closed structure) and the outer one.

Its cylinder connects between inner jib bar's upper joint and the outer jib bar's lower joint, also both lower joints are connecting with the basket, as the end part of the upper boom and the whole boom system itself.

4. APPLICATION OF THE THEORETICAL FOUNDATION

The boom is divided into lower and upper boom, a scissor like structure that is in the lower boom and the rest of the hydraulic cylinders are located in the upper boom. This means that the kinematics are obtained for every planar mechanism (from now on, closed structure) that involves a hydraulic cylinder. Every structure is analyzed in this chapter with the corresponding kinematic equations.

In the end of this chapter, exactly in 4.5, all actuators are summarized.

4.1 Dimensions

The dimensions of the Haulotte (Plan view) are shown in the following figure, and few of them are needed for the kinematic equations given in 3.1.

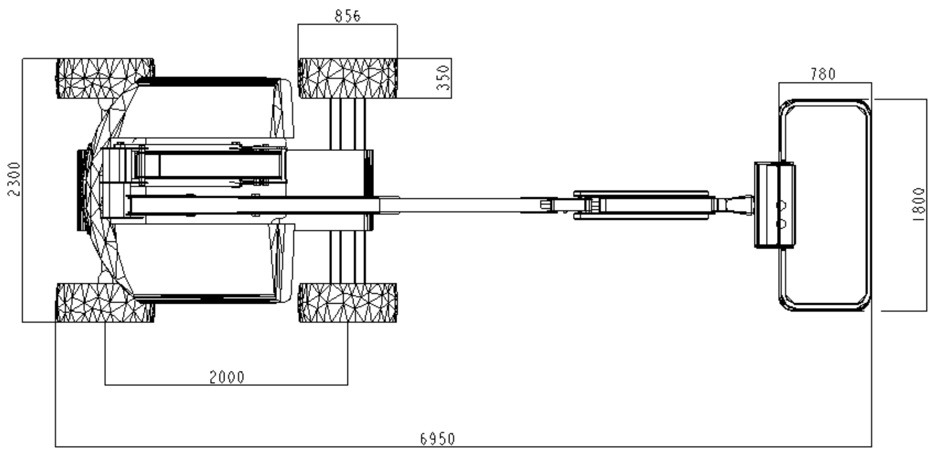

Figure 26. *Dimensions of the HA16 RTJ PRO (Plan view)*

4.2 Lower boom structure

To calculate the kinematics of the lower boom, because of the scissor like structure complexity, is simplified the structure as an isosceles trapeze which is expanding to the length of the cylinder (variable named as *c,* from now on).

Figure 27. *Lower boom structure and its simplification draw (in red)*

Therefore, the simplified geometry of the lower boom is the following, and the dimensions taken are explained in Table 9.

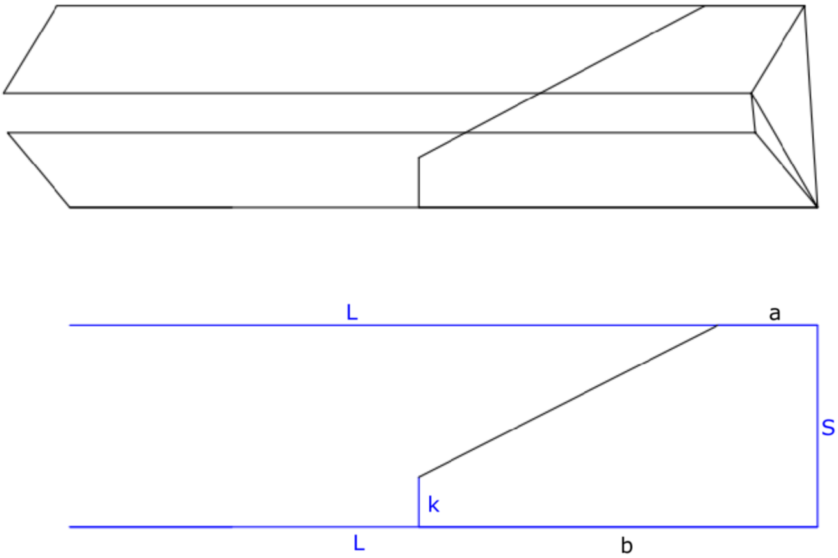

Figure 28. *Simplification of the lower boom's geometry*

Table 9. *Lower boom dimensions taken*

Dimensions	
L	3,00 m
s	0,81 m
a	0,40 m
b	1,60 m
k	0,20m

The **Initial position** is when the piston cylinder *c* is about its minimum displacement:

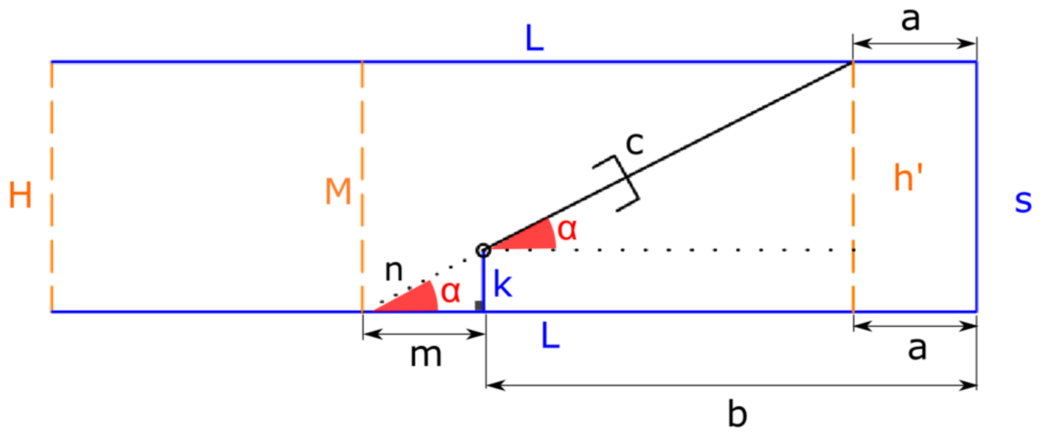

Figure 29. *Initial position of the lower boom (Cylinder stroke is minimum)*

The **Final position** is when the piston cylinder is about its maximum displacement:

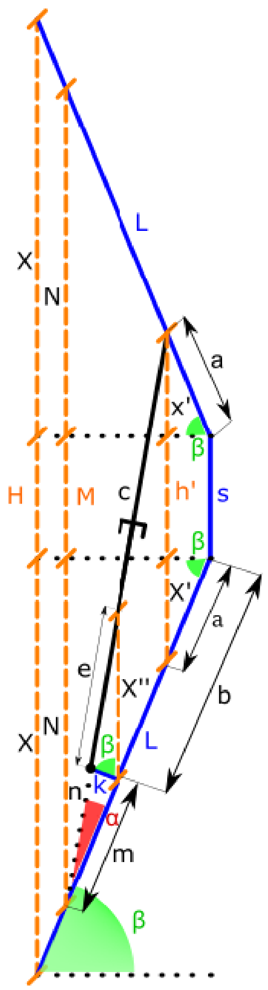

Figure 30. *Final position of the lower boom (cylinder stroke is maximum)*

Considering all the following equations (6 to 18), which relate all dimensions and angles, is possible by MATLAB to obtain the final position of the lower boom analytically.

13 equations with 13 unknowns.

The var. *c* is the input.

Table 10. *Lower boom outputs obtained after simulation*

	Initial position	Final position
H	0,81 m	6,35m
c	1,50m	2,66m
α	26,94º=0,4702 rad	7,804º=0,1362 rad
β	0º= 0 rad	67,50º=1,1781 rad
n	0,44 m	1,47m
m	0,39 m	1,46m

(Eq. 6) $\sin\beta = \frac{X}{L}$

(Eq. 7) $\frac{X}{N} = \frac{L}{m+b}$

(Eq. 8) $\frac{X}{X'} = \frac{L}{a}$

(Eq. 9) $H = 2 \cdot X + s$

(Eq. 10) $M = 2 \cdot N + s$

(Eq. 11) $h' = 2 \cdot X' + s$l h

(Eq. 12) $h'^2 = y^2 + (m+b-a)^2 - 2 \cdot y \cdot (m+b-a) \cdot \cos\alpha$

(Eq. 13) $y^2 = M^2 + (m+b-a)^2 - 2 \cdot M \cdot (m+b-a) \cdot \sin\beta$

(Eq. 14) $\tan\alpha = \frac{k}{m}$

(Eq. 15) $y = c + n$

(Eq. 16) $n = \sqrt{k^2 + m^2}$

(Eq. 17) $X''^2 = (n+\mathrm{e})^2 + m^2 - 2 \cdot (n+e) \cdot m \cdot \cos\alpha$

(Eq. 18) $\frac{\mathrm{e}}{\sin\beta} = \frac{X''}{\sin(90+\alpha)}$

The development of the initial position to final position during the time is shown in the chapter number 5, after the simulation. The final results are already shown in Table 10 , above.

4.2.1 Lower boom hydraulics

Once the kinematics of the lower boom are obtained, it is easy to obtain the flow rate needed to pump for different piston velocities.

Using the following hydraulic expression, we obtain the flow rate (LPM) needed for it:

(Eq. 19) $$Q(LPM) = 6 \cdot v_{p_{cyl}}(m/s) \cdot A(cm^2) = \frac{6 \cdot v_{p_{cyl}}(m/s) \cdot \pi \cdot \text{Ø}_p{}^2(\text{cm})}{4}$$

8 cm is the piston diameter of this cylinder.

4.3 Upper boom structure

For the upper boom, there are not scissor like structures like in the lower boom, so to calculate the kinematics the easiest way is using the vector loop equations of each closed structure.

We will obtain three vector loops, one for the closed structure formed by the displacement of boom lifting cylinder, for the basket leveling and for the jib lifting cylinders.

Figure 31. *Upper boom's different structures (from left to right: Boom lifting structure, basket leveling structure and jib structure)*

4.3.1 Boom lifting structure

We take this simplification of the boom lifting cylinder to obtain a vector loop which can give the information of the gaining angle θ_3, with respect to the cylinder's piston displacement.

In other words, we will obtain the relation between the height gained and the flow rate pumped to this cylinder, for different velocities (or situations).

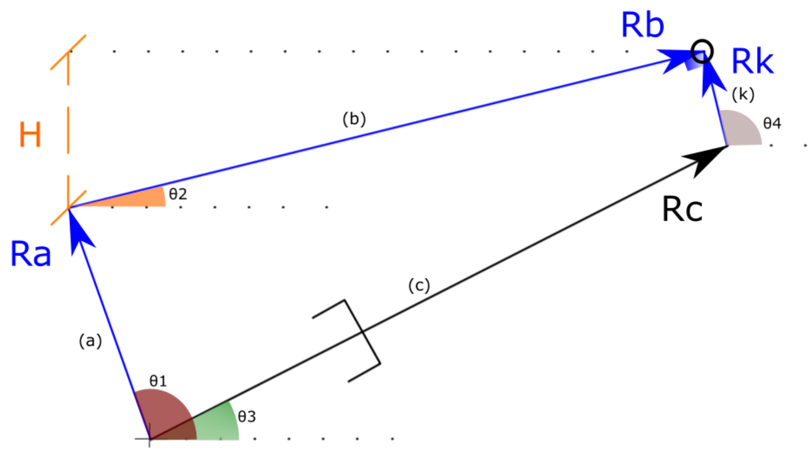

Figure 32. *Simplification of the boom lifting structure*

The vector loop is the following:

(Eq. 20) $$R_a + R_b = R_c + R_k$$

Euler transformation:

(Eq. 21) $$a \cdot e^{j\theta 1} + b \cdot e^{j\theta 2} - c \cdot e^{j\theta 3} - k \cdot e^{j\theta 4} = 0$$

(Eq. 22) $$a \cdot cos\,\theta_1 + b \cdot cos\,\theta_2 - c \cdot cos\,\theta_3 - k \cdot cos\,\theta_4 = 0$$

(Eq. 23) $$a \cdot j\,sin\,\theta_1 + b \cdot j\,sin\,\theta_2 - c \cdot j\,sin\,\theta_3 - k \cdot j\,sin\,\theta_4 = 0$$

(Eq. 24) $$\theta_4 = \theta_2 + 90º$$

Table 11. *Boom lifting structure dimensions taken*

Dimensions	
a	0,60 m
b	1,40 m
k	0,20m

The initial position is the position of the structure when the cylinder is at its minimum displacement and the angle θ_2 is zero, so the bar *b* is horizontal (In the reality we know is not exactly horizontal, but this considerations are taken to simplify the kinematics).

Table 12. *Boom lifting structure outputs after the simulation*

	Initial position	Final position
H	0 m	1,39m (3,50m considering the entire lifting bar)
θ_2	0º	83º
θ_4	43,98º	57,96º

The Height *H* (in Figure 32) in this case is calculated as:

(Eq. 25) $H = b \cdot sin\, \theta_2$

Notice, that in the boom lifting closed structure on the Figure 32, the bar named as *b* is longer because it reaches the telescope structure joint.

Then, considering the entire lifting bar when the maximum lifting angle θ_2 (cylinder at maximum extension), the total height *H* is 3,50m.

The telescopic structure joins the lifting bar end.

The telescopic cylinder is located inside the boom lifting structure, so the angle will be always the same as the boom lifting bar, θ_2.

4.3.2 Basket leveling structure

The basket leveling closed structure adjusts and compensates the level of the basket by means of the jib joint to make it gain or losing angle θ_8 (Figure 33) with respect to the upper boom bar. If we simplify this as a triangle, then is easy to find the angle with respect the boom in function of the displacement of the piston. The length and angle of the bar *a* remains constant, as the frame, but the cylinder *c* is gaining angle when it is expanding and thus *b* (which is the jib joint) is rotating.

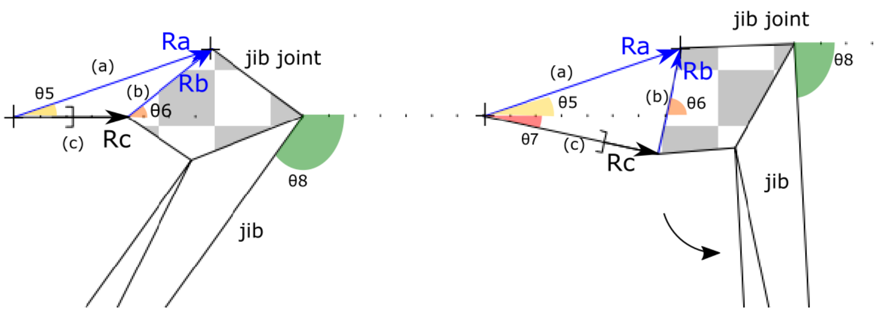

Figure 33. *Simplification of the basket leveling structure (From left to right: Initial position and the final position)*

Table 13. *Basket leveling structure dimensions taken*

Dimensions	
a	0,61 m
b	0,32 m
θ_5	18,91°

Vector loop equations ($Ra = Rb + Rc$) :

(Eq. 26) $a \cdot cos\,\theta_5 = b \cdot cos\,\theta_6 + c \cdot cos\,\theta_7$

(Eq. 27) $a \cdot j\,sin\,\theta_5 = b \cdot j\,sin\,\theta_6 + c \cdot j\,sin\,\theta_7$

Table 14. *Basket leveling structure outputs obtained after simulation*

	Initial position	**Final position**
c	0,33m	0,63m
θ_6	39,5°	97,4°
θ_7	0°	-10,95°
θ_8	-120,5°	-62,5°

4.3.3 Jib cylinder structure

The jib cylinder closed structure allows the jib to gain angle (increasing the height) by means of its long cylinder which is connected to the basket.

This cylinder can actuate when the basket leveling cylinder is at its maximum displacement, to get the maximum height as possible for the basket. We simplified this closed structure as a triangle.

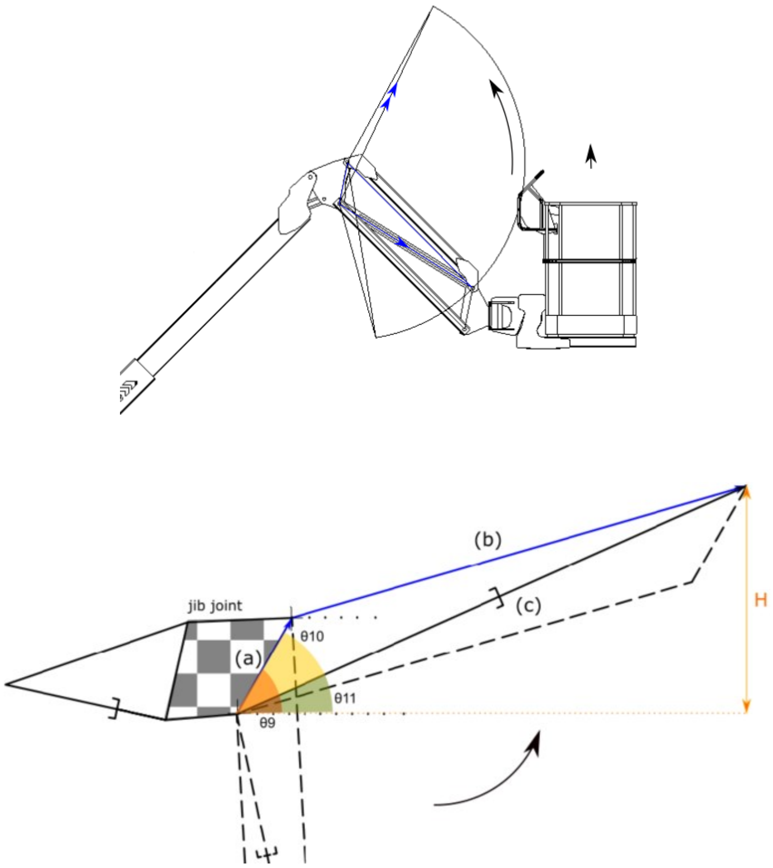

Figure 34. *Simplification of the jib structure*

Table 15. *Jib dimensions taken*

Dimensions	
a	0,36 m
b	1,51 m
θ_9	79,2 º

This time, to simplify this mechanism, the cosine law is applied:

(Eq. 28) $b^2 = c^2 + a^2 - 2 \cdot c \cdot a \cdot cos\, \theta_{10}$

(Eq. 29) $\theta_9 = \theta_{10} + \theta_{11}$

Table 16. *Jib outputs obtained after simulation*

	Initial position	**Final position**
Length *c*	1090mm	1750mm

The angles θ_{10} and θ_{11} are the outputs, simulated and obtained in chapter 5.

4.3.4 Upper boom hydraulics

Once the kinematics of the lower boom are obtained, it is easy to obtain the flow rate needed to supply by the main pump to develop different piston velocities.

Using the flow rate equation, the Eq. 19, we obtain the flow rate (LPM) needed.

- 9 cm is the piston diameter of the boom lifting cylinder.
- 5 cm is the piston diameter of the telescopic cylinder.
- 8 cm is the piston diameter of the leveling basket cylinder.
- 5,5 cm is the piston diameter of the jib cylinder.

4.4 Mobile platform

To get the different wheel velocities (for right and left wheels) of the Haulotte's Mobile platform when is turning or when is going straight, we have to take into account the kinematic equations of steered car-like mobiles, already shown in chapter 3.

The vehicle is originally designed to move with a speed from 0,5 to 5,6 km/h.

In 4WD mode, which is the autonomous and continuous operation mode for the modified Haulotte's vehicle discussed in this thesis, is 1,4 km/h the maximum speed by the manual. Therefore, the input velocity set for the vehicle to simulate the behavior of the hydraulic system in 5.2 is 0,40 m/s.

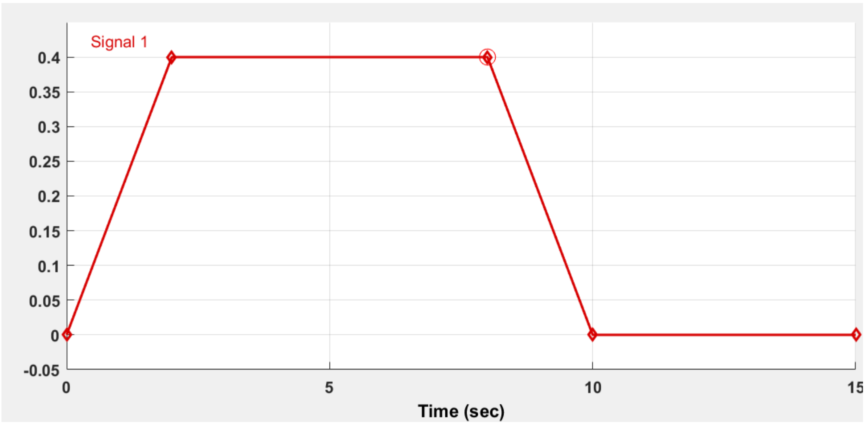

Figure 35. *Velocity input set, acceleration and decceleration values randomly asigned to analyse the performance in chapter 5 (vertical axis: units in m/s)*

4.5 Summary of hydraulic actuators

All actuators are summarized in the following table:

Table 17. *Summary of the main information for all the hydraulic actuators considered*

Group	Part	Actuator	Model	Specifications
Boom	Base/Turret	Base rotating motor	MR160 Gear motor	Volume: 159,6cm^3 Max flow: 60 L/min Max speed: 375 rpm Pressure: 175 bar
	Lower boom	Arm lifting cylinder	80/60 S1330	Cyl. stroke: 1330mm Piston Ø: 80mm
	Upper boom	Boom lifting cylinder	90/50 S620	Cyl. stroke: 620mm Piston Ø: 90mm
		Telescope cylinder	50/35 S1335	Cyl. stroke: 1335mm Piston Ø: 50mm
		Basket leveling cylinder	80/40 S300	Cyl. stroke: 300mm Piston Ø: 80mm
		Jib cylinder	55/40 S660	Cyl. stroke: 660mm Piston Ø: 55mm
		Basket rotating motor	No data	limited turning radius 165º
Mobile platform	Wheels	Travel motors (x4)	Danfoss OMS 100cc	Volume: 100cm^3 Max flow: 75L/min Max speed: 750 rpm

5. KINEMATIC AND HYDRAULIC RESULTS

All the results are obtained by Simulink in MATLAB[3], for every simulation is considered a different time until the cylinder gets the maximum displacement (complete stroke).

Then, 5 situations are considered, when the maximum displacement of each hydraulic actuator is reached in 4 seconds, in 8 seconds, in 12 seconds, in 16 seconds and in 20 seconds. We consider that more than 20 seconds is too low and would make the boom not very functional.

5.1 Boom simulation

The boom is divided into the lower boom and the upper boom (with every structure) as it shown in previous chapters. The simulations are done for every part and for each structure discussed in the previous chapter.

5.1.1 Lower boom kinematics

The cylinder length is the input, we consider 5 possible situations based on different hypothetical speeds of the piston displacement. For different speeds, the flow rate needed by the pump, changes as is shown in 5.1.2.

Velocities of the arm lifting cylinder taken:

- Situation 1: Maximum displacement of the piston in 4 seconds (0,29 m/s)
- Situation 2: Maximum displacement of the piston in 8 seconds (0,15 m/s)
- Situation 3: Maximum displacement of the piston in 12 seconds (0,10 m/s)
- Situation 4: Maximum displacement of the piston in 16 seconds (0,07 m/s)
- Situation 5: Maximum displacement of the piston in 20 seconds (0,06 m/s)

[3] MATLAB: https://es.mathworks.com/products/matlab.html

After the simulation, the height developed by the lower boom (taking the height as the difference between the lowest point of the lower bar and upper in the top arm is the following for each situation:

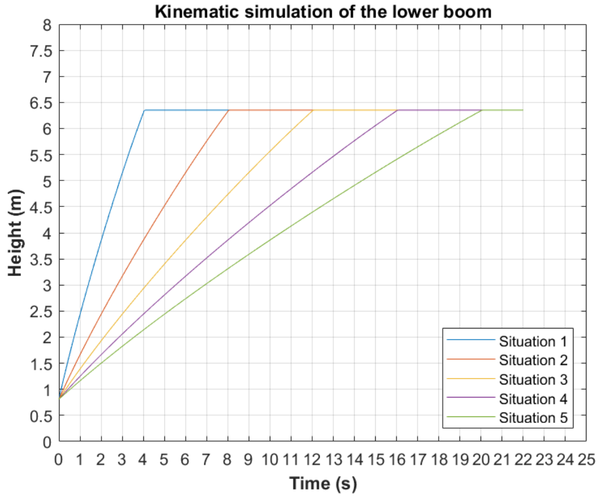

Figure 36. *Kinematic simulation for the lower boom*

Also the angles (Beta β and Alpha α, which can be seen in Figure 30) are developing like this during the time (Representation only about the Situation 1, considering 4 seconds as the time when the lower boom is getting the maximum height, for the rest of the situations the plot is the same just changes the scale of time (in seconds).

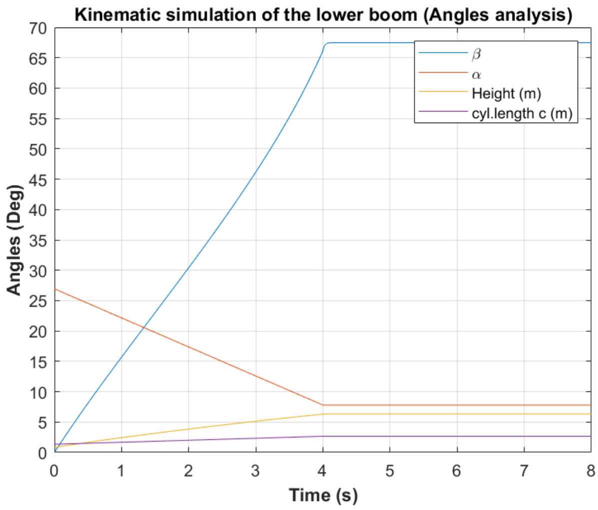

Figure 37. *Kinematic simulation for the lower boom (Situation 1)*

5.1.2 Lower boom hydraulics

The flow rate needed for the arm lifting cylinder for each speed taken (Using the equation(Eq. 19)):

- Situation 1: Flow rate of 87,52 LPM needed
- Situation 2: Flow rate of 49,55 LPM needed
- Situation 3: Flow rate of 33,05 LPM needed
- Situation 4: Flow rate of 24,80 LPM needed
- Situation 5: Flow rate of 19,82 LPM needed

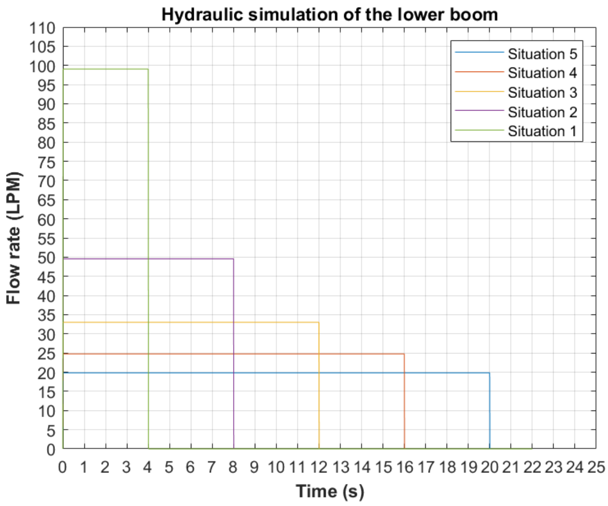

Figure 38. *Hydraulic simulation for the lower boom*

5.1.3 Upper boom kinematics

Boom lifting cylinder

The cylinder length *c* (due to the piston displacement) is always taken as the input, we consider 5 possible situations based on different hypothetical speeds of the piston. For different speeds, the flow rate needed by the pump changes as is shown in 0.

Minimum cylinder length: 0,78m

Maximum cylinder length: 1,40m

Velocities of the boom lifting cylinder taken (v_{cyl}):

- Situation 1: Maximum displacement of the piston in 4 seconds (0,16 m/s)
- Situation 2: Maximum displacement of the piston in 8 seconds (0.08 m/s)

– Situation 3: Maximum displacement of the piston in 12 seconds (0.05 m/s)

– Situation 4: Maximum displacement of the piston in 16 seconds (0,04 m/s)

– Situation 5: Maximum displacement of the piston in 20 seconds (0,03 m/s)

After the simulation, the height developed by the boom lifting closed structure is the following (taking Height as the difference between the lowest point and upper for each situation in the vertical axis):

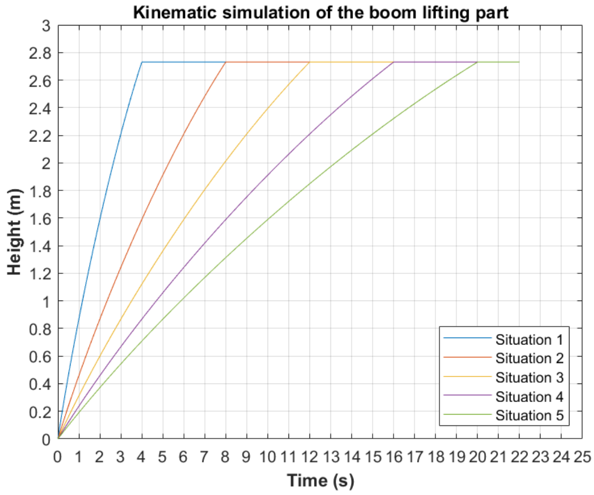

Figure 39. *Kinematic simulation for the boom lifting structure*

Telescoping cylinder

Velocities of the telescopic cylinder taken:

– Situation 1: Maximum displacement of the piston in 4 seconds (0,50 m/s)

– Situation 2: Maximum displacement of the piston in 8 seconds (0,25 m/s)

– Situation 3: Maximum displacement of the piston in 12 seconds (0,17 m/s)

– Situation 4: Maximum displacement of the piston in 16 seconds (0,13 m/s)

– Situation 5: Maximum displacement of the piston in 20 seconds (0,10m/s)

After the simulation, the height developed by the telescope part of the boom is 1,60m as is shown in the following figure:

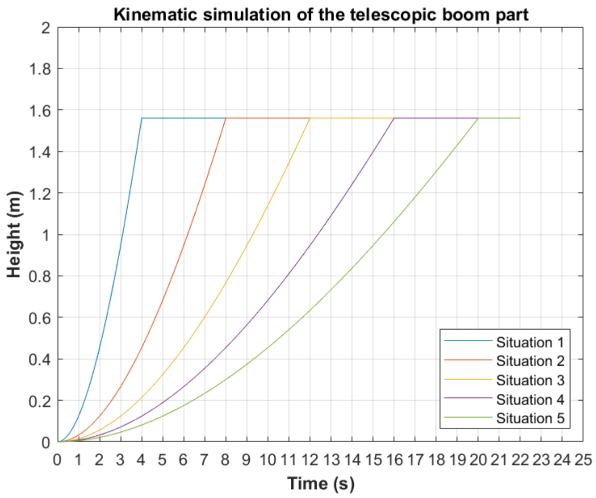

Figure 40. *Kinematic simulation for the telescope structure*

Considering the height as the distance between the lowest and upper part of the telescope in the vertical axis, and considering that has the maximum angle of the boom lifting part, because the telescope part is inside the boom lifting structure and has always the same angle.

Leveling basket cylinder

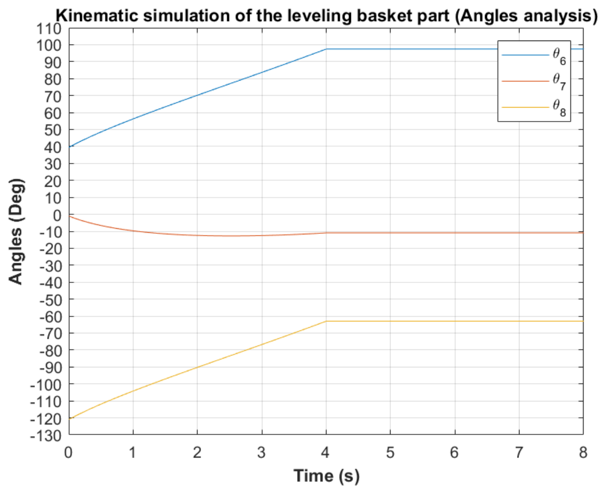

Figure 41. *Kinematic simulation for the telescope structure (Situation 1)*

- Situation 1: Maximum displacement of the piston in 4 seconds (0,08 m/s)
- Situation 2: Maximum displacement of the piston in 8 seconds (0,04 m/s)
- Situation 3: Maximum displacement of the piston in 12 seconds (0,03 m/s)
- Situation 4: Maximum displacement of the piston in 16 seconds (0,02 m/s)

– Situation 5: Maximum displacement of the piston in 20 seconds (0,01 m/s)

Jib cylinder

Velocities of the jib cylinder taken:

– Situation 1: Maximum displacement of the piston in 4 seconds (0,17 m/s)

– Situation 2: Maximum displacement of the piston in 8 seconds (0,08 m/s)

– Situation 3: Maximum displacement of the piston in 12 seconds (0,06 m/s)

– Situation 4: Maximum displacement of the piston in 16 seconds (0,04 m/s)

– Situation 5: Maximum displacement of the piston in 20 seconds (0,03 m/s)

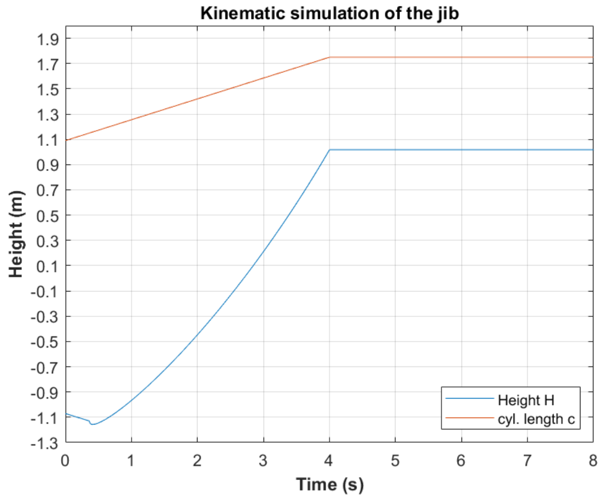

Figure 42. *Kinematic simulation for the jib structure (Situation 1)*

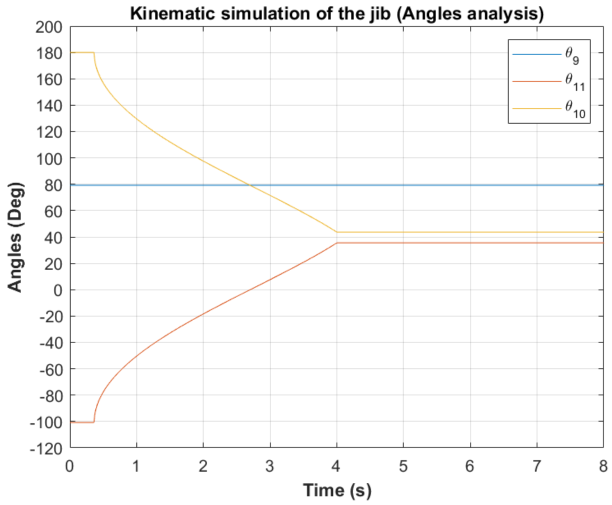

Figure 43. *Angles analysis for the jib structure*

5.1.4 Upper boom hydraulics

Boom lifting cylinder

The flow rate needed for the Boom lifting cylinder for each speed taken is:

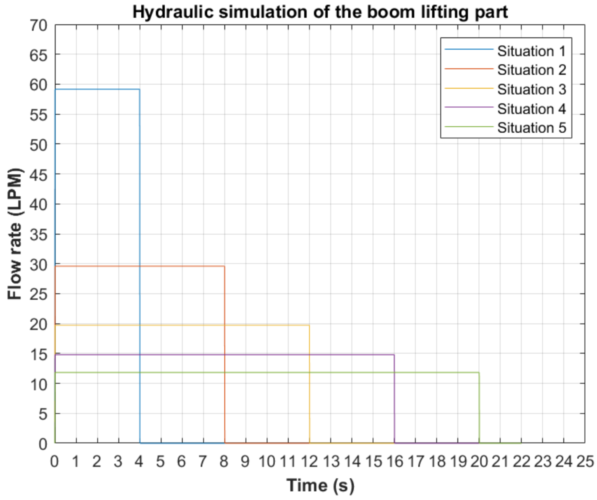

Figure 44. *Hydraulic simulation for the boom lifting cylinder*

- Situation 1: Flow rate of 59,16 LPM needed
- Situation 2: Flow rate of 29,60 LPM needed
- Situation 3: Flow rate of 19,72 LPM needed
- Situation 4: Flow rate of 14,80 LPM needed
- Situation 5: Flow rate of 11,83 LPM needed

Telescopic cylinder

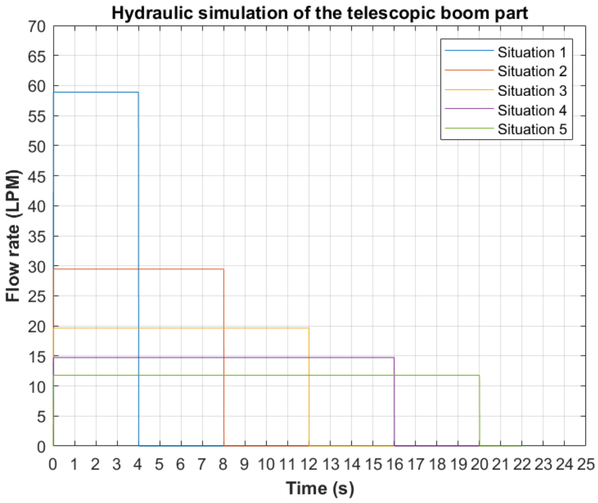

Figure 45. *Kinematic simulation for the telescope cylinder*

The boom lifting part and the telescope hydraulics are remarkably similar:

– Situation 1: Flow rate of 58,90 LPM needed

– Situation 2: Flow rate of 29,45 LPM needed

– Situation 3: Flow rate of 19,63 LPM needed

– Situation 4: Flow rate of 14,72 LPM needed

– Situation 5: Flow rate of 11,78 LPM needed

Leveling basket cylinder

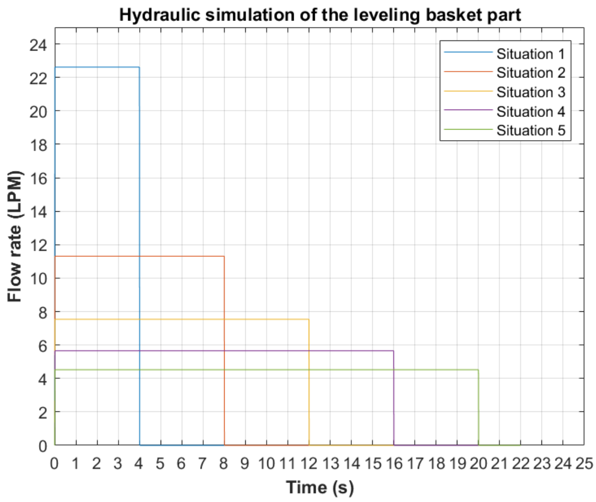

Figure 46. *Hydraulic simulation for the leveling basket cylinder*

– Situation 1: Flow rate of 22,62 LPM needed

– Situation 2: Flow rate of 11,31 LPM needed

– Situation 3: Flow rate of 7,54 LPM needed

– Situation 4: Flow rate of 5,66 LPM needed

– Situation 5: Flow rate of 4,52LPM needed

Jib cylinder

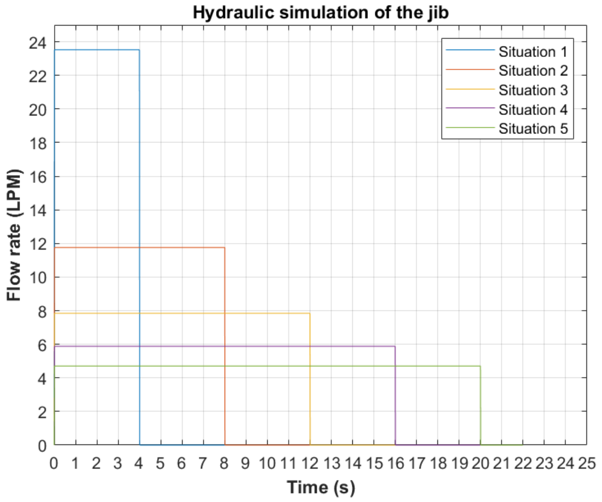

Figure 47. *Hydraulic simulation for the jib cylinder*

- Situation 1: Flow rate of 23,52 LPM needed
- Situation 2: Flow rate of 11,77 LPM needed
- Situation 3: Flow rate of 7,84 LPM needed
- Situation 4: Flow rate of 5,89 LPM needed
- Situation 5: Flow rate of 4,71 LPM needed

5.2 Mobile platform simulation

Straight path

When the mobile platform is going straight at its maximum velocity (set as input of 1,4 km/h or 0,4 m/s, as discussed previously), the flow rate for each travel motor is **15,83 LPM**, the total flow needed for the complete mobile platform is **63 LPM**.

This total value is exactly the maximum flow rate that the main pump can supply, therefore it is verified that 1,4 km/h is the maximum vehicle velocity.

(Eq. 30) $$Q\ (LPM) = \frac{Dm\ (cm^3) \cdot nm(RPM)}{1000}$$

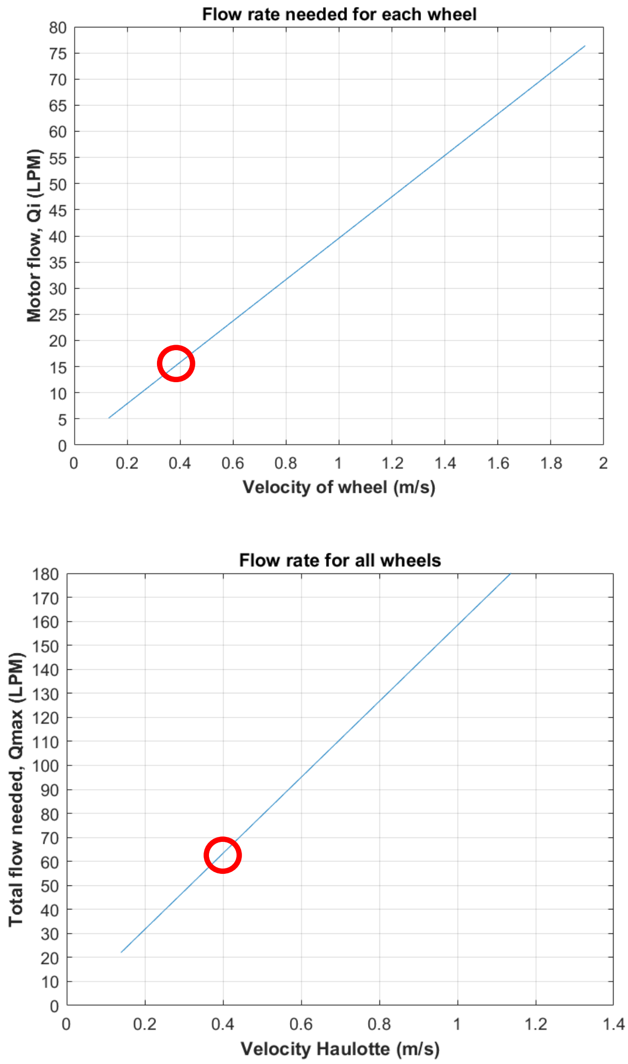

Figure 48. *Flow needed for each wheel (above) or for the 4 wheels (below)*

Turning path:

When the mobile platform is turning as the input set (figure below), the velocities of the right or left wheels experiment the highest velocity states.

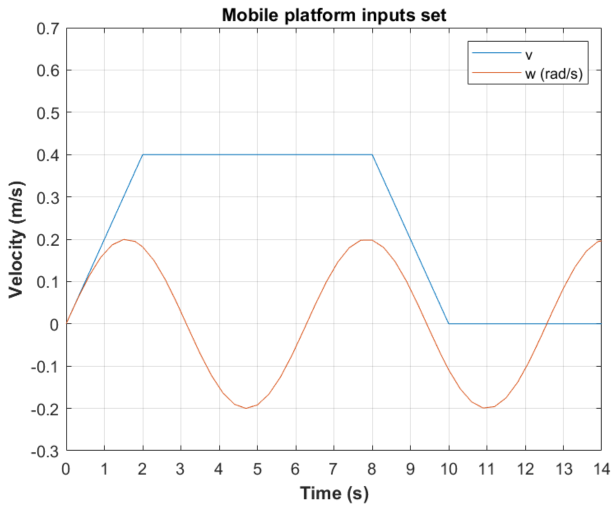

Figure 49. *Inputs set (Randomly set a deceleration at 8 seconds until the mobile stops at 10 seconds, just to analyze the flow rate perfomance.)*

- 0,56 m/s for each outer wheel (22,17 LPM flow rate each)
- 0,23 m/s for each inner wheel (9,13 LPM flow rate each)

The total amount of flow needed is again **63 LPM** due to the kinematic constraints. In other words, the velocity Input of the Haulotte mobile is the same when is turning as when is going straight.

The outputs (Steering angles and velocities for the wheels, variables introduced in 3.1) are shown in the picture below:

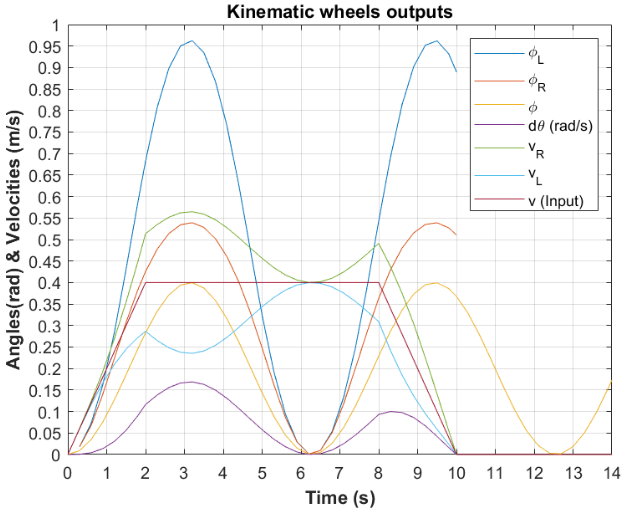

Figure 50. *Outputs obtained for the wheels.*

When the time *t* is 6,2 seconds due to the sinewave input, the mobile platform is finishing the turning and is almost going straight so the different wheel velocities are almost the same value as when the Haulotte is driving completely straight (steering angles of the wheels are 0 rad).

5.3 Base simulation

The hydraulic performance of the base or turret of the boom is easy to obtain from the (Eq. 30).

As indicates the summary of hydraulic actuators in Summary of hydraulic actuators in 4.5, the maximum rpm the base can develop is 375 rpm, then the maximum flow rate supplied is **59,85 LPM.**

The hydraulics for the base actuator can be seen in the plot below.

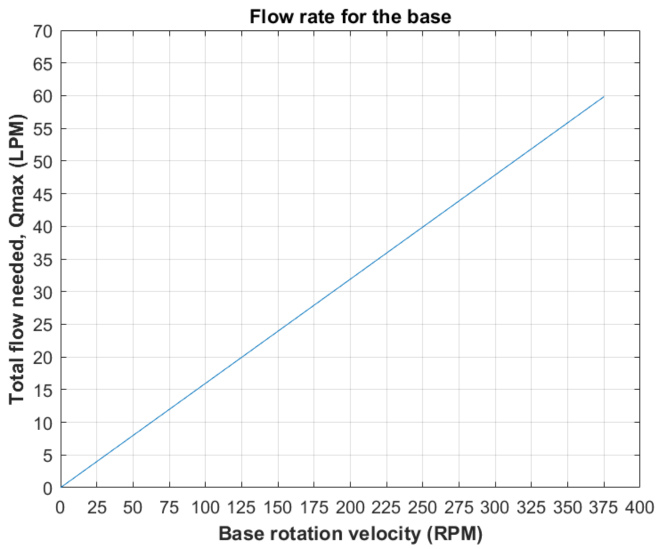

Figure 51. *Flow needed for the base depending on its rotation velocity*

If the base is moving at maximum RPM, is not possible to supply more flow to the rest of the actuators at the same time.

The gear ratio of the base/turret motor is unknown so is not possible to deduct the time that the base takes for rotating 360 degrees, the 375 rpm maybe is a very high value and is not necessary to be that fast, in other words, if the RPM are lower is possible to activate another actuator for the boom or even to move the mobile platform (at very low velocity) because there is hydraulic power available in the main pump.

6. CONCLUSIONS

The maximum flow rate supplied by the main pump, as calculated in 2.3 by means of the equation (Eq. 1), is 63 LPM, therefore, is not possible to supply more than this amount of liters per each minute.

All the flow rates for each actuator and for the five situations considered (4, 8, 12, 16 or 20 seconds until the complete stroke) are summarized in Table 18, below.

The red cells indicate is not possible to develop the complete stroke that fast for the actuator because the 63 LPM limit is surpassed.

Table 18. *Hydraulic summary comparison for boom actuators*

Q flow rate (LPM)	**Situation 1**	**Situation 2**	**Situation 3**	**Situation 4**	**Situation 5**
Time for the maximum. extension	4 s	8 s	12 s	16 s	20 s
Arm lifting cylinder	87,52	49,55	33,05	24,80	19,82
Boom lifting cylinder	59,16	29,60	19,72	14,80	11,83
Telescope cylinder	58,90	29,45	19,63	14,72	11,78
Basket leveling cylinder	22,62	11,31	7,54	5,66	4,52
Jib cylinder	23,52	11,77	7,84	5,89	4,71
All the boom at the same time	251,72	131,68	87,78	65,87	52,66

If all the boom's actuators were activated at the same time, the situation 5 is the only possible situation, the boom would reach the maximum height in 20 seconds.

Scenario 1

Considering the main pump is just supplying hydraulic oil to one system, the boom, or the mobile platform, but is not supplying oil to both of the systems at the same time.

<u>Scenario 1A:</u>

The Scenario 1A is produced when all the oil flow is being pumped to the mobile platform.

The hydraulic behavior is shown already in 5.2.

The maximum speed taken, due to the main pump capacity, is 0,4 m/s (1,4 km/h).

<u>Scenario 1B:</u>

In this situation or scenario, the Haulotte is already in the desired location, so the pump is always supplying oil to the boom, not to the wheels.

In this case, as shown in the previous table, if all actuators were activated at the same time to reach the maximum stroke of each one, the minimum time to get it would be 20 seconds.

If only the lower boom is required, the minimum time to open at maximum the scissor like structure (boom's arms) would be 8 seconds. When only the upper boom is required there are more combinations, as can be seen in the table above.

Scenario 2

In this situation the main pump is supplying half of its capacity for the boom and the other half for the mobile platform, in other words, the Haulotte is moving at the same time as the boom ins gaining height.

Then the maximum speed that the mobile platform can move is 0,20 m/s (0,72km/h), because 31,5 LPM is the amount of flow that is being supplied by the pump to this system (50% of its capacity).

On the other hand, 31,5 LPM is being supplied for the boom system (the other 50%). In this scenario and for activating all the actuators at the same time would be necessary simulate another situation which the maximum extension would be around 50 seconds or 1 minute, because for the Situation 5 (20 seconds) the boom needs minimum 52,66 LPM.

With the simulations already done, we consider that when the mobile platform is moving at 0,20 m/s then the upper boom can be activated at the same time (will take around 20 seconds for the complete extension) but the lower boom has to remain static. In the situation reversed, when the Haulotte is moving at 0,20 m/s, then the lower boom can be activated in 13 seconds (around), but the upper boom must remain static.

There are other multiple combinations (by the table above) but in all of them the lower boom (arm lifting cylinder) and the boom lifting and telescope cylinder will need quite more time than other hydraulic structures for the complete extension.

All of this considering the base is not rotating. If this hydraulic motor is being activated as well at the same time, then there are more hydraulic combinations but all of them will take an exceedingly long time to being the maximum of the boom height reached. Is not simulated but will take more than one minute which can make the boom not very functional for some purposes.

7. BIBLIOGRAPHY

[1] Henri Liikanen, Modelling, Simulation and Path-following Control of Heavy-Duty Wheeled Mobile robots, Tampere University of Technology, 2018, pp 13-18.

[2] Joni Grönholm, Jyrki Tirkkonen, Haulotte after Beckhoff, Tampere University of Technology, 2018, pp 4 - 24.

[3] Joni Grönholm, Haulotte Boom Report, Tampere University of Technology, 2018, pp 1 - 7.

[4] Joni Grönholm, Haulotte Boom Report, Tampere University of Technology, 2018, pp 12-14.

[5] Jyrki Tirkkonen, Haulotte 16RTJ PRO Hydraulic Systems, Tampere University of Technology, 2017.

[6] K. M. Lynch, F.C. Park, Modern Robotics, Mechanics, Planning and Control, University Printing House, Cambridge, United Kingdom, 2017, pp 524-528.

[7] Kubota, Workshop Manual WSM Diesel Engine 05-E2BG SERIES, ISSUU, p 10, https://issuu.com/1637912/docs/kubota_v1505-t-e2b_diesel_engine_se

[8] Majura F. Selekwa, Jonathan R. Nistler, Path Tracking Control of Four Wheel Independently Steered Ground Robotic Vehicles, 50TH IEEE Conference on Decision and Control and European Control Conference (CDC-ECC), 2011, pp 1-4, https://ieeexplore.ieee.org/document/6160677

[9] Paolo Tamburrano, Andrew R. Plummer, Elia Distaso and Riccardo Amirante, A review of Electro-Hydraulic Servovalve Research and Development, Research Gate, 2018, https://www.researchgate.net/publication/337030340_A_Review_of_Electro-Hydraulic_Servovalve_Research_and_Development

[10] Springer, Berlin, Heidelberg, Omni-Directional Robots in Embedded Robotics, 2008, pp 147-156. https://doi.org/10.1007/978-3-540-70534-5_9

[11] Yasser Anis, Position Analysis, Cairo University, 2015, https://scholar.cu.edu.eg/?q=anis/files/week04-mdp206-position_analysis-draft.pdf

[12] Wada Masayoshi, Research for an Omnidirectional Mobile Robot using ACROBAT, the Active-caster with a Dual ball Transmission, 2015, https://www.researchgate.net/figure/Omnidirectional-robot-with-three-omni-wheels

[13] Website of Haulotte machines, PDF data sheet catalogues, https://pdf.directindustry.com/pdf/haulotte/ha16-rtj-pro/7665-643723-_2.html

[14] Website of Haulotte, PDF Spare parts,55, http://hlt-group.com.ua/pic/file/k%D0%B0%D1%82%D0%B0%D0%BB%D0%BE%D0%B3%20%D0%B7%D0%B0%D0%BF%D1%87%D0%B0%D1%81%D1%82%D0%B5%D0%B9%20%E2%84%96%204000509190.pdf