MASTER THESIS

Automated Guided Vehicles for commercial aircraft manufacturing industry

Albert Grau Calvó

SUPERVISED BY

Juan Andrade Cetto
Adeline de Villardi de Montlaur

Universitat Politècnica de Catalunya
Master in Aerospace Science & Technology
April 2015

Automated Guided Vehicles for commercial aircraft manufacturing industry

BY

Albert Grau Calvó

DIPLOMA THESIS FOR DEGREE

Master in Aerospace Science and Technology

AT

Universitat Politècnica de Catalunya

SUPERVISED BY:

Juan Andrade Cetto

Director, Institut de Robòtica i Informàtica Industrial, CSIC-UPC

AND:

Adeline de Villardi de Montlaur

Associate professor at UPC and member of LaCàN research group

ABSTRACT

The automation level of the commercial aircraft manufacturing industry is growing every day. Its manufacturing procedures are changing due to the wide introduction of carbon fibre reinforced polymers and to the aim of achieving higher productivity with less waste according to lean manufacturing. For this reason, it is necessary to reduce and optimize all the operations that add no value to the production process.

Automated Guided Vehicles (*AGVs*) are an alternative to such optimization of operations. They will play a key role in the following decades inside commercial airplane production factories, assuming the logistics of all types of material, from small bolts to large airplane assemblies.

In order to move large airplane assemblies it is necessary to design vehicles with high manoeuvrability, different than the industrial *AGVs* currently used in intralogistics. The aim of this Master Thesis is to find which are the most adequate designs of *AGVs* in order to use them in the aerospace industry.

The *AGVs* currently working in the industry have been studied and their kinematic constrains have been analysed. We realized that the *AGVs* currently in use do not satisfy the application demands on mobility and flexibility. Their wheel arrangements are very simple and the vehicles are not omnidirectional.

It is necessary to find new wheel arrangements that allow the design of *AGVs* capable to move in any direction and rotate from any point. The Swedish wheels have rollers attached to the wheel perimeter that add an extra degree of freedom to the wheel and allow the vehicles to move omnidirectionally.

In this Master Thesis we propose a range of AGV configurations with omnidirectional manoeuvrability. Some of these designs have already been developed at the firm Aritex. We present empirical evaluation and experiences of their use in the aircraft manufacture industry. As a conclusion, it is expected that in the near future, the technology of *AGVs* with Swedish wheels will be widely present in the factories of commercial aircrafts.

TABLE OF CONTENS

List of figures

All the figures without citation are property of the author and can not be reproduced without permission.

List of tables

List of abbreviations

AGV	Automated Guided Vehicle
AIRBUS	Airbus S.A.S.
ARITEX	Aritex Cading (Compsa Empte Group)
BOEING	*The Boeing Company*
CAMI	Commercial Airplane Manufacturing Industry
CFRP	Carbon Fibre Reinforced Polymer
COMAC	Commercial Aircraft Corporation of China
CWB	Centre Wing Box
DF	Degrees of Freedom
EMBRAER	Embraer S.A.
HTP	Horizontal Tail Plane
ICR	Instantaneous Centre of Rotation
FAL	Final Assembly Line
FEM	Finite Elements Method
MGV	Manually Guided Vehicle
MHS	Material Handling System
MW	Main Wing
SAGV	Semi Automated Guided Vehicle
SPMU	Self Propelled Modular Unit
SKU	Stock-keeping Unit
VTP	Vertical Tail Plane
WFA	Wing Final Assembly
WMS	Warehouse Management System

List of symbols

$\{X_I\ ,\ Y_I\}$	Global reference frame
$\{X_R\ ,\ Y_R\}$	Local reference frame
O	Origin of global reference frame
P	Origin of local reference frame
C	Instantaneous centre of rotation
θ	Angle between global reference frame and local reference frame
β	Angle between wheel plane and the vehicle frame
ξ_I	Position of the vehicle in global reference
$\dot{\xi}_I$	Speed of the vehicle in global reference
ξ_R	Position of the vehicle in local reference
$\dot{\xi}_R$	Speed of the vehicle in global reference
$R(\theta)$	Orthogonal rotation matrix
$\dot{\varphi}_i$	Rotation speed of wheel *i*
d	Wheel diameter
r	Wheel radius
i	Reduction ration of wheel gearbox
Z_c/Z_p	Reduction ration of steering system
$\dot{x}_{wi}$	Vehicle motion in X-axis produced by wheel *i*
$\dot{y}_{wi}$	Vehicle motion in Y-axis produced by wheel *i*
$\dot{\theta}_{wi}$	Vehicle rotation around Z-axis produced by wheel *i*
L	Length
W	Width
H	Height
H_b	Height of the vehicle base without secondary system
m	Mass
PL	Payload
δ_M	Degree of manoeuvrability
δ_m	Degree of mobility
δ_s	Degree of steerability
n_{cm}	Number of control motors

INTRODUCTION

One of the objectives of the master thesis is to study the state of the art of Automated Guided Vehicles used in industry. The main objective is to propose how *AGVs* could be applied to commercial aircraft manufacturing industry and which tasks could be performed by these *AGVs*. The final objective is to find the best wheel configurations to use for the *AGVs* in the aerospace industry.

The methodology that is going to be used to achieve the objectives is:

- Research academic papers about omnidirectional vehicles.
- Research current manufacturers of *AGV*s and their solutions.
- Analyse the different approaches to *AGV*s found in the previous points. Type of wheels, number of wheels, geometrical disposition of the wheels, etc.
- Compare the different approaches to *AGVs* found and analyse their strengths and weaknesses.
- Propose innovative wheel arrangements for *AGVs.*
- Analyse the proposed innovative wheel arrangements and find applications in the commercial aircraft manufacturing industry for them.
- For each configuration, formulate closed kinematic expressions: calculate the required rotation speed of each wheel for a given vehicle velocity.

An overview of the commercial aircraft manufacturing industry and the possible roles of the *AGV*s in this industry is given in Chapter 1. The theoretical fundamentals used to generate the control matrices of *AGVs* are given in the Chapter 2. The state of the art of *AGVs* used in industry is studied in Chapters 3 and 4. Innovative *AGV* configurations with high manoeuvrability are proposed and studied in Chapter 5. These include the use of Swedish wheels, which are also overviewed in Chapter 5. Chapter 6 is devoted to concluding remarks.

Chapter 1

AGVs IN THE AIRPLANE MANUFACTURING INDUSTRY

The objective of this chapter is to give an overview of the Commercial Aircraft Manufacturing Industry and to find why Automated Guided Vehicles will be important in this industry and which will be the functions of these vehicles.

1.1. Overview of the commercial aircraft manufacturing industry

The manufacturing procedures used in the commercial aircraft factories are changing due to the wide introduction of Carbon Fibre Reinforced Polymers (*CFRP*) in the main parts of all the aircrafts and due to the automation of the manufacturing processes.

Every day, larger one-piece parts of *CFRP* are manufactured in the commercial aircraft industry. For instance, the skins of the horizontal tail plane and vertical tail plane of the A380 aircraft were the largest parts manufactured in *CFRP* by *AIRBUS* in the first decade of the 21st century (the wings of the A380 are not manufactured in *CFRP*). However, nowadays *AIRBUS* is manufacturing A350's wings in *CFRP*. The wing shells of the A350, manufactured in Stade (Germany) and Illescas (Spain), are the largest integrated carbon fibre components ever made by *AIRBUS*.

It is necessary to move the large moulds of the parts manufactured with *CFRP* from the lamination zone to the autoclave in order to cure the aircraft parts. Vehicles with good manoeuvrability and large payload are required for such manufacturing process.

The use of *CFRP* allows the aircraft manufacturers to create aircrafts with more aerodynamic wings. Current aircrafts like the *BOEING* 777 are renewed to improve performance and reduce fuel consumption. The *BOING* 777X will be the new version of the triple 7 with wings manufactured in *CFRP* [15].

The Chinese government-owned company *COMAC* plans to be a competitor of *AIRBUS* A320 and *BOEING* 737 in the future with the *COMAC* C919. Currently, the *COMAC* C919 program is under development and the first flight of the C919 is expected to take place during 2015. The production rate of the C919 will grow in the next decade to satisfy the hundreds of firm orders from the internal market [19].

In such commercial aircraft manufacturing industry it is necessary to move parts with very large dimensions. In order to carry out this task, dedicated vehicles or transport systems are used.

The purpose of this Master Thesis is to study what are the best configurations to manufacture Automated Guided Vehicles for the commercial aircraft manufacturing industry.

1.1.1. New materials in commercial aircrafts

Every day carbon fibre reinforced polymers are more present in the Commercial Aircraft Manufacturing Industry. The A380 was a masterpiece of engineering of the 1st decade of the century and the *CFRP* were widely used. However, the *BOEING 787* and the *AIRBUS A350* have gone one steep ahead; with all of their large subassemblies being manufactured with *CFRP*.

The newer the airplane, the higher the percentage of *CFRP* in it; and subsequently, its manufacturing procedures need to change to accommodate for such extended use of large assemblies of *CFRP* parts, and to the automation of the manufacturing procedures in general.

It in not easy to introduce the large *CFRP* parts into the autoclave; it is necessary to use dedicated dollies and push tractors or it is possible to automatize the procedure using *AGVs.*

The plot shown in Figure 1.1 displays the abovementioned large growth in the use of composites in the Commercial Aircraft Manufacturing Industry. The images shown in Appendix A.1 show the materials used for the aircrafts *A380, BOEING 787* and *A350.*

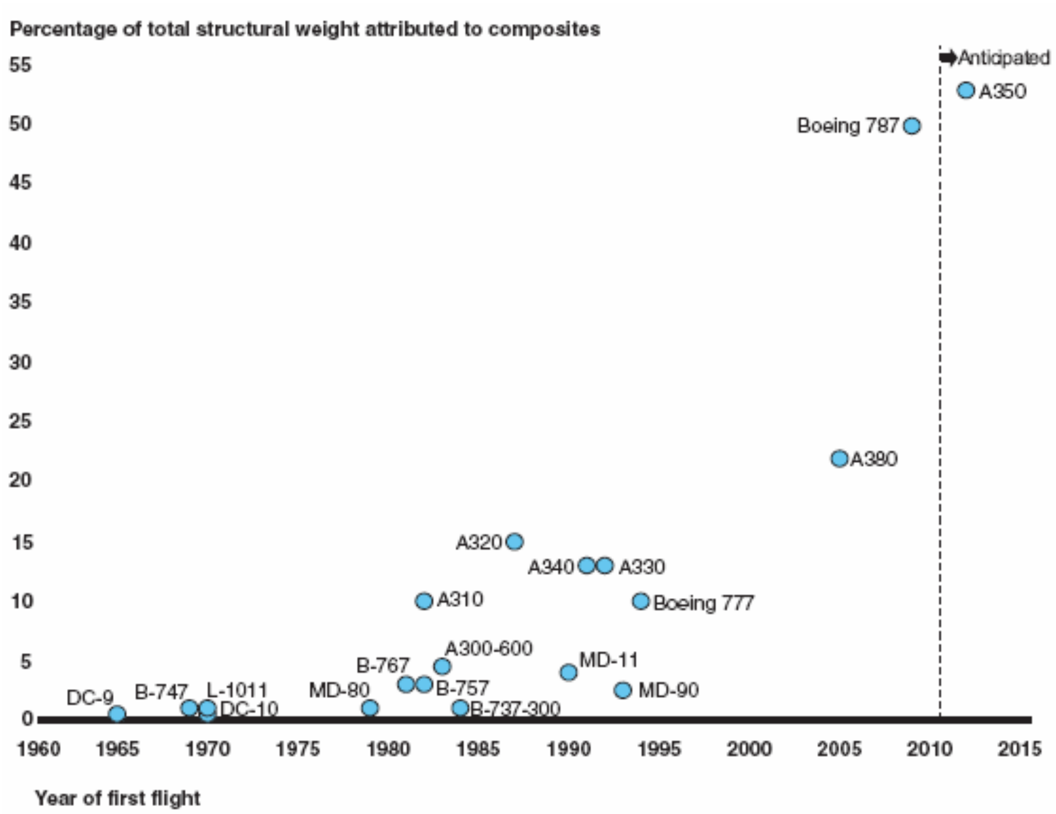


Figure 1.1 Commercial Airplane Models over Time by Percentage of Composites **[7]**

1.1.2. Handling systems used in commercial aircrafts manufacturing industry

There are different options to move large parts inside the airplane manufacture factories. Usually the parts can be moved using overhead systems like monorails or gantry cranes; or ground based systems like carts and push tractors, dedicated conveyors or special vehicles. Some examples are given next.

Figure 1.2 shows a dedicated overhead transfer system used to assemble fuselage sections. Figure 1.3 shows a mobile line where the *A320* HTPs are completed. None of these systems is very flexible.

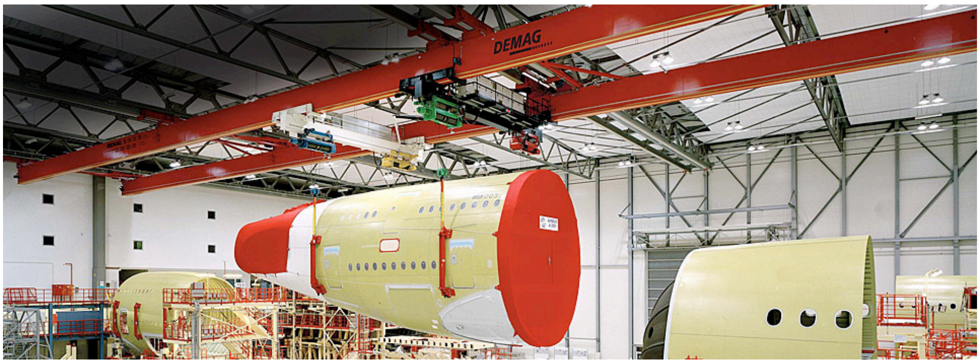


Figure 1.2 Overhead gantry crane dedicated to transport the fuselage sections **[21]**

Figure 1.3 Mobile line of A320 HTP manufactured by *ARITEX* **[11]**

It is possible to assemble the airplane parts in assembly carts or wheeled jigs. Then the manipulation of these carts is easier and more flexible. However it is necessary to use an external tractor to move these carts. An example is the *A320* wing dolly shown in Figure 1.4.

Figure 1.5 shows an assembly line to finish the *737* rudder. The rudder is assembled over a cart. This cart can be transferred between stations easily by pushing it. When the carts or the assembly jigs are much bigger it is necessary to use an external device to tug the cart. The external device to move the large wheeled loads can be a tractor with driver, an electric tug or automated solutions like *AGVs.*

Figure 1.4 *MASTERMOVER Tug* with A320 wing dolly **[30]**

Figure 1.5 *BOEING* Renton factory assembly line #1 in April 2013 **[10]**

Figure 1.6 shows how the large sections of the Airplane A380 are moved. The different fuselage sections are placed over an auxiliary structure. Then a radio-controlled vehicle is introduced below this auxiliary structure. The vehicle lifts the auxiliary structure with the fuselage and places the fuselage section in the desired position.

Figure 1.6 Dedicated vehicles to move *A380* section in the FAL **[14]**

1.2. *AGV* roles

Automated Guide Vehicles will take an important role in the commercial airplane manufacturing industry. *AGVs* can be used almost in all ground transports. *AGVs* allow having a very flexible automatic system dedicated to move goods inside the aircraft assembly factories.

The main functions of the *AGVs* in the commercial airplane manufacturing industry will be to automatize the following procedures:

- Logistics of large parts into the autoclave.
    - Stringer Curing Tools logistics from lamination zone to autoclave and from autoclave to assembly zone.
    - *CFRP* fuselage segments from constitution jig to autoclave.
    - *CFRP* wing skin, *HTP* skin and *VTP* skin from lamination zone to autoclave.
- Transfer and positioning of fuselage segments.
- Flow of the assembly jigs in an assembly line.
- Flow of the aircraft in the Final Assembly Lines.
    - Assembly and positioning of wings in the *FAL*.
    - Assembly and positioning of the landing gear in the *FAL.*
    - Assembly and positioning of the aircraft engines in the *FAL.*
- Logistics of auxiliary material and tools in the *FAL* or in other assembly lines.

Nowadays semi automatic vehicles are already used in the following procedures:

- Extraction of large assemblies from assembly jigs.
    - *HTP* extraction from vertical assembly jig, turn over and transport.
    - *VTP* extraction from vertical assembly jig, turn over and transport.
    - Fuselage panels extraction and transport from milling and riveting machine.
- Movement of assembly jigs between stations:
    - *CWB* Assembly line.
- Assembly of large parts in the fuselage in the *FAL*.
    - Wing final assembly.
- Movement of airplane fuselage in the *FAL.*

1.3. *AGV* requirements

The main requirements for the use of *AGVs* in the commercial aircraft industry are:

- High payload.
  - Form less than 1 Tm to 20 Tm or more.
  - From 1,5 Tm to 3,5 Tm per wheel.
- Move large components or subassemblies.
- High manoeuvrability. To move large components it is necessary be able to move the *AGV* in any direction and rotate from any point.
- No combustion engines or hydraulics systems if the *AGV* is used with fresh *CFRP* in order to avoid contamination.
- Battery autonomy range from 1km to 10km.
- Positioning precision up to $\pm$10mm in many applications.
- Possibility to optimize routes.
- Collision avoidance system.

The dimensions of some aircraft subassemblies that are mentioned in this master thesis are listed in Table 1.1. This table gives and idea of how are the parts that could be handled by *AGVs.*

The overall dimensions of all the airplanes mentioned in the text are given in Appendix A.2.

Table 1.1 Example of airplane subassembly dimensions and weight

Airplane	Part	Weight (kg)	Dimensions (m)		
			L	W	H
COMAC C919	*CWB*	1.500	2,8	4,2	1
	HTP box	1.200	1,2	6,5	0,4
	VTP box	600	3,5	0,6	6,4
	HTP mould	8.000	9	2,5	1
	Wing mould	20.000	19	4,5	1,1
	HTP mould support	5.000	9	3,7	0,8
AIRBUS A330	CWB	6.000	5,5	6,2	2,6
AIRBUS A350	*HTP box*	625	3	11	0,7
	VTP box	1.100	10,5	0,9	9,5
	Keel beam	1.500	16,5	4	1
EMBRAER E190-E2	Wing	4.500	16,5	4,2	1
BOEING 777X	Wing stringers	-	4 – 34	1,5	0,1

Chapter 2
THEORETICAL BACKGROUND OF WHEELED VEHICLES

The objective of this chapter is to introduce the theoretical fundamentals that are used to find the control matrices of the *AGVs* studied in the Chapters 4 and 5.
The theoretical fundamentals of this chapter come from the book *Introduction to Autonomous Mobile Robots* **[1]**.

2.1. Wheeled mobile platforms

2.1.1. Wheel design

The four basic wheel types are:

A. Standard wheel. Two degrees of freedom; rotation around the wheel axle and rotation around the contact point.

B. Castor wheel. Two degrees of freedom; rotation around the wheel axle and rotation around an offset steering joint.

C. Spherical wheel. The spherical wheel has no principal axis of rotation and then it has three degrees of freedom; rotation around an axis placed parallel to the ground (2 *DF*) and rotation around the contact point.

D. Swedish wheel. Three degrees of freedom; rotation around the wheel axle, rotation around the rollers, and rotation around the contact point.

These wheels can be unpowered or motorized in order to control the vehicle position. Then the wheels can be categorized in the following groups:

A1. Unpowered standard wheel
A2. Motorized standard wheel
A3. Steered standard wheel
A4. Motorized and steered standard wheel

B1. Free castor wheel
B2. Steered castor wheel
B3. Motorized and steered castor wheel

C1. Free spherical wheel
C2. Motorized spherical wheels

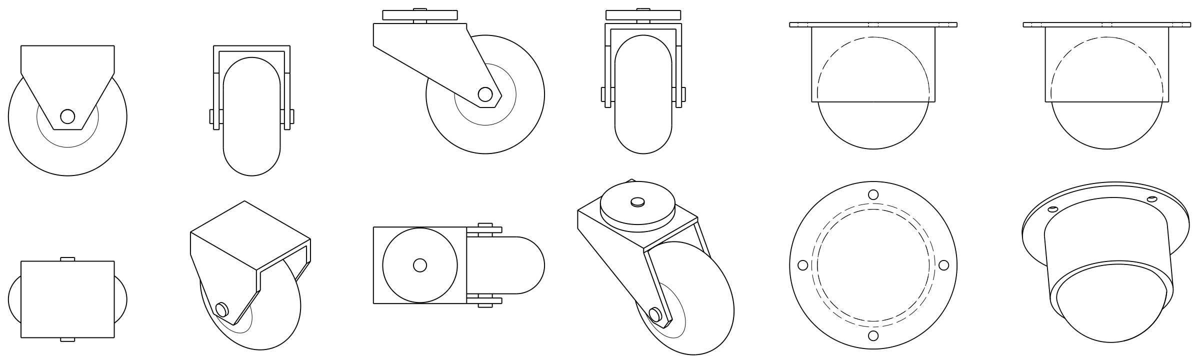
D1. Unpowered 45º Swedish wheel
D2. Motorized 45º Swedish wheel
D3. Unpowered 90º Swedish wheel
D4. Motorized 90º Swedish wheel

The spherical wheels are not used in the industrial environment because the payload per wheel is low and the design of the wheel itself is not easy. For this reason the spherical wheels are not present in the following chapters.

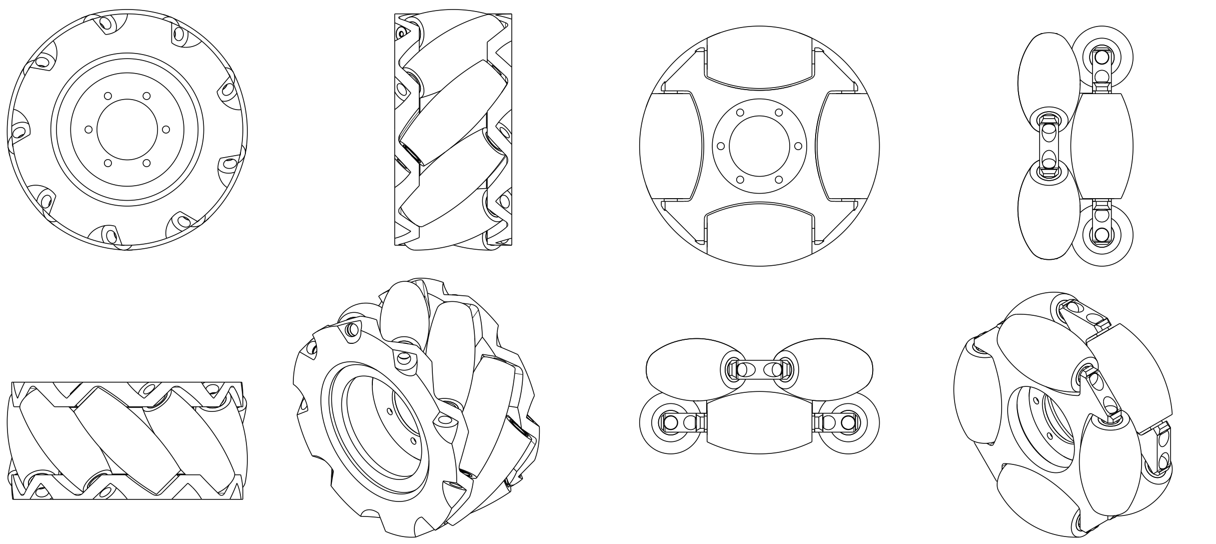
The caster wheels usually are not motorized; they are used to increase the stability of the vehicle and to distribute the load over additional contact points. For these reasons the motorized casters have no presence in the following chapters.

Sometimes the standard wheels are linked using a steering system that pivots 2 wheels at the same time like in the Ackermann steering system.

Figure 2.1 shows the different wheel types described above.



A. Standard wheel *B. Caster wheel* *C. Spherical wheel*



D1. 45º Swedish wheel *D3. 90º Swedish wheel*

Figure 2.1 Main views of the different wheel types

Figure 2.2 Commercial motorized wheel and driving & steering wheel **[18]**

Two examples of motorized wheels ready to install in industrial vehicles with 48V or 80V batteries are shown in Figure 2.2.

2.1.2. Stability

The static stability of the vehicle requires a minimum of three wheels and the centre of mass inside the triangle formed by the contact points of the three wheels. Stability can be improved adding more wheels, however then the geometry will be hyperstatic and a suspension will be required.

2.1.3. Manoeuvrability and controllability

The vehicles with Ackermann steering configuration, common in automobiles, require a turning diameter larger than the vehicle. Moreover the transversal movement of these vehicles is very limited and requires a manoeuvre consisting in repeat forward and backward movements combined with the steering system.

Other vehicles are able to move at any time in any direction along the ground plane regardless of the orientation of the vehicle around its vertical axis. These vehicles are omnidirectional; they can rotate from any point and translate in any direction with no constrains. Wheels with capability to move in more than one direction are required for this type of vehicles. Swedish or spherical wheels are used in omnidirectional vehicles.

Commonly there is an inverse correlation between controllability and manoeuvrability. An Ackerman steering vehicle (Figure 2.3) can go straight simply locking the steering system and driving the drive wheels. In a differential-drive vehicle (Figure 2.4) the two motors that control the wheels must have the same velocity. The difficulty is even harder on a four-wheels 45º Swedish vehicle because all the 4 wheels must have exactly the same speed, otherwise, the vehicle will not follow a straight line.

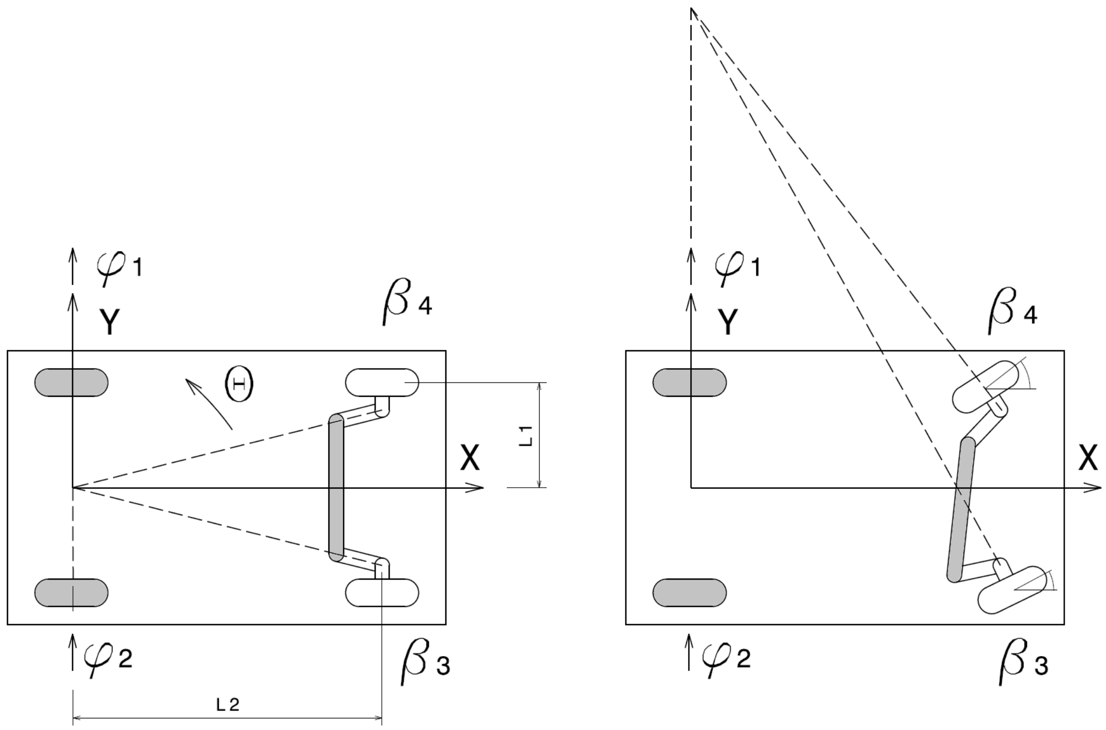


Figure 2.3 Schema of Ackermann steering vehicle

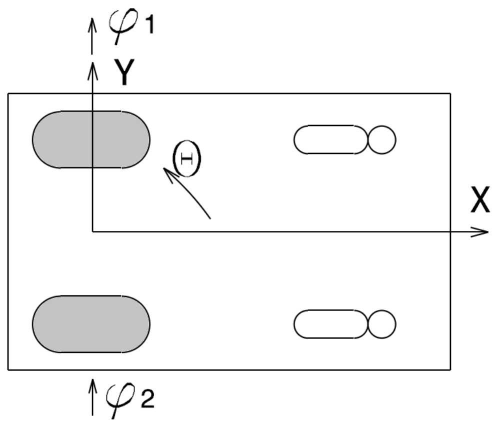


Figure 2.4 Schema of differential drive vehicle

2.2. Kinematic models and constraints

Considering the vehicle as a rigid body, the dimensionality of the vehicle on the plane is three; two for position in the plane and one for orientation along the vertical axis, which is orthogonal to the plane. The vehicle has internal variables such as the wheel rotation whose velocity can be related to the vehicle equations of motion according to the type of vehicle used (Ackerman, differential drive, etc).

To locate the vehicle on the plane it is necessary to:

- Define a local reference frame $\{X_R\ ,\ Y_R\}$ and a point P on the vehicle chassis as its position reference point.
- Define an arbitrary inertial basis as the global reference frame from some origin O: $\{X_I\ ,\ Y_I\}$.

Then the coordinates x and y give the position of P in global reference and the angle θ gives the angular difference between the global and local reference frames.

Position of the vehicle in global reference frame:

$$\xi_I = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} \tag{2.1}$$

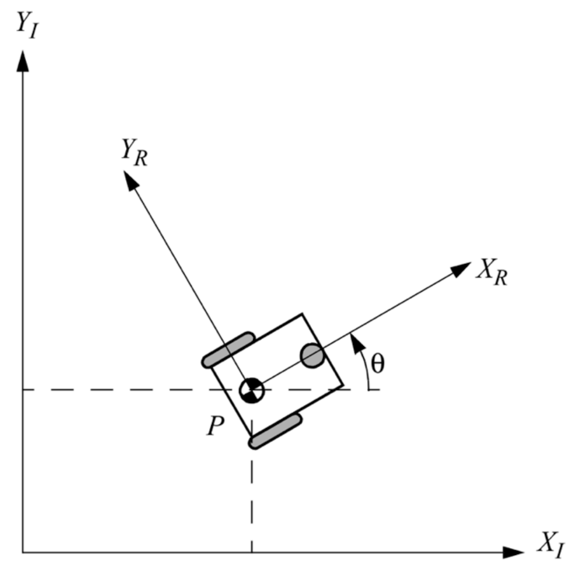


Figure 2.5 Global reference frame and local reference frame **[1]**

Then it is possible to define the vehicle velocity in global reference as:

$$\dot{\xi}_I = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{2.2}$$

An orthogonal rotation matrix can be used to map such velocity in the global reference frame, $\{X_I\ ,\ Y_I\}$ to motion in terms of the local reference frame $\{X_R\ ,\ Y_R\}$.

Orthogonal rotation matrix:

$$R(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \textbf{(2.3)}$$

Transformation from motion in global reference to motion in local reference:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix}_R = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix}_I \quad \textbf{(2.4)}$$

$$\dot{\xi}_R = R(\theta)\ \dot{\xi}_I \quad \textbf{(2.5)}$$

It is possible to invert the matrix $R(\theta)$ in order to find the vehicle velocity in the global reference frame from the motion of the vehicle in local reference.

$$R(\theta)^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \textbf{(2.6)}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix}_I = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix}_R \quad \textbf{(2.7)}$$

$$\dot{\xi}_I = R(\theta)^{-1}\ \dot{\xi}_R \quad \textbf{(2.8)}$$

2.2.1. Forward kinematic models

When the mobile vehicle is simple it is possible to find how the vehicle moves given its geometry and the speed of the wheels. A differential drive vehicle (like *KIVA Robot Drive Unit* or *SWISSLOG CarryPro* among others) has only 2 standard wheels with motor. It is easy to calculate the motion of the vehicle if the wheel speeds are known. The origin of the local reference is the point P in the middle of the two drive wheels, the wheel radius is r and the distance between the wheels and the origin is L_1. The rotational speed of the right wheel is $\dot{\varphi}_1$ and $\dot{\varphi}_2$ is the rotational speed of the left wheel.

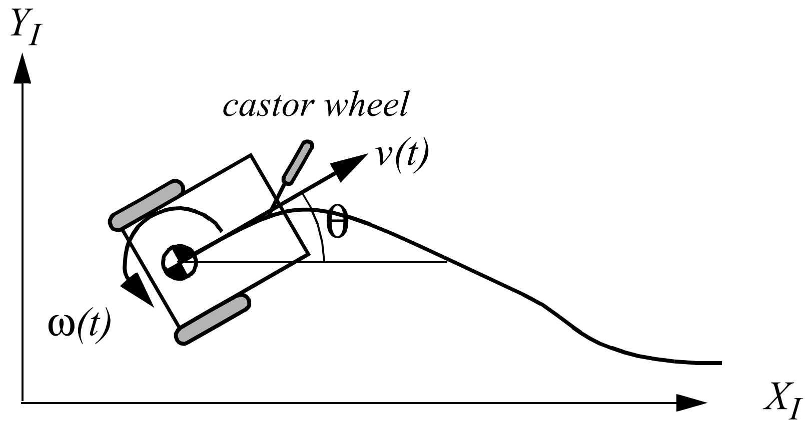


Figure 2.6 Differential drive vehicle **[1]**

It is possible to calculate the vehicle motion due to the speed of the wheels in local coordinates and then transform it to the global reference frame.

$$\dot{\xi}_R = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = f(L_1, r, \theta, \dot{\varphi}_1, \dot{\varphi}_2) \quad \textbf{(2.9)}$$

$$\dot{\xi}_I = R(\theta)^{-1}\, \dot{\xi}_R \quad \textbf{(2.10)}$$

If the right wheel spins with velocity $\dot{\varphi}_1$, while the left wheel is stopped, the vehicle will rotate with a speed $\dot{\theta}_{w1} = r\dot{\varphi}_1/L_1$ and the centre of the vehicle will move forward in $+X_R$ direction with half the linear speed of the wheel $\dot{x}_{w1} = \frac{1}{2} r\dot{\varphi}_1$. If left wheel spins while the right one is stopped; then the vehicle will rotate clockwise $\dot{\theta}_{w2} = -r\dot{\varphi}_2/L_1$ and move forward at linear speed $\dot{x}_{w1} = \frac{1}{2} r\dot{\varphi}_2$. None of the wheels introduce speed in Y_R.

Combining the results of the two wheels yields a kinematic model of the differential drive vehicle.

$$\dot{\xi}_R = \begin{bmatrix} \frac{r\dot{\varphi}_1}{2} + \frac{r\dot{\varphi}_2}{2} \\ 0 \\ \frac{r\dot{\varphi}_1}{2L_1} + \frac{-r\dot{\varphi}_2}{2L_1} \end{bmatrix} = \begin{bmatrix} \frac{r(\dot{\varphi}_1 + \dot{\varphi}_2)}{2} \\ 0 \\ \frac{r(\dot{\varphi}_1 - \dot{\varphi}_2)}{2L_1} \end{bmatrix} \tag{2.11}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix}_I = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \frac{r(\dot{\varphi}_1 + \dot{\varphi}_2)}{2} \\ 0 \\ \frac{r(\dot{\varphi}_1 - \dot{\varphi}_2)}{2L_1} \end{bmatrix}_R \tag{2.12}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix}_I = \begin{bmatrix} \cos\theta \frac{r(\dot{\varphi}_1 + \dot{\varphi}_2)}{2} \\ \sin\theta \frac{r(\dot{\varphi}_1 + \dot{\varphi}_2)}{2} \\ \frac{r(\dot{\varphi}_1 - \dot{\varphi}_2)}{2L_1} \end{bmatrix}_R \tag{2.13}$$

2.3. Wheel kinematic constraints

As described in Section 2.1.1, there are four basic wheel types. The kinematic properties of the vehicle are directly related with the type of wheels and their position. The motion of the vehicle can be computed combining the motion of the individual wheels.

The main assumptions that are taken into account in the kinematic analysis are:

- The wheel plane is always vertical and perpendicular to the floor.
- There is a single point of contact between the wheel and ground plane.
- There is no sliding of the wheel.

Then, the wheel suffers motion only due to pure rolling and rotation about the vertical axis.

There are two constraints that must be fulfilled by all wheels; the rolling constraint and the sliding constraint. In the following points we will see how are these equations depending on the wheel type.

- Rolling constraint → the wheel must roll when motion takes place in the appropriate direction.

- No sliding constraint → no lateral slippage; the wheel must not slide orthogonal to the wheel plane.

2.3.1. Fixed standard wheel

The position of the wheel from the vehicle frame $\{X_R\ ,\ Y_R\}$., is given by the polar coordinates of the point A: distance l and angle α. The wheel radius is r. β is the angle of the wheel plane relative to the chassis. If the wheel is fixed, then β is constant. If the wheel spins over time; the rotational position around its horizontal axle is a function of time t: $\varphi(t)$.

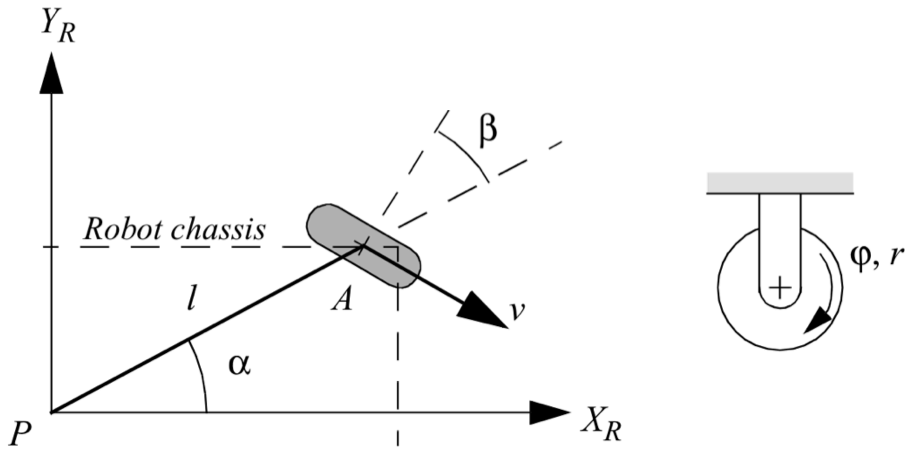


Figure 2.7 Fixed standard wheel and its parameters **[1]**

Rolling constraint fixed standard wheel

The rolling constraint for the fixed standard wheel imposes that all motion in the direction of the wheel plane must be equal to the motion accomplished by spinning the wheel, $r\dot{\varphi}$.

$$[\sin(\alpha+\beta),\quad -\cos(\alpha\ +\ \beta),\quad (-l)\cos\beta]\,R(\theta)\dot{\xi}_I - r\dot{\varphi}\ =\ 0 \qquad \textbf{(2.14)}$$

The first term of the rolling constraint is a vector of 1 row x 3 columns.

Sliding constraint fixed standard wheel

The sliding constraint for this fixed standard wheel imposes that the component of the wheel's motion orthogonal to the wheel plane must be zero.

$$[\cos(\alpha+\beta),\quad \sin(\alpha\ +\ \beta),\quad l\sin\beta]\,R(\theta)\dot{\xi}_I\ =\ 0 \qquad \textbf{(2.15)}$$

2.3.2. Steered standard wheel

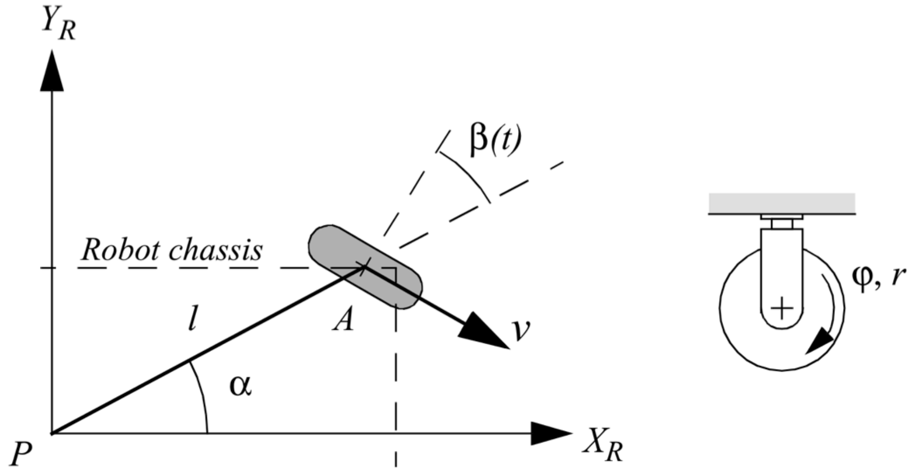


Figure 2.8 Steered standard wheel and its parameters **[1]**

The equations of the steered wheel (Figure 2.8) are identical to those of the fixed standard wheel shown in Figure 2.7 with one exception; the orientation of the wheel varies as a function of time: $\beta(t)$. The rolling and sliding constraints are identical to the fix standard wheel. The only difference is that the orientation of the wheel to the vehicle frame β is not constant. Instead, it varies as a function of time: $\beta(t)$.

Rolling constraint steered standard wheel

$$[\sin(\alpha+\beta), \quad -\cos(\alpha + \beta), \quad (-l)\cos\beta]\, R(\theta)\dot{\xi}_I - r\dot{\varphi} = 0 \tag{2.16}$$

Sliding constraint steered standard wheel

$$[\cos(\alpha+\beta), \quad \sin(\alpha + \beta), \quad l\sin\beta]\, R(\theta)\dot{\xi}_I = 0 \tag{2.17}$$

2.3.3. Castor wheel

Castor wheels are able to steer around a vertical axis. The vertical axis of rotation in a castor wheel does not pass through the ground contact point. B is the wheel contact point and it is linked to the vehicle with a rigid rod AB of length f. The parameters of the castor wheel are similar to the steered wheel; $\varphi(t)$ represents the wheel rotation and $\beta(t)$ represents the orientation of the wheel and the rod AB.

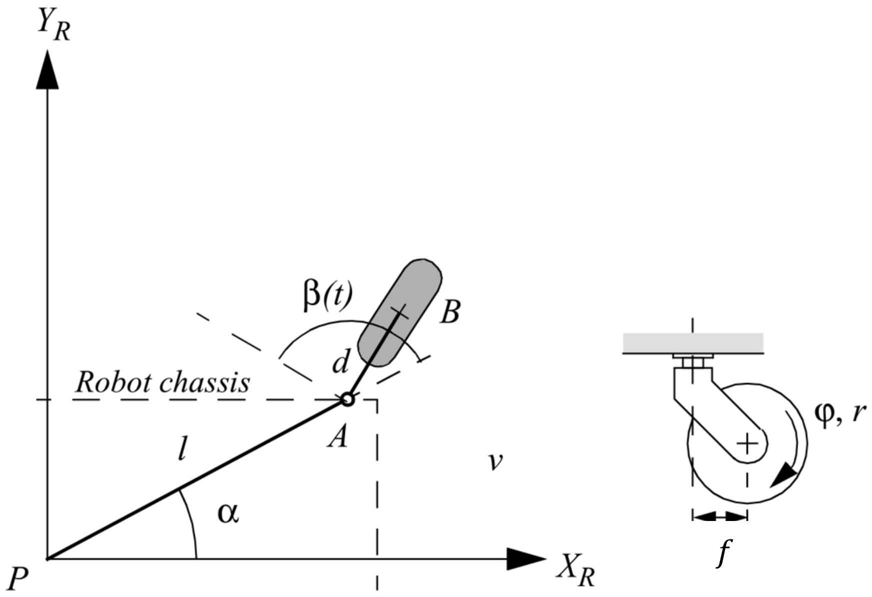


Figure 2.9 Castor wheel and its parameters **[1]**

Rolling constraint castor wheel

$$[\sin(\alpha+\beta), \quad -\cos(\alpha+\beta), \quad (-l)\cos\beta]\, R(\theta)\dot{\xi}_I - r\dot{\varphi} = 0 \tag{2.18}$$

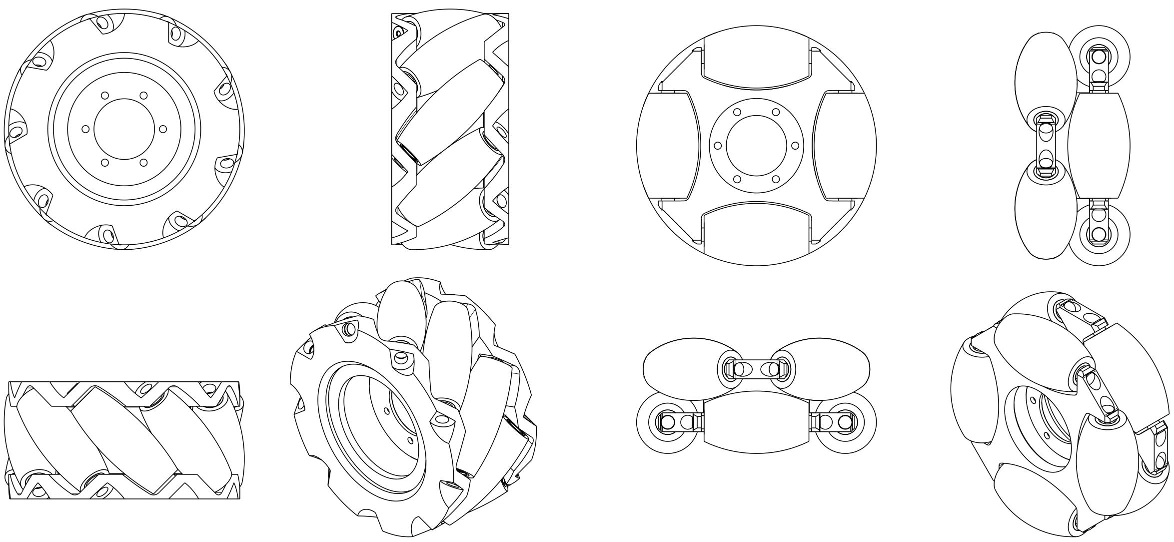
Sliding constraint castor wheel

$$[\cos(\alpha+\beta), \quad \sin(\alpha+\beta), \quad f + l\sin\beta]\, R(\theta)\dot{\xi}_I + d\dot{\beta} = 0 \tag{2.19}$$

The offset parameter f it is not present in the rolling constraint because during motion, the rod AB is aligned with the wheel plane. However the f offset of the pivot point changes the sliding constraint. The vehicle motion orthogonal to the wheel plane must be balanced by an opposite motion of the caster steering. In a standard steering wheel, the steering action does not by itself cause a movement of the vehicle chassis but in a castor wheel the steering action moves the vehicle chassis.

2.3.4. Swedish wheel

The Swedish wheels have rollers attached to the wheel perimeter. The angle between the rollers and the main axis of the wheel (γ) can vary depending on the wheel design. The most common designs of Swedish wheels have the rollers at 45º or at 90º as shown in Figure 2.10. The rollers add an extra degree of freedom to the wheel and allow the vehicles to move omnidirectionaly.



D1. 45º Swedish wheel *D2. 90º Swedish wheel*

Figure 2.10 Swedish wheels

Figure 2.11 shows the main axis of a 45º Swedish wheel. By combining the rotation of the wheel main axis with the rotation of the wheel rollers it is possible to generate a motion vector in any direction.

Commonly, the Swedish wheels are not steered, β is constant, and the only degree of freedom controlled is the wheel rotation $\varphi(t)$. A vehicle with a combination of Swedish wheels with different orientations β and/or different orientation of the rollers γ can be moved omnidirectionaly by combining the rotation of each wheel.

It is necessary to add the rollers orientation γ in the rolling constraint and no sliding constraint. Note that moving in the direction of the rollers axis without spinning the main axis is not possible without sliding; this is the connotation of the rolling constraint shown in equation (2.20). Similar to this, the sliding constraint (2.21) is given by balancing the rollers spin, the wheel spin and the motion perpendicular to the rollers axis.

The additional parameters of the Swedish wheel are the angle between the main wheel plane and the axis of rotation of the small rollers γ; the radius of the small rollers r_{sr}; and the rotation of the small rollers $\dot{\varphi}_{sr}$.

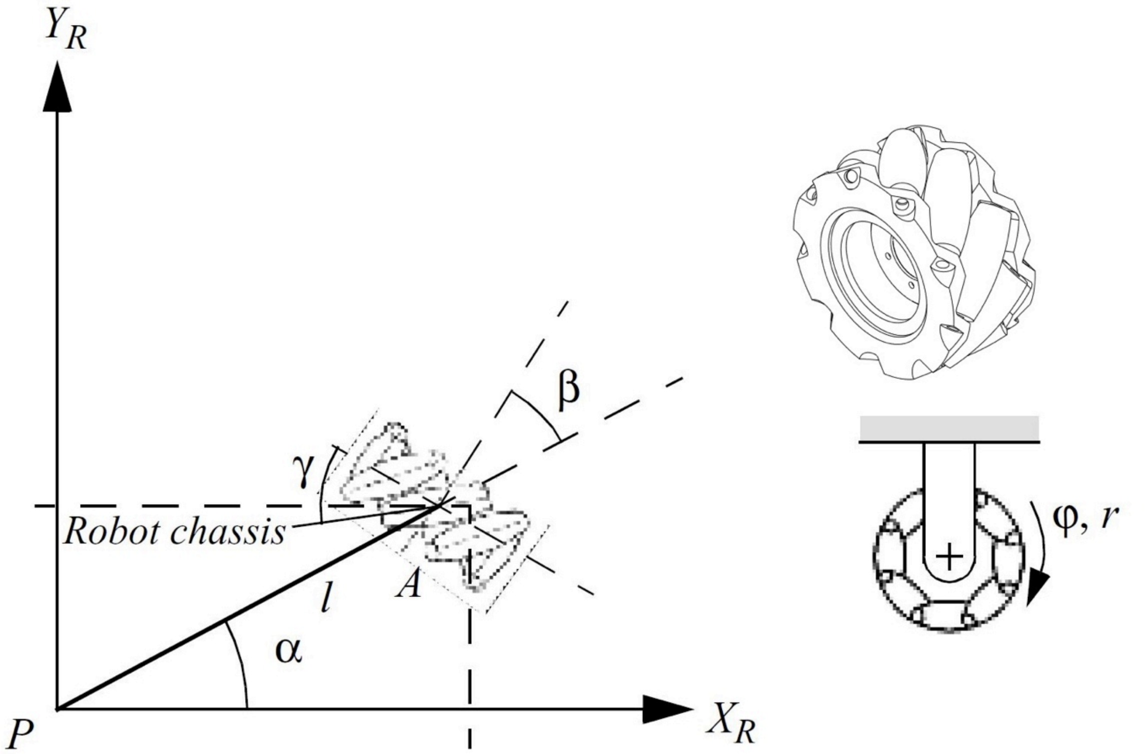


Figure 2.11 Swedish wheel and its parameters **[1]**

Rolling constraint Swedish wheel

$$[\sin(\alpha+\beta+\gamma), \quad -\cos(\alpha+\beta+\gamma), \quad (-l)\cos(\alpha+\gamma)]\, R(\theta)\dot{\xi}_I - r\dot{\varphi}\cos\gamma = 0 \tag{2.20}$$

Sliding constraint Swedish wheel

$$[\cos(\alpha+\beta+\gamma), \quad \sin(\alpha+\beta+\gamma), \quad l\sin(\beta+\gamma)]\, R(\theta)\dot{\xi}_I - r\dot{\varphi}\sin\gamma - r_{sr}\dot{\varphi}_{sr} = 0 \tag{2.21}$$

The angle between the main wheel plane and the axis of rotation of the small rollers is $\gamma = 0$ for the 90º Swedish wheel. Then the rolling constraint (2.20) is exact to the equation of the fixed standard wheel (2.14). For the 90º Swedish wheel the sliding constraint disappears; because of the rollers it is possible to move the wheel perpendicular to the wheel plane.

2.3.5. Spherical wheel

The last wheel type is the spherical wheel. The spherical wheel places no constraints on motion. The spherical wheel has no main axis of rotation; the rotation axis varies as a function of the speed of the vehicle frame. The spherical wheel is clearly omnidirectional and places no constraints on the vehicle chassis kinematics. In this particular case the rolling constraint only describes the roll rate of the ball in the direction of the vehicle motion. The wheel's rotation orthogonal to this direction is zero; this is the sliding constraint.

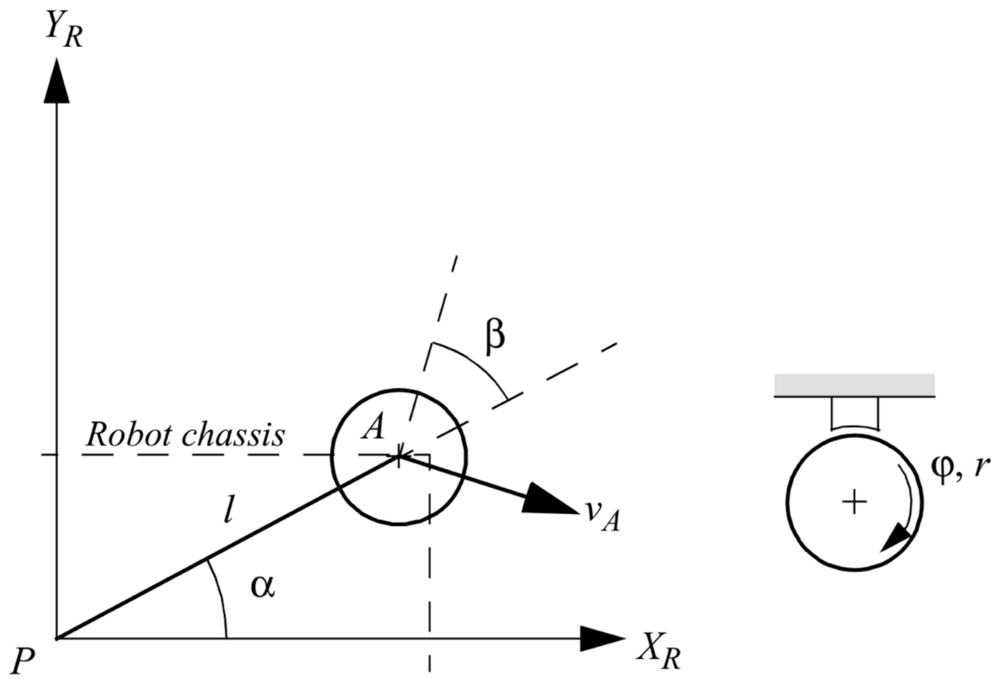


Figure 2.12 Spherical wheel and its parameters **[1]**

Rolling constraint spherical wheel

$$[\sin(\alpha+\beta), \quad -\cos(\alpha + \beta), \quad (-l)\cos\beta]\, R(\theta)\dot{\xi}_I - r\dot{\varphi} = 0 \tag{2.22}$$

Sliding constraint spherical wheel

$$[\cos(\alpha+\beta), \quad \sin(\alpha + \beta), \quad l\sin\beta]\, R(\theta)\dot{\xi}_I + d\dot{\beta} = 0 \tag{2.23}$$

2.4. Vehicle kinematic constraints

As seen in Section 2.3 each wheel type imposes kinematic constraints to the vehicle chassis. Then, given the wheel arrangement in an *AGV,* it is possible to compute the kinematic constraints imposed by each wheel based on the wheel type and its position.

The only wheels that impose no kinematic constraints on the vehicle are the omnidirectional wheels:

B1. Castor wheel
C1. Spherical wheel
D1. Free 45º Swedish wheel
D3. Free 90º Swedish wheel

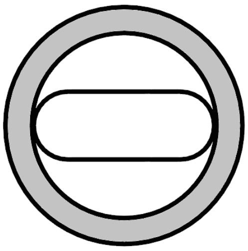
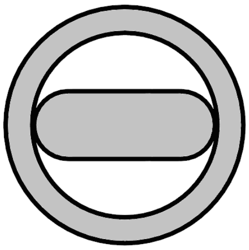
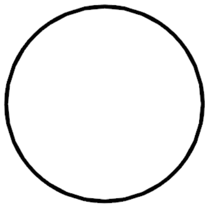
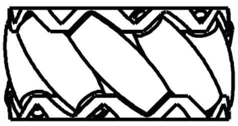
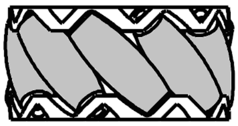
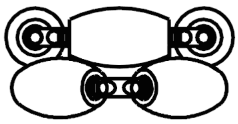
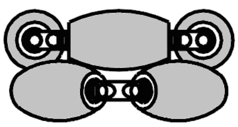
All the other wheel types will have an impact on the vehicle kinematics.

A1. Free standard wheel
A2. Motorized standard wheel
A3. Steered standard wheel
A4. Motorized and steered standard wheel
D2. Motorized 45º Swedish wheel
D4. Motorized 90º Swedish wheel

Table 2.1 shows the symbols used in the following chapters to represent the different wheel types.

Now that one understands all the kinematic models for the different wheel types, the wheel arrangements of industrial *AGVs* are analysed in Chapter 4; and innovative AGV wheel arrangements are proposed and analysed in Chapter 5.

Table 2.1 Wheel symbols

A1.	Free standard wheel		2 DF 2 free
A2.	Motorized standard wheel		2DF 1 free + 1 controlled
A3.	Steered standard wheel		2DF 1 free + 1 controlled
A4.	Free standard wheel		2DF 2 controlled
B1.	Castor wheel		3DF 3 free
C1.	Spherical wheel		3DF 3 free
D1.	Free 45º Swedish wheel		3DF 3 free
D2.	Motorized 45º Swedish wheel		2DF 2 free + 1 controlled
D3.	Free 90º Swedish wheel		3DF 3 free
D4.	Motorized 90º Swedish wheel		3DF 2 free + 1 controlled

Chapter 3

STATE OF THE ART

The objective of this chapter is to present the state of the art of Automated Guided Vehicles used in industry in general in order to know the current technology and how it can be applied to the particular case of the aerospace Industry.

3.1. Automated guided vehicles in industry

3.1.1. Warehouse material handling forklift

There are different manufactures that have solutions to handle material in standard pallets. Many companies can benefit from the automation of their material handling process. Advantages of automation in material handling include easy tracking of goods, just-in-time picking, less damage and fewer operator hours.

An example is the *TOYOTA BT Autopilot* shown in Figure 3.1. It allows driverless operation for repetitive movements, or order picking of goods, reducing labour efforts. Other examples are the *SWISSLOG Hybrid AGV, SWISSLOG Standard AGV.* These vehicles are like a standard electric forklift or pallet truck with a control system that enables the autonomous operation with no need of driver. More examples and details are given in Appendix A.3.1.

Figure 3.1 *TOYOTA BT Autopilot* forklift **[37]**

3.1.2. Paper reel handling AGVs

Very similar to autonomous forklifts, there are the paper reel handling *AGVs*. These vehicles are dedicated to load paper reels in the printing press of the newspaper companies or similar. *ATAB* [12] and *CTI Systems* [20] manufacture simple *AGVs* to manipulate the paper reels. They resemble an adaptation of a forklift with a driverless control system. Probably the wheel arrangement is the same as in the forklifts. Images of these AGVs are given in Appendix A.3.2.

3.1.3. Automatic warehouse

The company owned by Amazon, Kiva Systems LLC has an innovative solution to automate the material handling in Amazon warehouses. The main components of this system are the robotic drive units (bots), the mobile inventory shelves (pods), and the software. Using hundreds of autonomous mobile robots (like the one shown in Figure 3.2) and sophisticated control software, the *KIVA* Mobile-robotic Fulfilment System enables extremely fast cycle times with reduced labour requirements, from receiving to picking to shipping. The result is a building that is quick and low-cost to set up, inexpensive to operate and easy to change anywhere in the world.

Figure 3.2 *KIVA* robot drive unit **[28]**

The *SWISSLOG Carry Pro* is an *AGV* with very similar design as the *KIVA Robot Drive Unit.* The wheel arrangement is the same as the *KIVA Robot Drive Unit*. The *CarryPro* Automated Guided Vehicle stores and retrieves *SKUs* to supply pallets, to picking robots and palletizers. The *AGV* holds mobile racks, pallet conveyors, case conveyors or other custom-designed structures. Further details of these *AGVs* are given in Appendix A.3.3.

3.1.4. Vehicle assembly line AGVs

In car manufacture plants, the vehicle chassis is usually transferred between assembly stations with skids. These skids are moved using dedicated transport systems like a chain or a conveyor. Instead of this solution, in few occasions, the vehicle manufacturers have used *AGVs* to transfer the vehicle between assembly stations. The use of AGVs allow to have a very flexible assembly line but the cost of implementing this solution is much higher than the use of skids when the production rates are high. Two images of vehicle assembly line *AGVs* are given in Appendix A.3.4.

3.1.5. Hospital cart transporters

Automated Guided Vehicles are used to move goods inside hospitals providing a safer system of work and reducing the risk of moving and handling injuries. They are people friendly and will allow efficient and reliable deliveries to the different hospital areas. An example is the *SWISSLOG TransCar AGV* system; it helps multiple hospital departments using specialized carts for the distribution of bulk food, medical and surgical supplies, pharmaceuticals, patient food, soiled dishes, clean and soiled linens, trash, and regulated medical waste. It is possible to see the wheel arrangement of this *AGV* in Figure 3.3. Additional information is given in Appendix A.3.5.

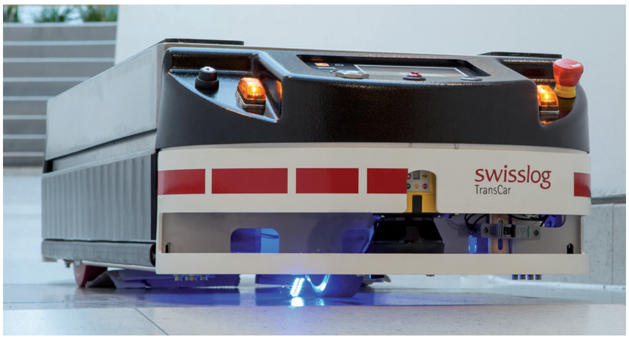


Figure 3.3 *SWISSLOG TransCar AGV* with adapted carts **[37]**

3.1.6. AGV container system

A very singular application of *AGVs* is the system designed by *VDL* to transport logistic containers in the port of Rotterdam. The containers are automatically unloaded from the cargo ship using a crane and placed over an *AGV*. Then the *AGV* carries the container to the storage zone and another crane removes the container from the *AGV* automatically. Using a centralized control system it is possible to optimize the paths and reduce the time used to load and unload container ships. More information is given in Appendix A.3.6.

Figure 3.4 *VDL container system AGV* **[39]**

3.1.7. Helicopter and airplane tug

There is a manufacturer called *MOTOTOK* that manufactures radio-controlled vehicles dedicated to move helicopters or airplanes. Also it offers to possibility to equip the tug vehicle with a camera underneath that scans a steering line painted on the production hall floor. Bar codes can be added near the guiding line in order to give additional information to the vehicle.

One of the very interesting points of the *MOTOTOK AGVs* is that it can be used to move an helicopter or airplane with no need of additional interfaces on the helicopter or plane. This offers the possibility to use the *MOTOTOK AGV* with no need of additional equipment in the final assembly lines of airplanes if they have the landing gear installed; or in the *FAL* of helicopters if they have the skids.

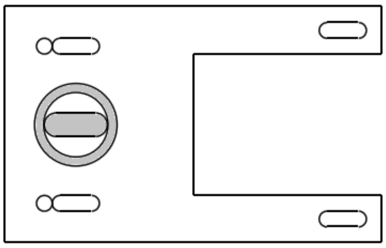
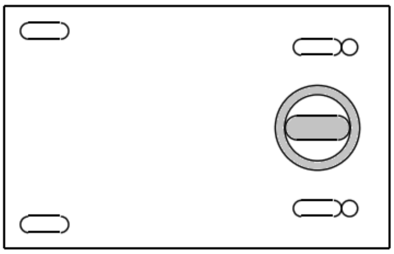
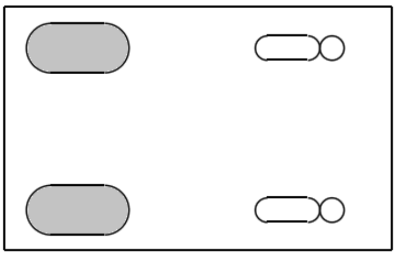
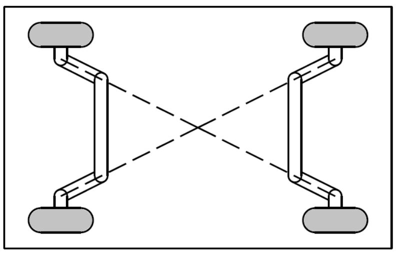
Figure 3.5 shows a *MOTOTOK AGV* during airplane production. The airplane is moved with no need of an additional interface. Additional images and technical details are given in Appendix A.3.7.

Figure 3.5 *MOTOTOK* during airplane production **[32]**

3.2. Summary of industrial AGVs

Table 3.1 shows the different wheel arrangements found in the previous analysed systems.

Table 3.1 Summary of industrial *AGV* arrangements.

	Arrangement	*Description*
A		Single drive and steer wheel vehicle 1 driving and steering wheel in the rear 2 caster wheels in the rear and 2 free wheels in front. 2 Motors
A'		Same configuration as above but opposite direction of motion.
B		Differential drive vehicle 2 motorized wheels in the rear and 2 caster wheels in the front 2 Motors
C		Double Ackermann Steering vehicle 4 Hydraulic motors drive the 4 wheels[1] 2 Electric motor steers the 4 wheels with 2 Ackermann steering systems[2]

[1] The *VDL AGV* has a hydraulic motor in each wheel instead of 1 driving motor with 3 differentials as a 4x4 car because it is cheaper.
[2] The *VDL AGV* uses independent steering motors in the front and rear axle instead of only 1 motor coupled with a bevel gearbox with 2 output shafts, 2 pinions and 2 racks because it is cheaper and easier for large vehicles.

A arrangement

- 5 Wheels: 1 driving and steering wheel in the rear, 2 caster wheels in the rear and 2 free wheels in front.
- 1 Driving motor + 1 Steering motor → Total 2 motors
- Forklift AGV
    - *TOYOTA BT Autopilot*
    - *SWISSLOG Standard AGV*
- Paper reel logistics
    - *CTI System*

A' arrangement

- Hospital logistics AGV
    - *SWISSLOG TransCar*

B arrangement

- 4 wheels: 2 motorized wheels in the rear and 2 caster wheels in the front.
- 2 Driving motors → Total 2 motors
- Intelligent warehouse AGV
    - *KIVA Robotic Drive Unit*
    - *SWISSLOG CarryPro*
- Helicopter and airplane tug
    - *MOTOTOK*

C arrangement

- 4 Wheels: double Ackermann steering system with 4-wheel drive.
- 2 Driving motors + 2 Steering motors → Total 4 motors[3]
- Container logistics
    - *VDL Container System*

[3] The same solution is possible with only 2 motors: 1 driving motor and 1 steering motor.

Chapter 4

KINEMATIC ANALYSIS OF INDUSTRIAL AGVs

The objective of this chapter is to study the *AGV* arrangements found in the industry and see if it is possible to apply analogous solutions to the specific case of commercial aircraft manufacturing industry.

The closed kinematic expressions of these *AGV* configurations are going to be analysed in the present chapter.

4.1. AGV with single driving and steering wheel

4.1.1. AGV arrangement overview

The first arrangement to analyse is the most common *AGV* used in *intralogistics*.

The wheel arrangement is simple:

- 1 Driving and steering wheel
- 2 Standard wheels
- 2 Additional casters to add stability

This wheel arrangement is found in the automated forklifts and the majority of industrial *AGVs*.

The main characteristics of the vehicle are:

- The vehicle is able to move forward/backward.
- The vehicle is able to rotate form a point placed in the axis defined by the fixed standard wheels. The *IRC* must lay in the axis of the fixed standard wheels.
- The vehicle is not able to move sideways.
- The degree of manoeuvrability is 2.
- The number of driving wheels is only 1.
- The number of motors is 2.

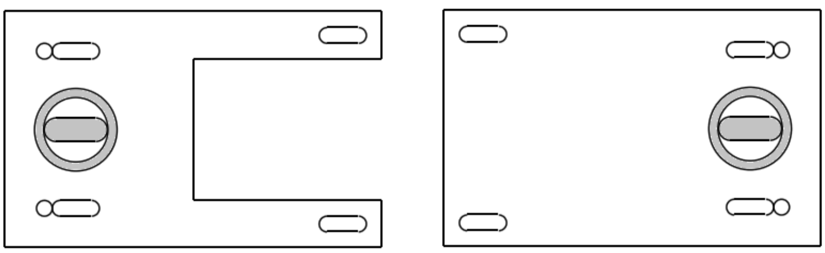


Figure 4.1 Schema of single wheel steering and driving vehicle

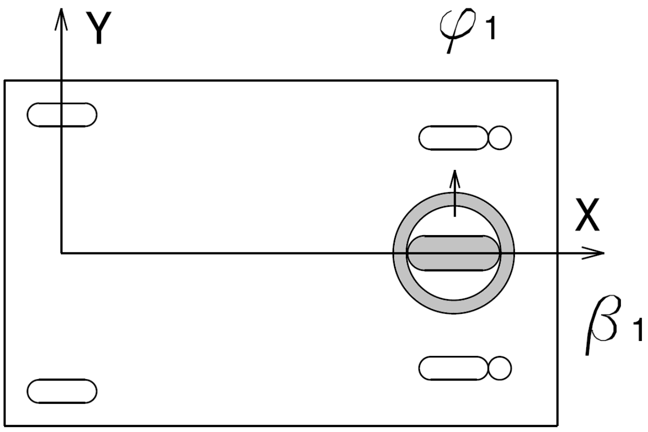


Figure 4.2 Schema of *AGV* with single wheel steering and driving

4.1.2. Definition of variables and parameters

Main variables of the vehicle

$\dot{x}$ ≡ Speed of the vehicle in longitudinal axis (X-axis)
$\dot{\theta}$ ≡ Rotation speed of the vehicle in vertical axis (Z-axis)

Intrinsic variables of the vehicle

$\dot{\varphi}$ ≡ Rotation speed of the driving and steering wheel
β_1 ≡ Angle of the driving and steering wheel

Parameters of the vehicle

L_2 ≡ Distance in X-axis from the driving wheel to the fixed standard wheels
r ≡ Wheel radius
i ≡ Reduction ratio of the gearbox installed between the wheel and the driving motor
Z_c/Z_p ≡ Reduction ratio of the steering system

The variable L_1, that is the distance between the standard wheels in the Y-axis, and has no effect on the vehicle motion.

4.1.3. Formulation

$$\begin{bmatrix} v_1 \\ \beta_1 \end{bmatrix}_{wheels} = \begin{bmatrix} \sqrt{\dot{x}^2 + (L_2 \cdot \dot{\theta})^2} \\ \operatorname{atan}\left(\frac{L_2 \cdot \dot{\theta}}{\dot{x}}\right) \end{bmatrix} \quad (4.1)$$

$$\begin{bmatrix} \dot{\varphi}_1 \\ \beta_1 \end{bmatrix}_{motors} = \begin{bmatrix} \frac{i}{r} \cdot \sqrt{\dot{x}^2 + (L_2 \cdot \dot{\theta})^2} \\ \frac{Z_c}{Z_p} \cdot \operatorname{atan}\left(\frac{L_2 \cdot \dot{\theta}}{\dot{x}}\right) \end{bmatrix} \quad (4.2)$$

An alternative way is to calculate the speed of the vehicle on the driving wheel in X-axis and Y-axis; and then to calculate the steering angle and the rotational speed of the driving and steering wheel.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \end{bmatrix}_{wheels} = \begin{bmatrix} \dot{x} \\ L_2 \cdot \dot{\theta} \end{bmatrix} \quad (4.3)$$

$$\begin{bmatrix} \dot{\varphi}_1 \\ \beta_1 \end{bmatrix}_{motors} = \begin{bmatrix} \frac{i}{r} \cdot \sqrt{\dot{x}_1{}^2 + \dot{y}_1{}^2} \\ \frac{Z_c}{Z_p} \cdot \operatorname{atan}\left({}^{\dot{y}_1}/_{\dot{x}_1}\right) \end{bmatrix} \quad (4.4)$$

It is also possible to find the inverse formulation. The motion of the vehicle as a function of the motors spin

$$\dot{\xi}_R = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \dot{\varphi}_1 \cdot r \cdot \cos\beta_1 \\ 0 \\ \frac{\dot{\varphi}_1 \cdot r \cdot \sin\beta_1}{L_2} \end{bmatrix}_{wheels} \quad (4.5)$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \frac{1}{i} \begin{bmatrix} \dot{\varphi}_1 \cdot r \cdot \cos\left(\beta_1 \cdot \frac{Z_p}{Z_c}\right) \\ 0 \\ \frac{\dot{\varphi}_1 \cdot r \cdot \sin\left(\beta_1 \cdot \frac{Z_p}{Z_c}\right)}{L_2} \end{bmatrix}_{motors} \quad (4.6)$$

4.2. Differential drive AGV

4.2.1. AGV arrangement overview

The wheel arrangement is very simple:

- 2 Driving wheels
- 2 Additional casters to add stability.

This wheel arrangement is found in the *KIVA POD* and *SWISSLOG Carry Pro,* among others.

The main characteristics of the vehicle are:

- The vehicle is able to move forward/backward.
- The vehicle is able to rotate form a point placed in the axis defined by the fixed standard wheels. The *IRC* must lay in the axis of the fixed standard wheels.
- The vehicle is not able to move sideways.
- The degree of manoeuvrability is 2.
- The number of driving wheels is 2.
- The number of motors is 2.

The vehicle manoeuvrability and stability is similar to the AGV with a single driving and steering wheel. The main difference is that the differential drive vehicle has more traction because it can have a higher normal force in the driving wheels. The *AGV* with 2 driving wheels is a very simple design and it could be a good solution when the omnidirectional wheels are not necessary.

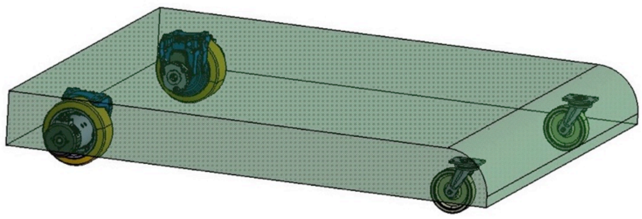


Figure 4.3 Isometric views of vehicle with 2 driving wheels and 2 swivel casters

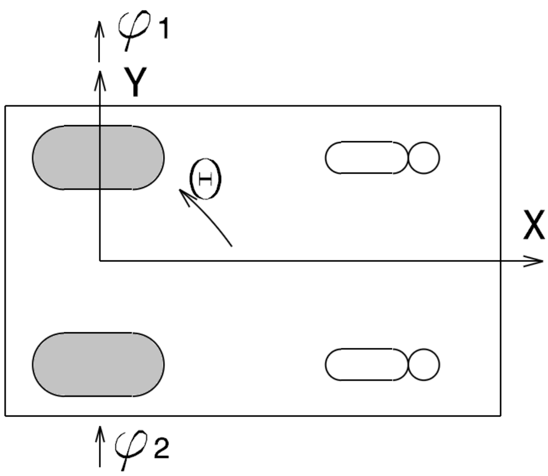


Figure 4.4 Schema of differential drive *AGV*

4.2.2. Definition of variables and parameters

The main control variables of the vehicle are $\dot{x}$ and $\dot{\theta}$. The variable $\dot{y}$ must be 0. There are 2 intrinsic variables of the vehicle: the rotational speed of the left wheel $\dot{\varphi}_1$ and the rotational speed of the right wheel $\dot{\varphi}_2$. The distance from the wheel centre to the origin P is a necessary parameter to define the vehicle kinematics; this distance is L_1.

4.2.3. Inverse differential kinematics

The differential drive vehicle has no redundant variables. It is possible to compute the rotational speed of each wheel for a given velocity vector of the vehicle (inverse kinematics); or to calculate the vehicle velocity if the wheel speeds are given (forward kinematics).

In the inverse kinematic model it is mandatory that $\dot{y} = 0$, otherwise, the wheels will have lateral slippage.

$$\begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{bmatrix} = \frac{1}{r} \cdot \begin{bmatrix} 1 & 0 & L_1 \\ 1 & 0 & -L_1 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{4.7}$$

4.2.4. Forward differential kinematics

The forward kinematic matrix shows clearly that the *AGV* will not have lateral motion, regardless of the wheels speed. Also it is easy to see that when the vehicle follows a straight line any small difference on the wheel speed will produce a rotation of the vehicle frame $\dot{\theta}$.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ 0 & 0 \\ \frac{r}{2L_1} & \frac{-r}{2L_1} \end{bmatrix} \cdot \begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{bmatrix} \tag{4.8}$$

4.3. AGV with double Ackermann steering system

4.3.1. AGV arrangement overview

An interesting approach to *AGVs* is to use a standard transport vehicle and add all the necessary sensors to use it with no need of a driver. One of the most common wheel arrangements of the transport vehicles is 2 fixed standard wheels on the rear axle and 2 wheels with an Ackermann steering system on the front axle. This is the same wheel arrangement as in the majority of automobiles. The turning radius of this vehicle configuration usually is larger than the vehicle.

Probably due to the high directionality and reduced manoeuvrability of the steering system used in the automobiles, the configuration with 2 fixed wheels and 2 wheels with an Ackerman steering systems is not widely used to manufacture industrial *AGVs*; however there are many companies that are developing cars that will be able to transport people or goods without a driver.

An improvement to the vehicle with a pair of standard wheels on the rear axle and an Ackermann steering system on the front axle is to have an Ackerman steering system in both axles. The main advantage of this modification is that the minimum turning radius is reduced to ½ of the radius obtained with a single Ackermann steering geometry.

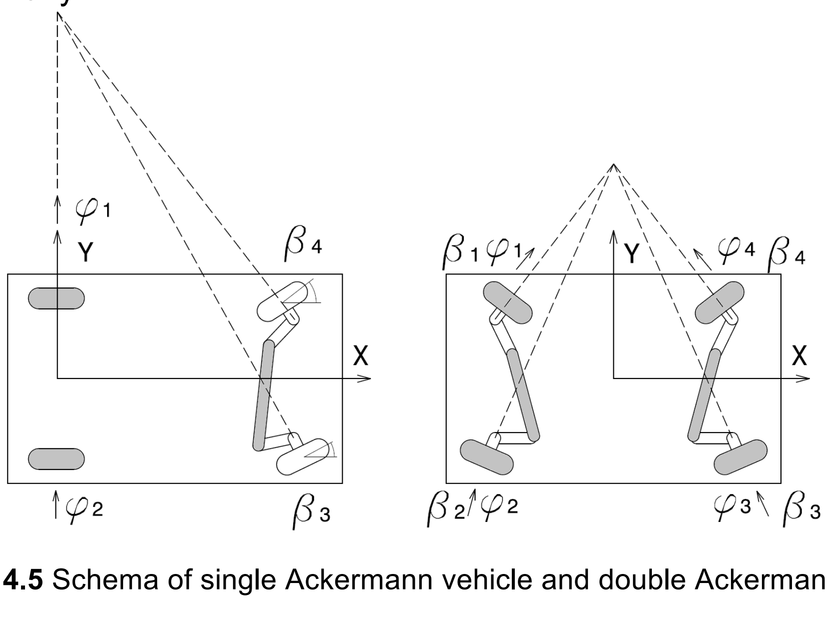


Figure 4.5 Schema of single Ackermann vehicle and double Ackermann vehicle

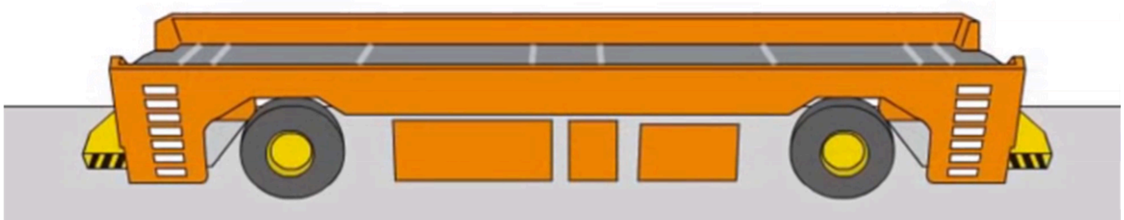


Figure 4.6 Isometric view of VDL container system AGV **[39]**

The wheel arrangement of the double Ackermann vehicle is not simple. The wheels of the front axle as well as the wheel of the rear axle are linked with rigid rods. These rods have a specific geometry that enables a common rotation reference for the two steering systems.

The speed of the driving wheels must be different when the vehicle is turning; the wheels placed further from the centre of rotation must spin faster than the inner wheels. Usually this problem is solved using a mechanical differential.

A vehicle with a double Ackermann drive needs at least 1 motor for the steering system and 1 motor with a differential system for at least 2 driving wheels. Also a third differential can distribute traction to the 4 wheels of the *AGV.*
There are other solutions like using one hydraulic motor in each wheel and one electric motor in each steering system (6 motors in total); or intermediate solutions like one motor to transmit power to the front wheels and another to transmit power to the rear ones.

The configuration studied in the current section uses the minimum number of motors and it is an all-wheels drive vehicle. The vehicle has only one driving motor with a triple differential transition that drives the 4 wheels. The *AGV* has also a steering motor that actuates the front and rear steering systems at the same time.

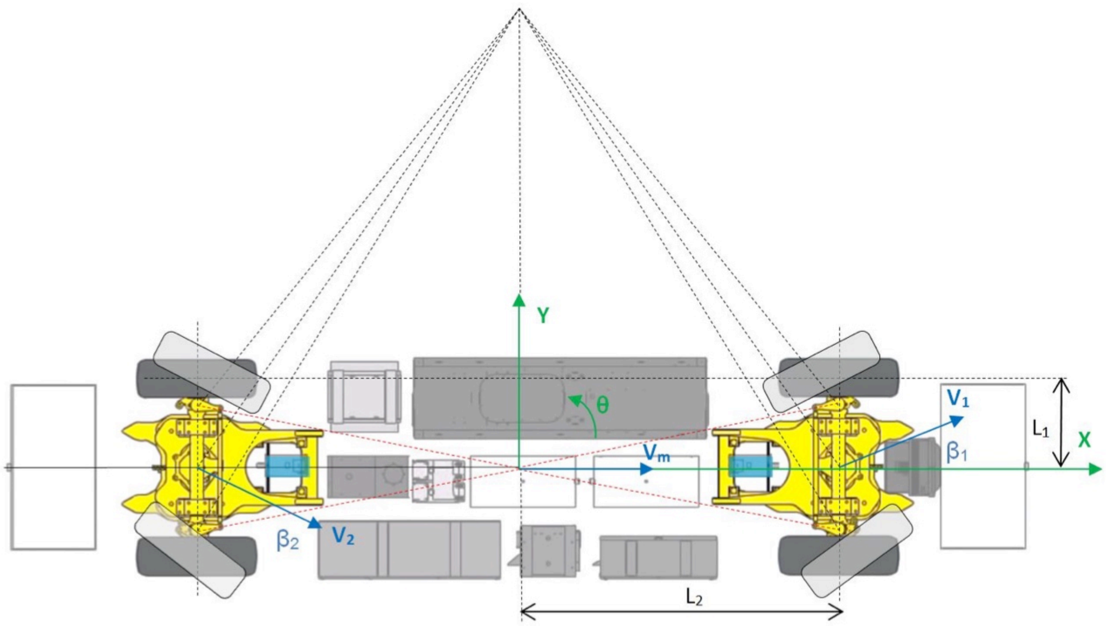


Figure 4.7 Top view of vehicle with double Ackermann steering

The main characteristics of the vehicle are:
- The vehicle is able to move forward/backward.
- The vehicle is able to rotate form a point placed Y-axis.
- The vehicle is not able to move sideways.
- The degree of manoeuvrability is 2.
- The number of driving wheels is 4.
- The minimum number of motors is 2.

4.3.2. Definition of variables and parameters

The main variables of the vehicle are $\dot{x}$ and $\dot{\theta}$. The variable $\dot{y}$ must be 0. The intrinsic variables of the AGV are the average rotation speed of front shaft $\dot{\varphi}_1$ and rear shaft $\dot{\varphi}_2$. Also the average orientation angle of the front wheels β_1 and of the rear wheels β_2 . In the present case the variables $\dot{\varphi}_1$ and $\dot{\varphi}_2$ must be equal; and the variables β_1 and β_2 must be symmetrical (same absolute value but different sign). The parameters L_1 and L_2 (shown in Figure 4.7) are necessary to define the position of each wheel.

4.3.3. Formulation

The average speed of each shaft and the average angle of the steering system can be calculated easily with simple triangles.

$$\begin{bmatrix} \dot{\varphi}_1 \\ \beta_1 \\ \dot{\varphi}_2 \\ \beta_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{r} \cdot \sqrt{\dot{x}^2 + (L_2 \cdot \dot{\theta})^2} \\ \operatorname{atan}\left(\frac{L_2 \cdot \dot{\theta}}{\dot{x}}\right) \\ \frac{1}{r} \cdot \sqrt{\dot{x}^2 + (L_2 \cdot \dot{\theta})^2} \\ -\operatorname{atan}\left(\frac{L_2 \cdot \dot{\theta}}{\dot{x}}\right) \end{bmatrix} \tag{4.9}$$

For a wheel drive reduction i and a steering system reduction Z_c/Z_p, the speed of the driving motors and the position of the steering motors is given by formula (4.10).

$$\begin{bmatrix} \dot{\varphi}_1 \\ \beta_1 \\ \dot{\varphi}_2 \\ \beta_2 \end{bmatrix}_{motors} = \begin{bmatrix} \frac{i}{r} \cdot \sqrt{\dot{x}^2 + (L_2 \cdot \dot{\theta})^2} \\ \frac{Z_c}{Z_p} \cdot \operatorname{atan}\left(\frac{L_2 \cdot \dot{\theta}}{\dot{x}}\right) \\ \frac{i}{r} \cdot \sqrt{\dot{x}^2 + (L_2 \cdot \dot{\theta})^2} \\ -\frac{Z_c}{Z_p} \cdot \operatorname{atan}\left(\frac{L_2 \cdot \dot{\theta}}{\dot{x}}\right) \end{bmatrix} \tag{4.10}$$

An alternative way to calculate it is: first, calculate speed on the middle of front shaft in X-axis and Y-axis then calculate angles and speed in the front shaft.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{x}_2 \\ \dot{y}_2 \end{bmatrix}_{wheels} = \begin{bmatrix} \dot{x} \\ L_2 \cdot \dot{\theta} \\ \dot{x} \\ -L_2 \cdot \dot{\theta} \end{bmatrix} \tag{4.11}$$

$$\begin{bmatrix} \dot{\varphi}_1 \\ \beta_1 \\ \dot{\varphi}_2 \\ \beta_2 \end{bmatrix}_{motors} = \begin{bmatrix} \frac{i}{r} \cdot \sqrt{\dot{x}_1{}^2 + \dot{y}_1{}^2} \\ \frac{Z_c}{Z_p} \cdot \operatorname{atan}\left({}^{\dot{y}_1}/_{\dot{x}_1}\right) \\ \frac{i}{r} \cdot \sqrt{\dot{x}_2{}^2 + \dot{y}_2{}^2} \\ \frac{Z_c}{Z_p} \cdot \operatorname{atan}\left({}^{\dot{y}_2}/_{\dot{x}_2}\right) \end{bmatrix} \tag{4.12}$$

Considering only 2 independent variables $\dot{\varphi}_1$ and β_1, it is easy to find the motion of the vehicle because $\dot{\varphi}_1 = \dot{\varphi}_2$ and $\beta_1 = -\beta_2$.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \dot{\varphi}_1 \cdot r \cdot \cos \beta_1 \\ 0 \\ \frac{\dot{\varphi}_1 \cdot r \cdot \sin \beta_1}{L_2} \end{bmatrix} \tag{4.13}$$

The position and speed of the driving and steering motors is computed adding the transmission reduction rations.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \frac{1}{i} \begin{bmatrix} \dot{\varphi}_1 \cdot r \cdot \cos \beta_1 \\ 0 \\ \frac{\dot{\varphi}_1 \cdot r \cdot \sin \beta_1}{L_2} \end{bmatrix}_{motors} \tag{4.14}$$

4.4. Conclusions of the kinematic analysis

The majority of *AGV*s used in the industrial environment have a simple wheel arrangement. The most common driving and steering options are:

- Single driving and steering wheel.
- Differential drive.

Both options need only 2 motors to move the vehicle. A reduced number of driving and steering motors make the control easier and the vehicle cheaper.

One weak point of these options is their manoeuvrability. The degree of mobility of both options is 2. However the dimensions of the majority of *AGV* with these wheel arrangements are not very large and the final performance is very good.

The pallets used in *intralogistics* have a maximum base of 1,2m x 1,2m approx. The biggest pallet used in Europe is the *Euro-pallet 2* that has a base of 1,2m x 1m and the biggest one used in the United States is the 48” x 48” pallet that has a base o 1,219 m x 1,219m. Usually the parts moved in the commercial aircraft manufacturing industry are much larger and it is necessary to find different approaches to the Automated Guided Vehicles, with better manoeuvrability properties.

Another weak point to apply both configurations to the aerospace industry is the reduced number of driving wheels. There is only one driving wheel in the *Single driving and steering wheel AGV* and only two in the *Differential drive AGV.*

Aside from these two configurations, single driving and steering wheel and differential drive, we have the alternative design of Ackermann steering, borrowed from the design of conventional cars. It includes 2 fixed standard wheels on the rear axle and 2 wheels with an Ackermann steering system on the front axle. It has the same weak manoeuvrability properties as the abovementioned methods. However, the *AGVs* studied in Section 4.3 present an improvement of the wheel arrangement found on the majority of cars. Instead of having only an Ackermann steering system in the front axle it has one in each axle. The improvement achieved is that the minimum-cornering radius is reduced to a half.

The *Double Ackermann AGV* has the same degree of manoeuvrability as the *Single driving and steering wheel AGV* and in the *Differential drive AGV;* $\delta_M = 2$. However the number of driving wheels is 4. That is, this *AGV* is an all-wheels drive vehicle. This solution it is very interesting to carry large loads. It hence could be applied in the aerospace industry for applications where it in not necessary to have fine positioning accuracy and it is not necessary an *omnidirectional* vehicle.

Many examples of industrial *AGV*s were shown in Chapter 3 and 4. They have significant drawbacks with regards to manoeuvrability and load distribution for their use in the commercial aircraft manufacturing industry. The purpose of the following chapters is to find which configurations of *AGVs* are most appropriate for such application.

Chapter 5

PROPOSAL OF INNOVATIVE AGV CONFIGURATIONS

The objective of this chapter is to propose and analyse wheel arrangements that could be applied to large *AGVs*.

5.1. Future scenarios

The possible fields of application of *AGVs* with high manoeuvrability are:

- Fully automated and flexible final assembly line (*FAL*) where *AGVs* with high manoeuvrability and large payload are dedicated to move the airplane, the wings, the landing gear and other large assemblies. Standard AGVs with degree of manoeuvrability 2 can be used to supply small parts like fasteners, tools… automatically to the operators.

- Fully automated assembly line of airplane large assemblies like the centre wing box. *AGVs* could move the *CWB* between stations.

- Fully automated cell to produce large composite parts. An example is the stingers used to reinforce the wing skin of the airplanes with *CFRP* wings. The wing of an airplane like the 777X has around 80 stringers that have to be produced in 2 days if the production rate is around 10. That means that is necessary to move at least 40 curing tools in 2 days from the lamination zone to the autoclave and from the autoclave to the assembly area. All this functions can be automatized using *AGVs.*

- Logistics of large subassemblies inside the factory. *AGVs* could be used to move the finished parts like the pylons, engines, CWB, HTP… form the final assembly station to the delivery zone or to the final assembly line.

- Logistics of large moulds and curing tools in an autoclave.

A very interesting function to develop is the capacity to use 2 or more *AGVs* to move a single load.

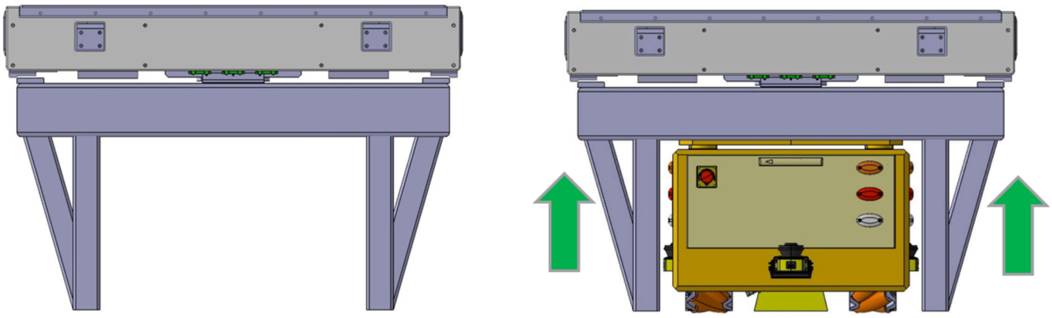


Figure 5.1 *AGV* loading a lay-up table

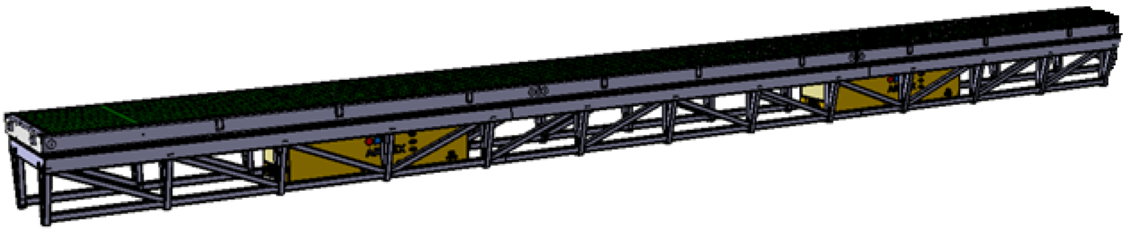


Figure 5.2 Two *AGVs* moving a lay-up table of 16m

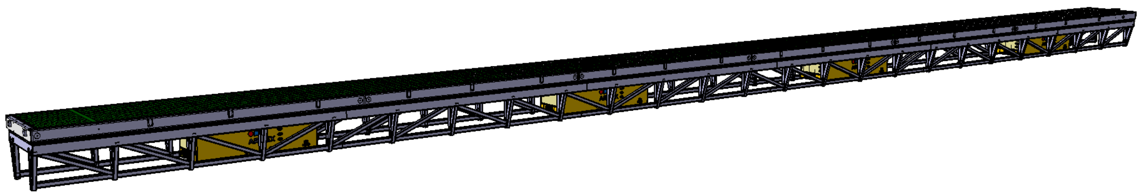


Figure 5.3 Four *AGVs* moving a layup table of 34m

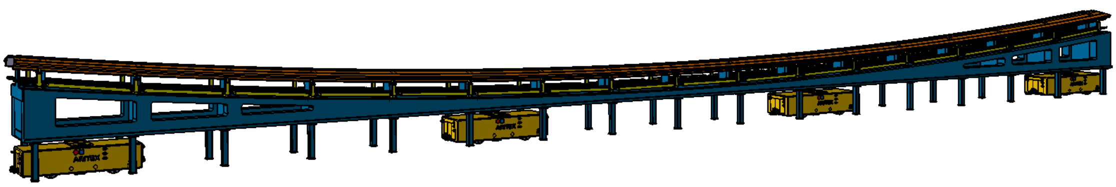


Figure 5.4 Four *AGVs* moving a Curing Tool of 34m

Figures 5.1, 5.2, 5.3 and 5.4 are simulations of how a large load could be transported using cooperative *AGVs.*

The mechanical design of all the vehicles will be the same. The vehicles would be able to move independently or together depending on the load.
It is necessary to have high precision positioning systems to control the relative position of the AGV in order to move the loads safely.

During the current research it has been impossible to find *AGVs* that cooperate. It will be very interesting in the future to develop the level of technology necessary to make it possible because it will be very useful in the *CAMI* among other industries.

5.2. Requirements of the innovative wheel arrangements

The potential applications of large *AGV*s in the aerospace industry are described in the previous point. Regarding all these potential applications, the main requirements of the large *AGVs* are:

- High payload.
    - High traction capacity. The number of driving wheels must be 2 or higher in order to have multiple traction wheels.
    - High load wheels. The load per wheel was to be more than 1.000 kg. However in order avoid damaging the concrete floor of the manufacturing plants the load per wheel should not exceed 3.000 kg.
    - The use of spherical wheels is not feasible in the industrial area because the load concentration is very high. Moreover the design of the spherical wheel is complicate. For both reasons the spherical wheels are discarded.
- High manoeuvrability.
    - Ability to move in any direction and rotate from any point. The *ICR* is not fixed in an axis and could be placed anywhere in the plane.
    - Degree of manoeuvrability 3.
- High positioning accuracy.
    - It is mandatory when the *AGVs* are used to install large assemblies in the *FAL* or when the *AGVs* are used to position large parts on assembly jigs.
    - It is not necessary if the *AGVs* are only used to transport goods.
- Cooperative AGVs.
    - Possibility to use 2 *AGVs* or more to move a single load or to position a large assembly in the right place.
        - High manoeuvrability is mandatory in this particular application.
        - High global positioning accuracy and local positioning accuracy between the *AGVs* is also required.
    - High-speed commination between *AGVs* is mandatory.

- Easy controllability.
  - The control of the *AGVs* must be as easy as possible. The number of variables that control the vehicle motion must be as little as possible in order to reduce the vehicle cost.
  - The control errors of the independently motorized wheels that are linked to the same chassis can introduce internal loads on the vehicle. Also the wheels can have small slippage due to these errors and this can produce premature wearing on the wheels. The incremental encoders installed in all the wheel drives will help to minimize these errors.

The wheel arrangements presented in the following sections are designed and analysed keeping in mind all these requirements.

5.3. AGV with 2 driving and steering wheels

5.3.1. AGV arrangement overview

A very simple design of a vehicle with high manoeuvrability is to use 2 driving and steering wheels with additional casters. The caster wheels help distributing the load and making the vehicle stable.

The caster wheels are oriented according the movement of the vehicle due to the eccentricity of the pivot axis with the contact point. Then the vehicle chassis must rotate from the caster wheel contact point; but this is not possible because the driving and steering wheels have no eccentricity. For these reasons theoretically the wheels must slide in some sharp changes of trajectory.

The vehicle with 2 driving and steering wheels has been studied but I have not designed nor manufactured a vehicle like this. It will be interesting to manufacture a vehicle with driving and steering wheels in order to cheek the behaviour of the casters together with the driving and steering wheels.

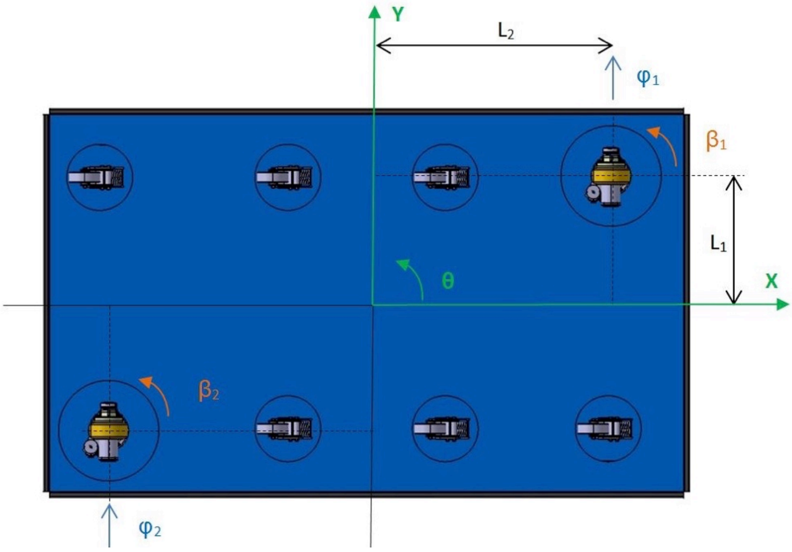


Figure 5.5 Top view of vehicle with 2 driving and steering wheels and 6 swivel casters

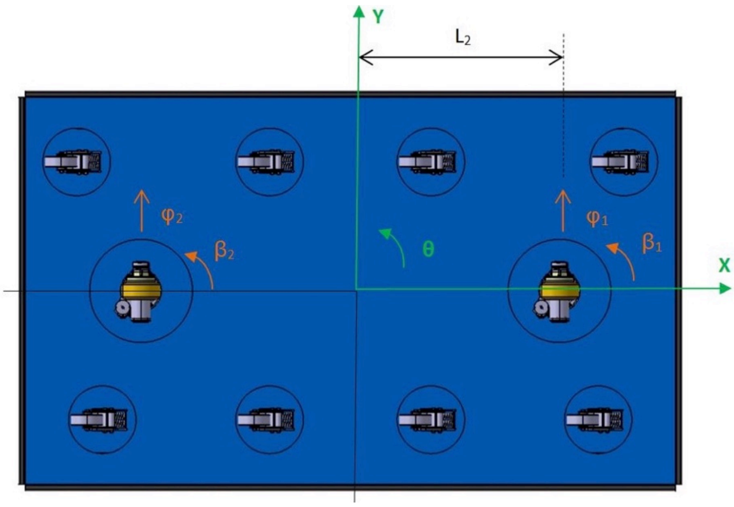


Figure 5.6 Top view of vehicle with 2 driving and steering wheels and 8 swivel casters

Figures 5.5 and 5.6 show two very simple *AGV* designs with two driving and steering wheels. The configuration shown in Figure 5.6 is a particular case of the configuration shown in Figure 5.5, where L_1=0. The formulation presented below is valid for both cases.

The wheel arrangement is simple:

- 2 Driving and steering wheels
- Additional casters to add stability

The main characteristics of the vehicle are:

- The vehicle is able to move in any direction.
- The vehicle is able to rotate form any point.
- The degree of manoeuvrability is 3.
- The number of driving wheels is 2.
- The number of motors is 4; 2 driving motors plus 2 steering motors.

The interesting point of this wheel arrangement is that all the material used in the *AGV* is commercial and it is not necessary to develop customized wheels as it happens in the wheel arrangements presented after Section 5.4.

5.3.2. Definition of variables and parameters

The main control variables of the vehicle are $\dot{x}$, $\dot{y}$ and $\dot{\theta}$. The intrinsic variables of the vehicle are the rotational speed of each wheel ($\dot{\varphi}_i$) and its orientation β_i. The main parameters are shown in Figures 5.5 and 5.6.

5.3.3. Formulation if AGV only can rotate from the origin P

First the speed of each wheel is calculated for a given $\dot{\xi}_R$.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{x}_2 \\ \dot{y}_2 \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} 1 & 0 & -L_1 \\ 0 & 1 & L_2 \\ 1 & 0 & L_1 \\ 0 & 1 & -L_2 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{5.1}$$

Then the rotation speed and the orientation of the wheels can be computed.

$$\begin{bmatrix} \dot{\varphi}_1 \\ \beta_1 \\ \dot{\varphi}_2 \\ \beta_2 \end{bmatrix}_{wheels} = \begin{bmatrix} \frac{1}{r} \cdot \sqrt{\dot{x}_1{}^2 + \dot{y}_1{}^2} \\ \operatorname{atan}\left({}^{\dot{x}_1}/_{\dot{y}_1} \right) \\ \frac{1}{r} \cdot \sqrt{\dot{x}_2{}^2 + \dot{y}_2{}^2} \\ \operatorname{atan}\left({}^{\dot{x}_2}/_{\dot{y}_2} \right) \end{bmatrix} \tag{5.2}$$

If the reduction ratios of the driving motor and the steering system motor are known then it is possible to calculate the speed of the driving motors and steering motors. The wheel drive has reduction i and the steering system Z_c/Z_p. Z_c/Z_p is the number of teeth of the steering crown divided by the number of teeth of the steering pinion.

$$\begin{bmatrix} \dot{\varphi}_1 \\ \beta_1 \\ \dot{\varphi}_2 \\ \beta_2 \end{bmatrix}_{motors} = \begin{bmatrix} \frac{i}{r} \cdot \sqrt{\dot{x}_1{}^2 + \dot{y}_1{}^2} \\ \frac{Z_c}{Z_p} \cdot \operatorname{atan}\left({}^{\dot{x}_1}/_{\dot{y}_1} \right) \\ \frac{i}{r} \cdot \sqrt{\dot{x}_2{}^2 + \dot{y}_2{}^2} \\ \frac{Z_c}{Z_p} \cdot \operatorname{atan}\left({}^{\dot{x}_2}/_{\dot{y}_2} \right) \end{bmatrix} \tag{5.3}$$

5.3.4. Formulation if AGV can rotate from any point C

As seen in the previous point, the speed of each wheel is calculated for a given $\dot{\xi}_R$ and $C = (c_x\, , c_y)$.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{x}_2 \\ \dot{y}_2 \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} 1 & 0 & -L_1 + c_y \\ 0 & 1 & L_2 - c_x \\ 1 & 0 & L_1 + c_y \\ 0 & 1 & -L_2 - c_x \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{5.4}$$

Then the rotation speed and the orientation of the wheels can be computed using equation 5.2. Finally the speed and position of the control motors can be computed using equation 5.3.

5.4. AGV with 3 or more driving and steering wheels

5.4.1. AGV arrangement overview

The design of the *AGV* of the previous section can be improved in order to avoid the castor wheels to slip in the sharp changes of trajectory. An option is to steer all the wheels to avoid the castor wheels slippage when they are self-aligned. To keep the vehicle stable it is necessary to use at least 3 wheels. Then a solution to use the minimum number of motors will be to design an *AGV* with 3 steered wheels and at least 2 driving wheels; 5 motors in total.

The proposed design of Figure 5.7 has 4 driving and steering wheels, one installed in each corner of the rectangle. The kinematic analysis will be analogue to the analysis done in the previous section. The main difference is that the vehicle has more redundant variables and the control will be more complex.

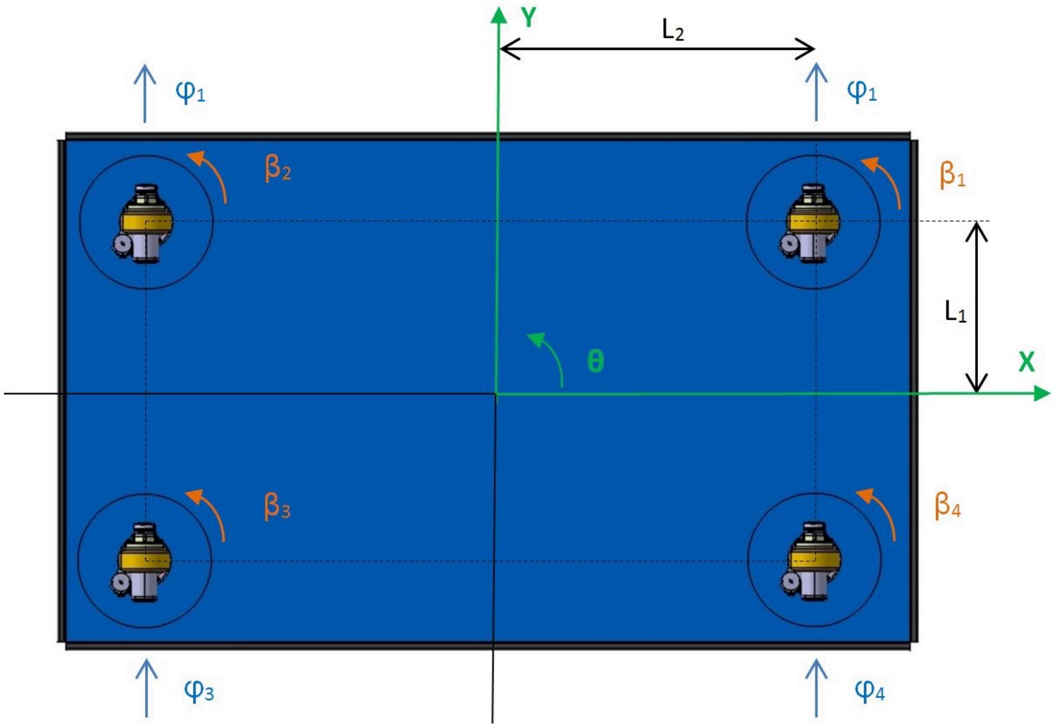


Figure 5.7 Top view of vehicle with 4 driving and steering wheels and 6 swivel casters

The wheel arrangement is simple:

- 4 driving and steering wheels installed in the 4 corners of a rectangle.

The main characteristics of the vehicle are:

- The vehicle is able to move in any direction.
- The vehicle is able to rotate form any point.
- The degree of manoeuvrability is 3.
- The number of driving wheels is 4.
- The number of motors is 8; 4 driving motors plus 4 steering motors.

It is possible to make similar wheel arrangements with fewer motors reducing the number of wheels or the number of wheel with driving motor. A minimum of 3 wheels and 2 driving motors is recommended.

As seen in Section 5.3 all the material used in this wheel arrangement is commercial and it is not necessary to develop customized wheels as it happens in the following sections.

5.4.2. Definition of variables and parameters

Figure 5.7 shows the main variables and parameters of the following formulation.

5.4.3. Formulation if AGV only can rotate from the origin P

First the speed of each wheel is calculated for a given $\dot{\xi}_R$.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{x}_2 \\ \dot{y}_2 \\ \dot{x}_3 \\ \dot{y}_3 \\ \dot{x}_4 \\ \dot{y}_4 \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} 1 & 0 & -L_1 \\ 0 & 1 & L_2 \\ 1 & 0 & -L_1 \\ 0 & 1 & -L_2 \\ 1 & 0 & L_1 \\ 0 & 1 & -L_2 \\ 1 & 0 & L_1 \\ 0 & 1 & L_2 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{5.5}$$

Then the rotation speed and the orientation of the wheels can be computed.

$$\begin{bmatrix} \dot{\varphi}_1 \\ \beta_1 \\ \dot{\varphi}_2 \\ \beta_2 \\ \dot{\varphi}_3 \\ \beta_3 \\ \dot{\varphi}_4 \\ \beta_4 \end{bmatrix}_{wheels} = \begin{bmatrix} \frac{1}{r} \cdot \sqrt{\dot{x}_1{}^2 + \dot{y}_1{}^2} \\ \operatorname{atan}\left({}^{\dot{x}_1}/_{\dot{y}_1} \right) \\ \frac{1}{r} \cdot \sqrt{\dot{x}_2{}^2 + \dot{y}_2{}^2} \\ \operatorname{atan}\left({}^{\dot{x}_2}/_{\dot{y}_2} \right) \\ \frac{1}{r} \cdot \sqrt{\dot{x}_3{}^2 + \dot{y}_3{}^2} \\ \operatorname{atan}\left({}^{\dot{x}_3}/_{\dot{y}_3} \right) \\ \frac{1}{r} \cdot \sqrt{\dot{x}_4{}^2 + \dot{y}_4{}^2} \\ \operatorname{atan}\left({}^{\dot{x}_4}/_{\dot{y}_4} \right) \end{bmatrix} \tag{5.6}$$

If the reduction ratios are known it is possible to compute the speed and position of the control motors.

$$\begin{bmatrix} \dot{\varphi}_1 \\ \beta_1 \\ \dot{\varphi}_2 \\ \beta_2 \\ \dot{\varphi}_3 \\ \beta_3 \\ \dot{\varphi}_4 \\ \beta_4 \end{bmatrix}_{motors} = \begin{bmatrix} \frac{i}{r} \cdot \sqrt{\dot{x}_1{}^2 + \dot{y}_1{}^2} \\ \frac{Z_c}{Z_p} \cdot \operatorname{atan}\left({}^{\dot{x}_1}/_{\dot{y}_1} \right) \\ \frac{i}{r} \cdot \sqrt{\dot{x}_2{}^2 + \dot{y}_2{}^2} \\ \frac{Z_c}{Z_p} \cdot \operatorname{atan}\left({}^{\dot{x}_2}/_{\dot{y}_2} \right) \\ \frac{i}{r} \cdot \sqrt{\dot{x}_3{}^2 + \dot{y}_3{}^2} \\ \frac{Z_c}{Z_p} \cdot \operatorname{atan}\left({}^{\dot{x}_3}/_{\dot{y}_3} \right) \\ \frac{i}{r} \cdot \sqrt{\dot{x}_4{}^2 + \dot{y}_4{}^2} \\ \frac{Z_c}{Z_p} \cdot \operatorname{atan}\left({}^{\dot{x}_4}/_{\dot{y}_4} \right) \end{bmatrix} \tag{5.7}$$

5.4.4. Formulation if AGV can rotate from any point C

It is possible to calculate the speed on each wheel for a rotating centre C.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{x}_2 \\ \dot{y}_2 \\ \dot{x}_3 \\ \dot{y}_3 \\ \dot{x}_4 \\ \dot{y}_4 \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} 1 & 0 & -L_1 + c_y \\ 0 & 1 & L_2 - c_x \\ 1 & 0 & -L_1 + c_y \\ 0 & 1 & -L_2 - c_x \\ 1 & 0 & L_1 + c_y \\ 0 & 1 & -L_2 - c_x \\ 1 & 0 & L_1 + c_y \\ 0 & 1 & L_2 - c_x \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{5.8}$$

Then the rotation speed and the orientation of the wheels and motors can be computed using equations 5.6 and 5.7.

5.5. High load omnidirectional wheels

The Swedish wheel has small rollers attached around the circumference of the wheel. These rollers are passive and the only controlled axis is the wheel's primary axis. The rollers add an extra degree of freedom to the wheel, and then the wheel can kinematically move along many possible trajectories.

The Swedish wheels are well known in the robotics departments of all universities and it is possible to purchase small Swedish wheels for robot kits. However it has been impossible to purchase Swedish wheels with high payload. There are manufacturers that use these special wheels in mobile lifting platforms or large vehicles with high manoeuvrability but they do not sell the wheels to other competitors.

Figures 5.8 and 5.9 show an example of the commercial Swedish wheels available; the wheel diameter is 0,1m and the material of the wheel rim is nylon.

Figure 5.8 *VEX Robotics* 45º Swedish wheel 4" diameter **[38]**

Figure 5.9 *VEX Robotics* 90º Swedish wheel 4" diameter **[38]**

I have developed, manufactured, and tested 2 types of Swedish wheels for *AGVs* with high payload in the company where I work. Both wheels have exactly the same diameter and the same wheel flange in order to be interchangeable.

I have developed and designed Swedish wheels with the rollers at ±45º from the wheel shaft (Figure 5.10) and Swedish wheels with the rollers at 90º (Figure 5.11).

The wheels have independent driving system and independent shock absorbers. These types of wheels have been used in semi-automated vehicles applied to the *CAMI* with good results.

In the next future probably I will design a smaller version of the wheels and a different shock absorber in order to fit the omnidirectional wheels in smaller vehicles with similar load per wheel.

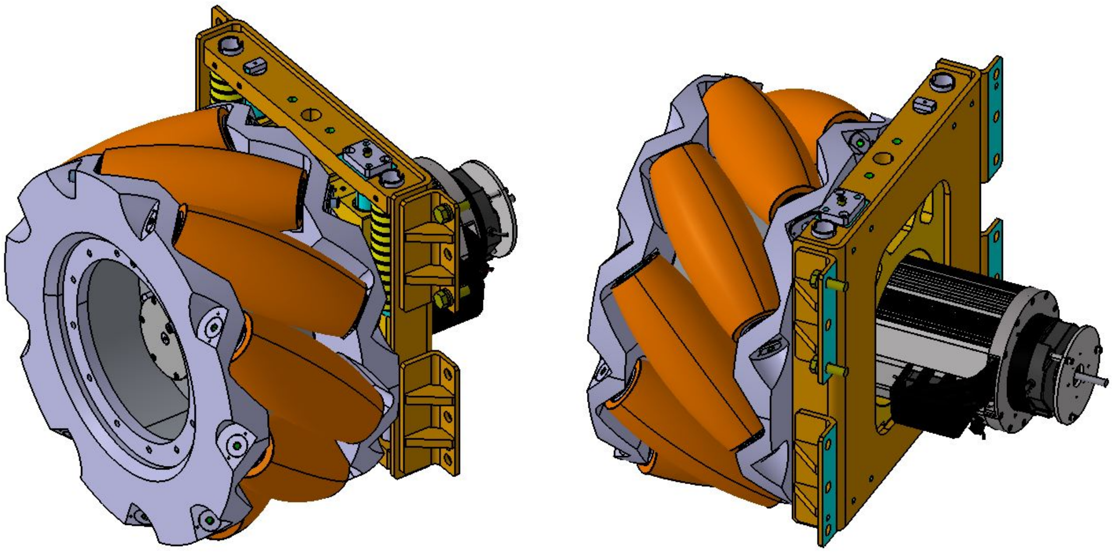


Figure 5.10 *ARITEX* 45º Swedish wheel

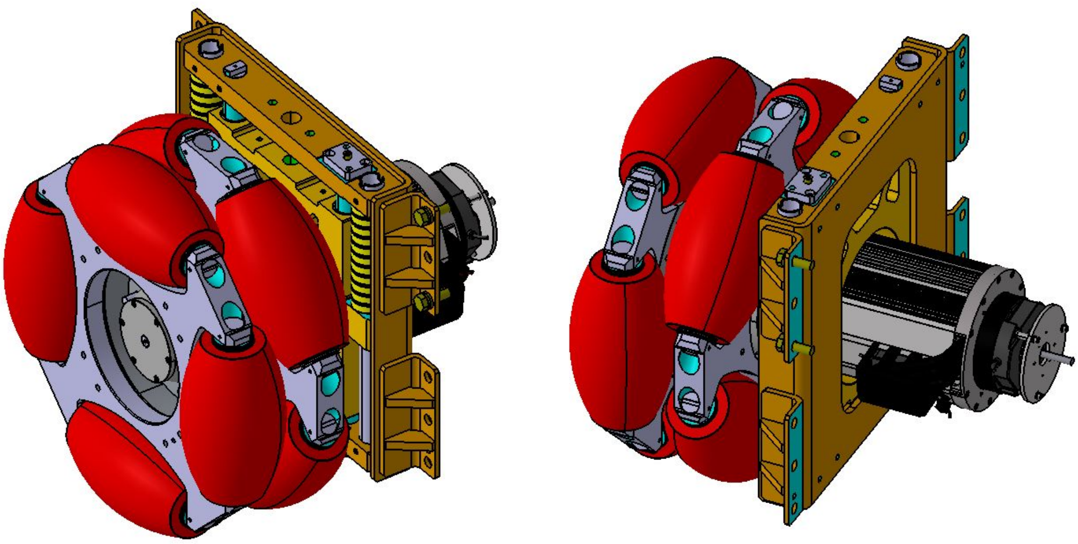


Figure 5.11 *ARITEX* 90º Swedish wheel

The key characteristics of the *ARITEX* Swedish wheels are:

- 2 Types of wheels with same dimensions. They are interchangeable.
    - 45º Swedish wheel.
    - 90º Swedish wheel.
- Wheel diameter of 0,6 m.
- Payload of 3.000 kg per wheel.
- Driving motor of 2,5 kW with independent control per wheel.
- Integrated gearbox with high radial load capacity.
- Independent shock absorber system.
- Roller shafts manufactured with hardened steel.
- Rollers with high capacity combined bearings (axial-radial).
- Wheel rim manufactured with high strength aluminium.

The high load Swedish wheels allow the design *AGV* and *SAGV* for the aeronautic industry with degree of manoeuvrability 3; that means that the instantaneous rotation centre can be located anywhere in the plane and the vehicle has very high manoeuvrability.

5.6. AGV with 3 motorized 90º Swedish wheels

5.6.1. AGV arrangement overview

The 90º Swedish wheel only give velocity to the vehicle in one direction, for this reason it is necessary to install wheels in different orientations in order to move the vehicle in any direction. In this particular case the 3 driving wheels have been installed dividing the circumference in 3 equal arcs.

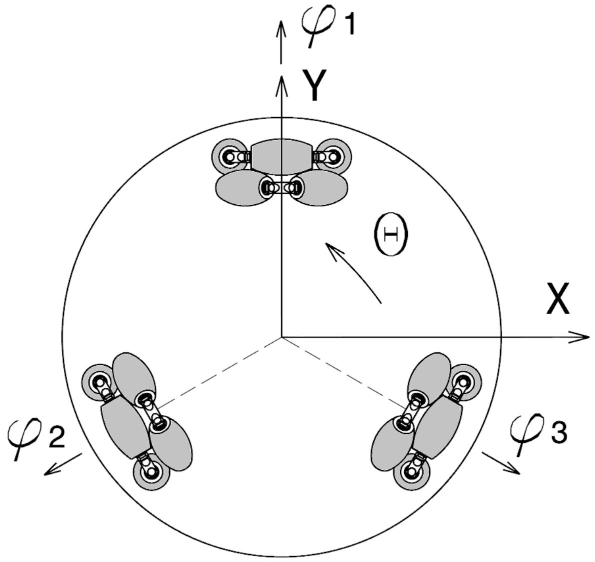


Figure 5.12 Schema of 3 90º Swedish *AGV*

This wheel configuration is not common in the industrial environment however there are many university robots with the same wheel arrangement.

The degree of manoeuvrability is 3; the *IRC* can be placed at any point of the plane and the *AGV* is able to move in any direction and rotate form any point. There are 3 driving wheels, however during motion, the wheel plane of some wheels is not always aligned with the desired velocity vector and hence, the effective number of driving wheels is only 2.

The degrees of freedom of the vehicle are 3; the displacement in the longitudinal axis X, the displacement in the transversal axis Y and the rotation in the vertical axis Z. The number of control variables is 3; the rotational speed of the motor installed in the 3 wheels. Then the system is not hyperstatic nor over determined.

This system is simple in terms of control and there are no redundant variables. Moreover it is not necessary to have a levelling system on the *AGV* because there are only 3 contact points (the 3 wheels) and then these 3 wheels will be always in contact with the ground.

5.6.2. Antecedents

COMAC purchased to *ARITEX* the assembly line of the centre wing box (*CWB*) of the airplane C919. One semi automated guided vehicle with 3 motorized wheels is part of this assembly line. The main functions of the *SAGV* are to transfer the assembly jig with the *CWB* between the working stations of the assembly line.

The *CWB* is assembled on top of an assembly jig in different stations. Once all the operations performed in a working station are done, the S*AGV* picks up the assembly jig with the *CWB* being assembled and transfers it to the next station. The *SAGV* is also used to rotate the *CWB* in the drilling station.

The *CWB SAGV* has an optical positioning system that enables the vehicle to follow lines painted in the floor, to identify the assembly station and to rotate the vehicle with respect to the assembly station. The optical positioning system is based on a camera installed on board the vehicle and a set of led lights. I was the design leader of this *SAGV.* All the responsibilities of this job are described in Appendix A.4. The *CWB SAGV* was delivered and accepted by *COMAC* in October 2014.

Figure 5.13 shows the vehicle used in the *COMAC* Centre Wing Box assembly line.

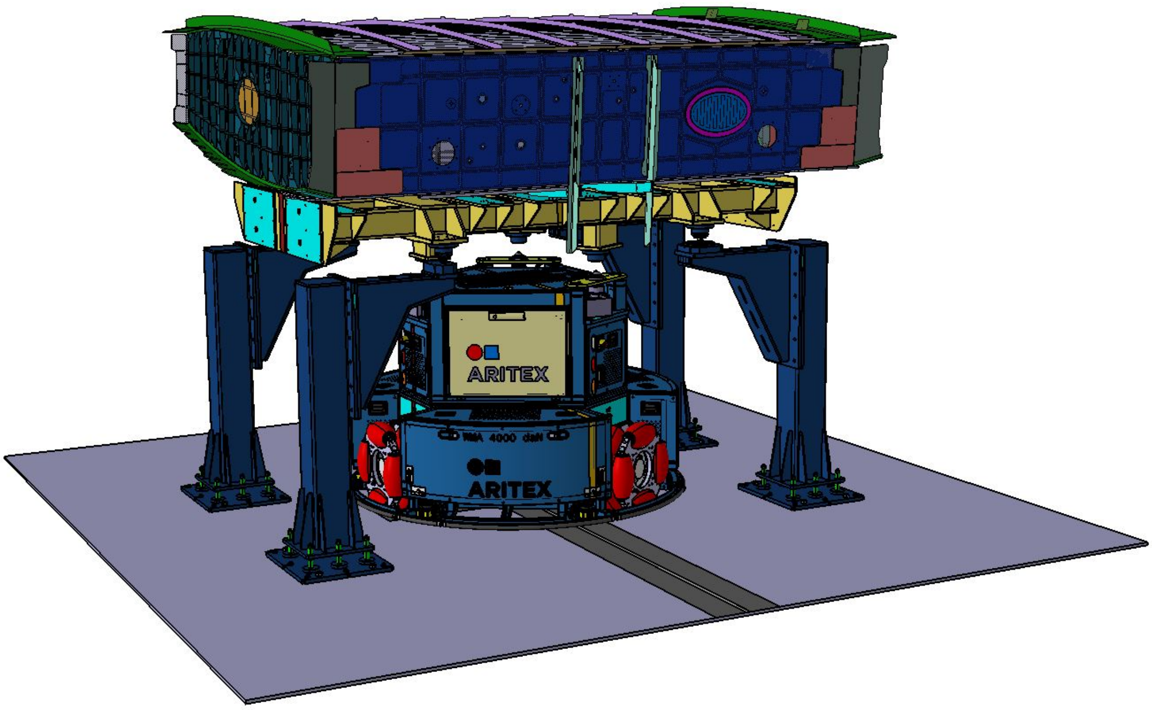


Figure 5.13 *SAGV* with assembly jig, *CWB* and support columns

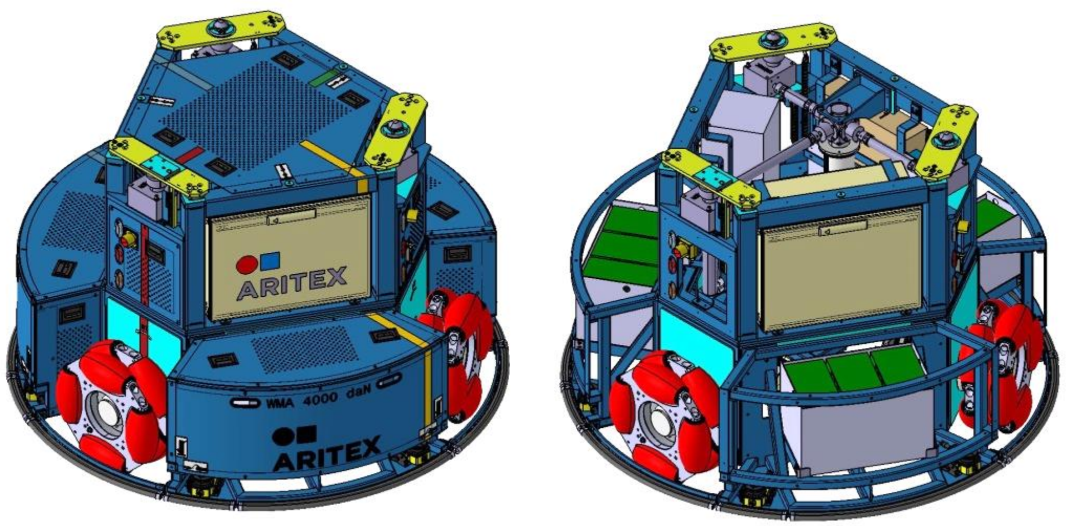


Figure 5.14 Isometric views of *CWB SAGV*

Figure 5.14 right shows the vehicle without the metal sheet covers. It is possible to see the battery cells in green colour, the lifting system in the top, the control box in the front and the 3 Swedish wheels in the sides. Also it is possible to see the safety laser and the safety edge around the lower perimeter of the vehicle.

The overall dimensions, mass and payload of the vehicle used in the *CWB* assembly line are: D = 2,4 m, H = 1,5 m, m = 3.100 kg, and PL = 3.700 kg.

The *CWB SAGV* with the 3 motorized wheels is an optimal solution in terms of number of wheels and number of motors. The vehicle only has 3 sustaining points, the 3 wheels. Then it is not necessary to install a levelling system to ensure the wheel contact.

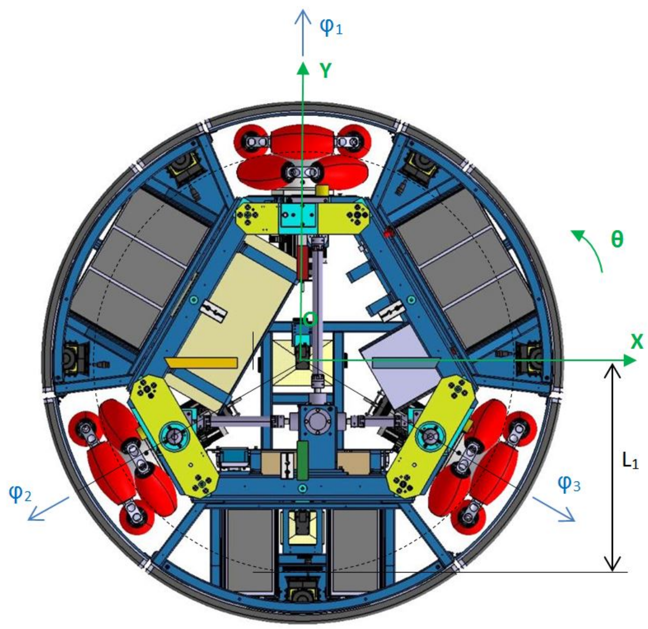


Figure 5.15 Top view of 3 motorized 90º Swedish wheel *SAGV*

5.6.3. Definition of variables and parameters

The main variables of the *AGV* with 3 90º Swedish wheels are show in Figures 5.12 and 5.15. An inherent parameter of the *CWB AGV* is the angle between the driving wheels. The wheels are uniformly distributed in a circumference of radius L_1, then the angle between driving wheels is 120º. The orientations of the different wheel planes relative to the chassis are: $\beta_1 = 0$, $\beta_2 = 120º$ and $\beta_3 = 240º$.

5.6.4. Formulation if AGV only can rotate from the origin P

$$\begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} \cos\beta_1 & \sin\beta_1 & -L_1 \\ \cos\beta_2 & \sin\beta_2 & -L_1 \\ \sin\beta_3 & \sin\beta_3 & -L_1 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \quad \textbf{(5.9)}$$

$$\begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} 1 & 0 & -L_1 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} & -L_1 \\ \frac{-1}{2} & -\frac{\sqrt{3}}{2} & -L_1 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \quad \textbf{(5.10)}$$

Then:

$$\begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \end{bmatrix} = A \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \quad \textbf{(5.11)}$$

$$A^{-1} \begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \end{bmatrix} = A^{-1} \cdot A \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \quad \textbf{(5.12)}$$

$$A^{-1} = \frac{r}{i} \cdot \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ \frac{1}{L_1} & \frac{1}{L_1} & \frac{1}{L_1} \end{bmatrix} \quad \textbf{(5.13)}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \frac{r}{3\,i} \cdot \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ \frac{1}{L_1} & \frac{1}{L_1} & \frac{1}{L_1} \end{bmatrix} \cdot \begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \end{bmatrix} \quad \textbf{(5.14)}$$

5.6.5. Formulation if AGV can rotate from any point C

The point C is the instantaneous centre of rotation. In an omnidirectional vehicle the *ICR* can be located anywhere. In a non-omnidirectional vehicle the location of the *ICR* has more constraints. $C = \left(c_x\,, c_y\right)$ is on the vehicle reference frame and can be considered as point of the rigid body. The origin P is $P = (0\,,0)$ in local reference. Then, the speed of any point $Q = \left(q_x\,, q_y\right)$ can be calculated.

$$\overrightarrow{PC} = (c_x - p_x \;, \quad c_y - p_y) = (c_x \;, \quad c_y) \tag{5.15}$$

$$\overrightarrow{CP} = (p_x - c_x \,, \quad p_y - c_y) = (-c_x \,, \quad -c_y) \tag{5.16}$$

$$\vec{V}_Q = \vec{V}_C + \dot{\theta} \times \overrightarrow{CQ} \tag{5.17}$$

The speed of any point Q is expressed as the speed of the *ICR* plus the rotational speed around the *ICR*.

Now the *IRC* is not located in the origin P, it is necessary to add the term $\dot{\theta} \times \overrightarrow{CQ}$ to equation (5.15).

$$\begin{bmatrix}\dot{\varphi}_1\\ \dot{\varphi}_2\\ \dot{\varphi}_3\end{bmatrix} = \frac{i}{r}\cdot\begin{bmatrix}1 & 0 & -L_1\\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & -L_1\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & -L_1\end{bmatrix}\cdot\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} - \dot{\theta}\cdot\frac{i}{r}\cdot c_x\cdot\begin{bmatrix}0\\ \frac{\sqrt{3}}{2}\\ -\frac{\sqrt{3}}{2}\end{bmatrix} - \dot{\theta}\cdot\frac{i}{r}\cdot c_y\cdot\begin{bmatrix}-1\\ \frac{1}{2}\\ \frac{1}{2}\end{bmatrix} \tag{5.18}$$

Equation (5.18) can also be expressed as:

$$\begin{bmatrix}\dot{\varphi}_1\\ \dot{\varphi}_2\\ \dot{\varphi}_3\end{bmatrix} = \frac{i}{r}\cdot\begin{bmatrix}1 & 0 & -L_1 + c_y\\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & -L_1 - \frac{\sqrt{3}}{2}c_x - \frac{c_y}{2}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & -L_1 + \frac{\sqrt{3}}{2}c_x - \frac{c_y}{2}\end{bmatrix}\cdot\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} \tag{5.19}$$

5.7. AGV with 4 motorized 90º Swedish wheels

5.7.1. AGV arrangement overview

As seen in the previous section it is necessary to install the 90º Swedish in different orientations in order to be able to move the vehicle in any direction. An alternative to the wheel arrangement found in the preceding point is to add an extra 90º Swedish wheel and distribute the wheels in the 4 corners of a rectangle, as shown in Figure 5.16.

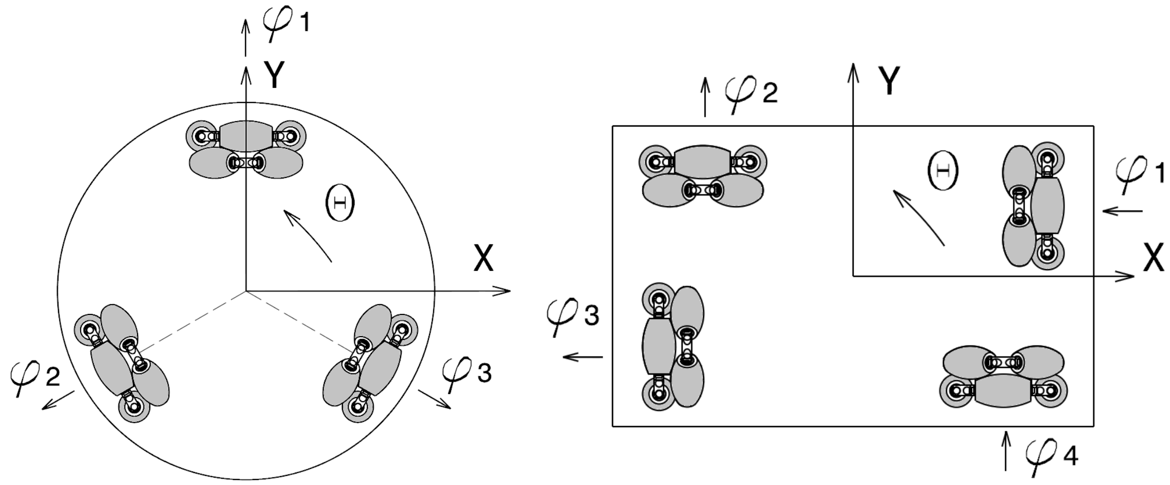


Figure 5.16 Schema of 3 90º Swedish *AGV* and 4 90º Swedish *AGV*

There are 4 driving wheels. However, some wheels have no influence on the vehicle motion because they are not aligned with the desired velocity vector. It is easy to see that wheels 2 and 4 do not transmit power to the vehicle in the longitudinal displacements and that wheels 1 and 3 do not transmit power in the transversal axis. Then the effective number of driving wheels is only 2.

The system is hyperstatic and over determined. One of the wheels has to copy the other 3, otherwise, the wheels will slip. Moreover it is necessary to have a levelling system in order to make sure that all the wheels are in contact with the ground.

The main characteristics of the vehicle are:

- The vehicle is able to move in any direction.
- The vehicle is able to rotate form any point.
- The degree of manoeuvrability is 3.
- The number of driving wheels is 4, but the effective driving wheels are 2.
- The number of motors is 4.

5.7.2. Antecedents

COMAC purchased to *ARITEX* the assembly line of the horizontal tail plane of the airplane C919. One auxiliary vehicle with 4 motorized wheels is part of this assembly line.

The main functions of the vehicle are extracting the *HTP* from the assembly jig (Figure 5.18) and transferring it from the assembly area to the delivery zone. The *HTP* is assembled inside a vertical assembly jig with the shape of a rectangular frame. This frame is transferred between stations with an overhead transport system and once all the assembly process of the *HTP* is done, the auxiliary vehicle extracts the *HTP* from the assembly frame and places it in the final delivery area.
The *HTP* is extracted from the vehicle using slings.

In order to have a vehicle with high manoeuvrability, 4 90º Swedish wheels were used. Combining the speed of the 4 wheels, the vehicle is able to move in any direction and rotate form any point.

An operator controls freely the vehicle using a radio frequency remote control.
Mechanical guides are installed in front of the assembly area in order to help the operator to place the vehicle in the right position before extracting the *HTP.*
The level of automation is low; the vehicle is manually guided.

The overall dimensions, mass and payload of the vehicle used to extract the *HTP* are: L = 4,7 m, W = 1,85 m, H_b = 1 m, m = 6.250 kg, and PL = 1.000 kg.

As with the abovementioned design, I was also the design leader of this *MGV.*

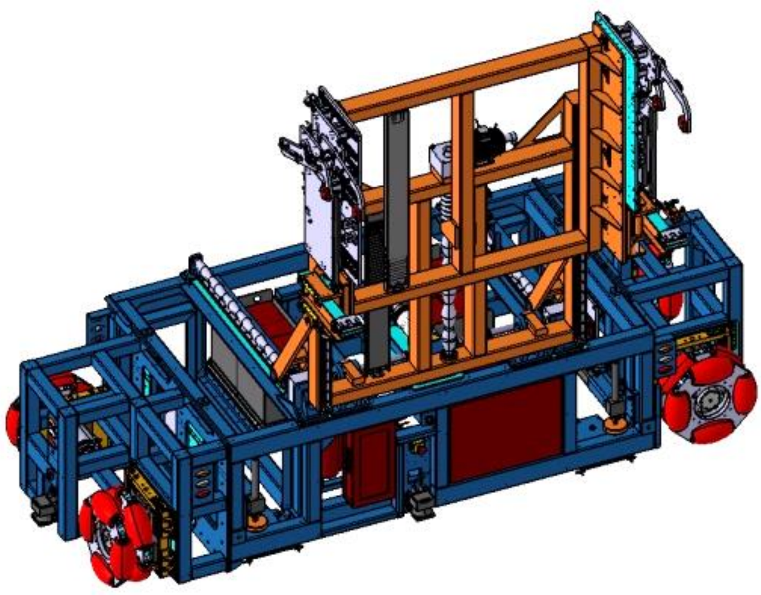


Figure 5.17 Isometric view of *HTP MGV*

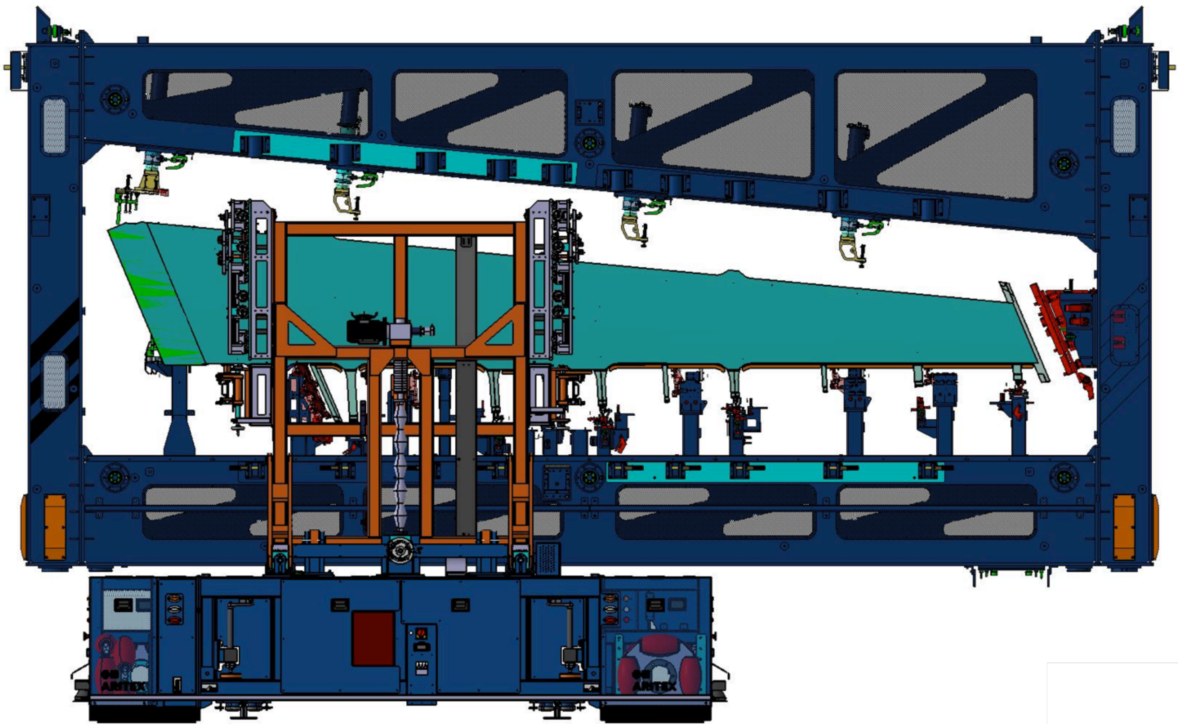


Figure 5.18 Front view of the *MGV* extracting the *HTP*

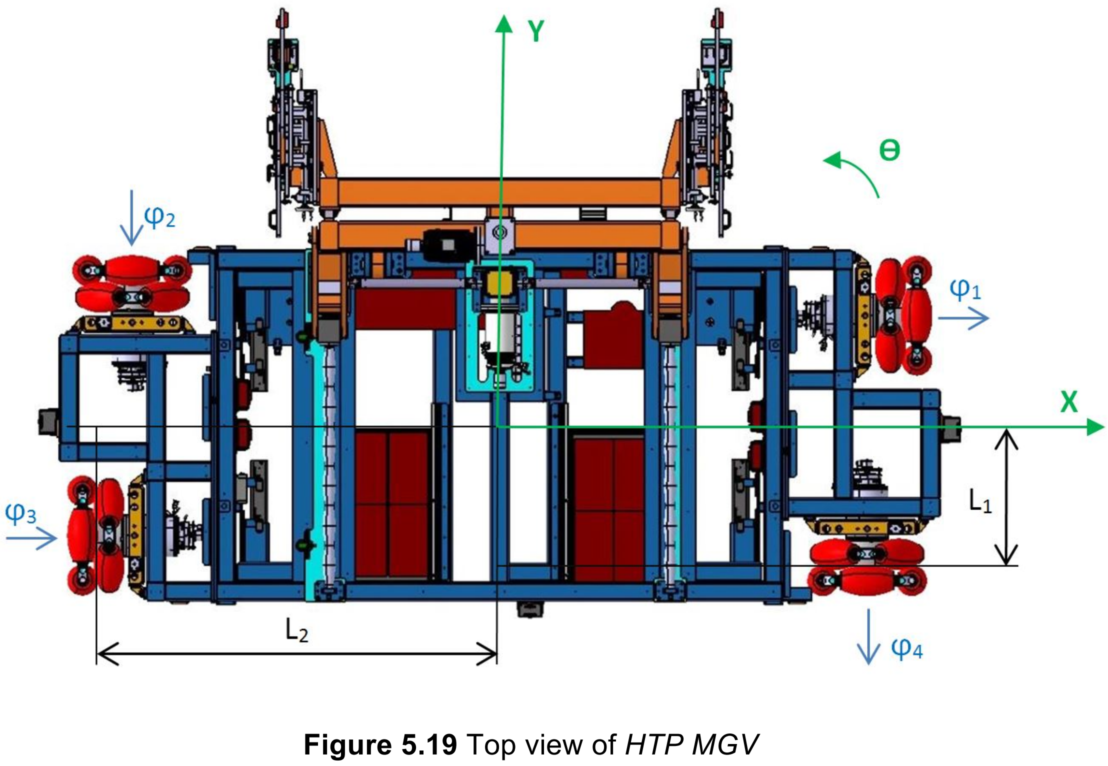


Figure 5.19 Top view of *HTP MGV*

5.7.3. Definition of variables and parameters

Figure 5.19 shows the main variables of the *AGV.*

5.7.4. Formulation if AGV only can rotate from the origin P

$$\begin{bmatrix}\dot{\varphi}_1\\\dot{\varphi}_2\\\dot{\varphi}_3\\\dot{\varphi}_4\end{bmatrix}=\frac{1}{r}\cdot\begin{bmatrix}0&1&L_2\\1&0&L_1\\0&1&L_2\\1&0&L_1\end{bmatrix}\cdot\begin{bmatrix}\dot{x}\\\dot{y}\\\dot{\theta}\end{bmatrix} \tag{5.20}$$

Equation (5.21) is a simplification of notation. Where $[\dot{\varphi}_{4x1}]$ is the vector of motor speeds, $\dot{\xi}_R$ is the vector of vehicle speeds and $[D_{4x3}]$ is a matrix related with the configuration of the vehicle.

$$\dot{\xi}_R=\begin{bmatrix}\dot{x}\\\dot{y}\\\dot{\theta}\end{bmatrix}$$

$$[\dot{\varphi}_{4x1}]=\frac{1}{r}\cdot[D_{4x3}]\cdot\dot{\xi}_R \tag{5.21}$$

5.7.5. Formulation if AGV can rotate from any point C

It is necessary to add the speed introduced by $\dot{\theta}$ and the distance $\overrightarrow{PC}$ to the previous matrix.

$$\begin{bmatrix}\dot{\varphi}_1\\\dot{\varphi}_2\\\dot{\varphi}_3\\\dot{\varphi}_4\end{bmatrix}=\frac{i}{r}\cdot\begin{bmatrix}0&1&L_2\\1&0&L_1\\0&1&L_2\\1&0&L_1\end{bmatrix}\cdot\begin{bmatrix}\dot{x}\\\dot{y}\\\dot{\theta}\end{bmatrix}-\dot{\theta}\cdot\frac{i}{r}\cdot c_x\cdot\begin{bmatrix}-1\\1\\-1\\1\end{bmatrix}-\dot{\theta}\cdot\frac{i}{r}\cdot c_y\cdot\begin{bmatrix}-1\\-1\\-1\\-1\end{bmatrix} \tag{5.22}$$

Equation (5.22) could be condensed as:

$$[\dot{\varphi}_{4x1}]=\frac{i}{r}\cdot[D_{4x3}]\cdot\dot{\xi}_R-\dot{\theta}\cdot\frac{i}{r}\cdot c_x\cdot\begin{bmatrix}-1\\1\\-1\\1\end{bmatrix}-\dot{\theta}\cdot\frac{i}{r}\cdot c_y\cdot[-1_{4x1}] \tag{5.23}$$

5.8. AGV with 8 motorized 90º Swedish wheels

5.8.1. AGV arrangement overview

In order to carry heavy loads a vehicle with 8 driving 90º Swedish wheels has been designed. The wheel arrangement is very similar to the design of the previous section. The main difference is that it has double the number of driving wheels, eight driving wheels in total. Four driving wheels have been installed aligned with the longitudinal axis and the other four aligned with the transversal axis. Combining the speed of these 8 wheels the vehicle is able to move in any direction and rotate form any point. Also it has 10 free Swedish wheels that do not constraint the *AGV* motion. The main problem is that the system has more redundant variables and it is hyperstatic.

The main characteristics of the vehicle are:

- The vehicle is able to move in any direction.
- The vehicle is able to rotate form any point.
- The degree of manoeuvrability is 3.
- The number of driving wheels is 8, but the effective driving wheels are 4.
- The number of motors is 8.

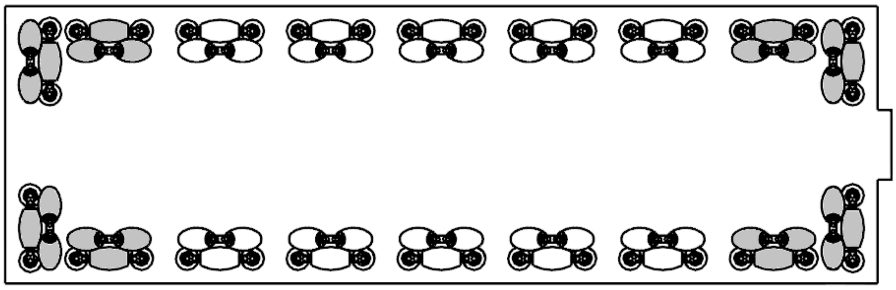


Figure 5.20 Schema of *MW* and *HTP* moulds *SAGV*

The schema of Figure 5.20 can be simplified as shown in Figure 5.21 because the 10 middle wheels have no contribution on the vehicle motion.

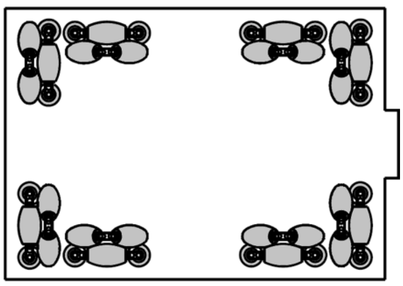


Figure 5.21 Schema of *MW* and *HTP* moulds *SAGV*

5.8.2. Antecedents

COMAC purchased to *ARITEX* two omnidirectional vehicles to introduce and extract the wing skin mould and the HTP skin mould in an autoclave.

These *SAGV* have 8 motorized wheels and 10 free wheels and could work separately to transport the *HTP* mould or together to transport the Main Wing mould.

The overall dimensions, mass and payload of the *HTP* mould and Main Wing mould *SAGV* are: L = 9,5 m, W = 2,1 m, H = 0,7 m, m = 13.000 kg, and PL = 25.000 kg.

The vehicles have been designed and manufactured by *ARITEX*. I was also the design leader of this project. This *SAGV* is under the final acceptance in the *COMAC* facilities in March 2015.

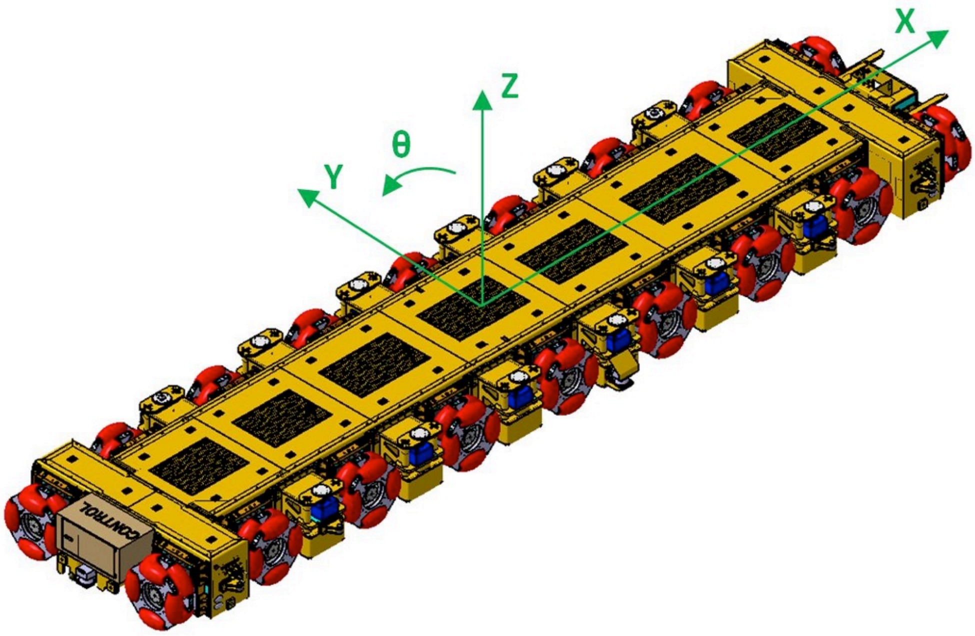


Figure 5.22 Isometric view of *MW* and *HTP* moulds *SAGV*

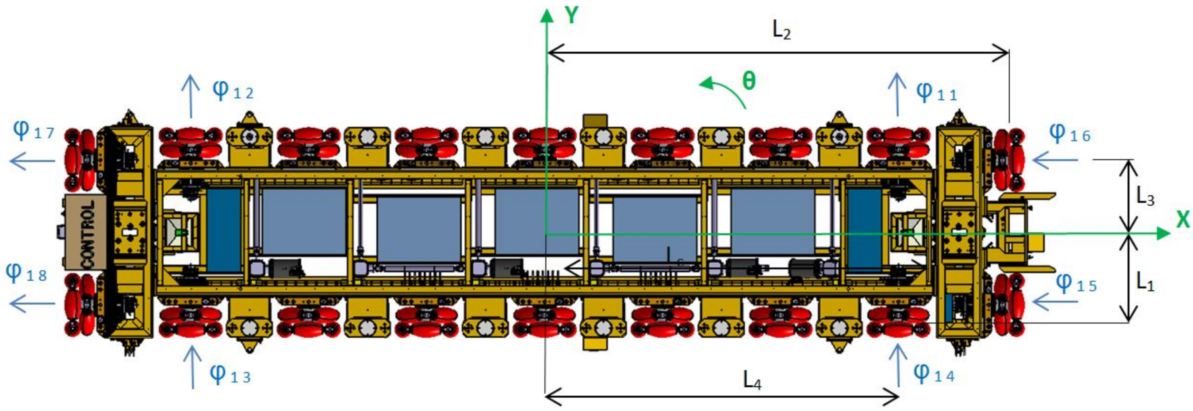


Figure 5.23 Top view of *MW* and *HTP* moulds *SAGV*

5.8.3. Definition of variables and parameters

Figure 5.23 shows the main variables and parameters of the *AGV.*

5.8.4. Formulation if AGV only can rotate from the origin P

$$\begin{bmatrix} \dot{\varphi}_{1\,1} \\ \dot{\varphi}_{1\,2} \\ \dot{\varphi}_{1\,3} \\ \dot{\varphi}_{1\,4} \\ \dot{\varphi}_{1\,5} \\ \dot{\varphi}_{1\,6} \\ \dot{\varphi}_{1\,7} \\ \dot{\varphi}_{1\,8} \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} 1 & 0 & -L_1 \\ 1 & 0 & -L_1 \\ 1 & 0 & L_1 \\ 1 & 0 & L_1 \\ 0 & 1 & L_2 \\ 0 & 1 & L_2 \\ 0 & 1 & -L_2 \\ 0 & 1 & -L_2 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{5.24}$$

5.8.5. Formulation if AGV can rotate from any point C

$$\begin{bmatrix} \dot{\varphi}_{1\,1} \\ \dot{\varphi}_{1\,2} \\ \dot{\varphi}_{1\,3} \\ \dot{\varphi}_{1\,4} \\ \dot{\varphi}_{1\,5} \\ \dot{\varphi}_{1\,6} \\ \dot{\varphi}_{1\,7} \\ \dot{\varphi}_{1\,8} \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} 1 & 0 & -L_1 \\ 1 & 0 & -L_1 \\ 1 & 0 & L_1 \\ 1 & 0 & L_1 \\ 0 & 1 & L_2 \\ 0 & 1 & L_2 \\ 0 & 1 & -L_2 \\ 0 & 1 & -L_2 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} + \dot{\theta} \cdot \frac{i}{r} \cdot (-c_x) \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} + \dot{\theta} \cdot \frac{i}{r} \cdot (-c_y) \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{5.25}$$

$$\begin{bmatrix} \dot{\varphi}_{1\,1} \\ \dot{\varphi}_{1\,2} \\ \dot{\varphi}_{1\,3} \\ \dot{\varphi}_{1\,4} \\ \dot{\varphi}_{1\,5} \\ \dot{\varphi}_{1\,6} \\ \dot{\varphi}_{1\,7} \\ \dot{\varphi}_{1\,8} \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} 1 & 0 & -L_1 - c_y \\ 1 & 0 & -L_1 - c_y \\ 1 & 0 & L_1 - c_y \\ 1 & 0 & L_1 - c_y \\ 0 & 1 & L_2 - c_x \\ 0 & 1 & L_2 - c_x \\ 0 & 1 & -L_2 - c_x \\ 0 & 1 & -L_2 - c_x \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{5.26}$$

$$[\dot{\varphi}_{8x1}] = \frac{i}{r} [A_{8x3}] \cdot \dot{\xi}_R - \dot{\theta} \cdot \frac{i}{r} \cdot c_x \begin{bmatrix} 0_{4x1} \\ 1_{4x1} \end{bmatrix} - \dot{\theta} \cdot \frac{i}{r} \cdot c_y \begin{bmatrix} 1_{4x1} \\ 0_{4x1} \end{bmatrix} \tag{5.27}$$

5.9. Two synchronized AGVs with 8 motorized 90º Swedish wheels

5.9.1. AGV arrangement overview

The *AGV* studied in the previous point has been doubled to transport longer payloads. Then the total number of driving wheels is 16; 8 wheels are aligned with the longitudinal axis and 8 with the transversal one.

The main characteristics of the vehicle are:

- The vehicle is able to move in any direction.
- The vehicle is able to rotate form any point.
- The degree of manoeuvrability is 3.
- The number of driving wheels is 16, but the effective driving wheels are 8.
- The number of motors is 16.

5.9.2. Antecedents

A very interesting solution to move large loads is to use more than a single *AGV*.
The easiest solution will be to mechanically couple 2 *AGVs* and move them as a single one. The next step will be to use 2 separated *AGVs* that cooperate to move a large payload.

The Main Wing mould of the *COMAC* C919 airplane will be moved using 2 *SAGV*.
Each *SAGV* has 8 motorized 90º Swedish wheels and 10 free 90º Swedish wheels.

ARITEX has designed and manufactured 2 *SAGV* and 2 auxiliary structures. I was the design leader of this project. These vehicles are under the final acceptance phase in *COMAC* in March 2015.

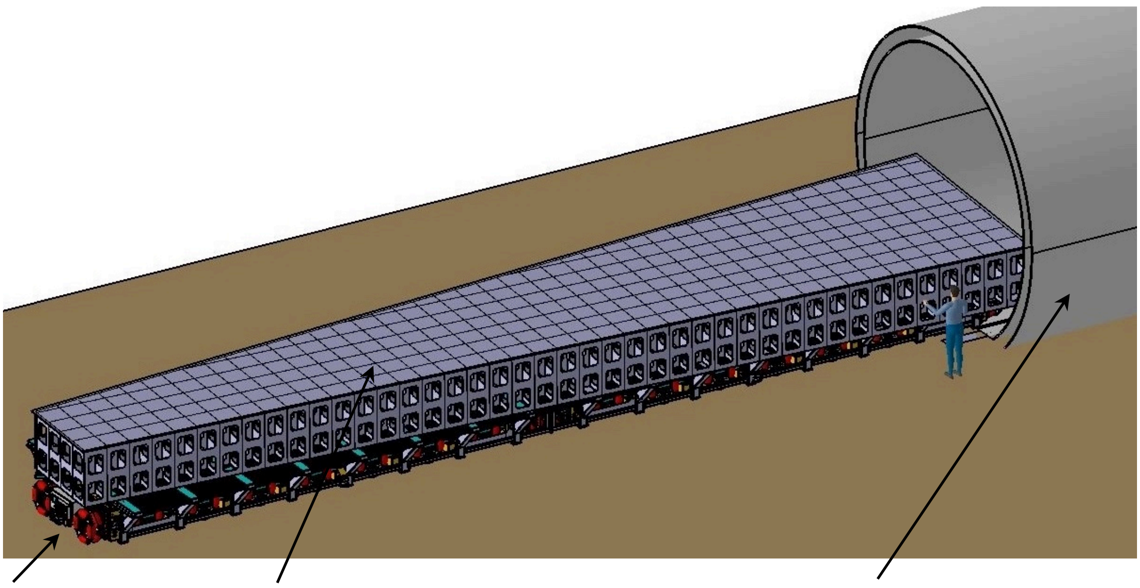


Figure 5.24 Wing skin mould being introduced in an autoclave

Figure 5.24 shows a simulation of 2 *SAGV* introducing the wing skin mould of the airplane *COMAC* C919 into an autoclave.
The overall dimensions, mass and payload of the *SAGV* used to transfer the wing mould are: L = 19 m, W = 2,1 m, H = 0,7 m, m = 26.000 kg, and PL = 50.000 kg.

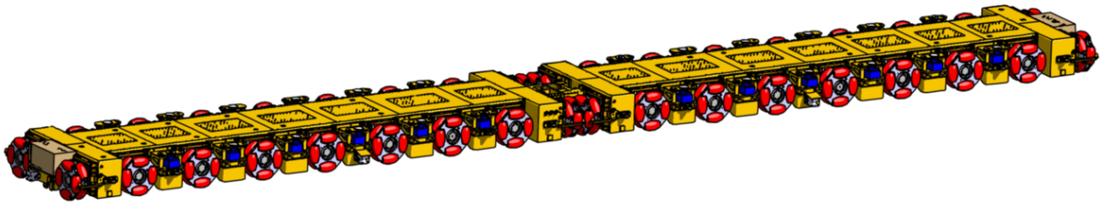


Figure 5.25 Double *SAGV*

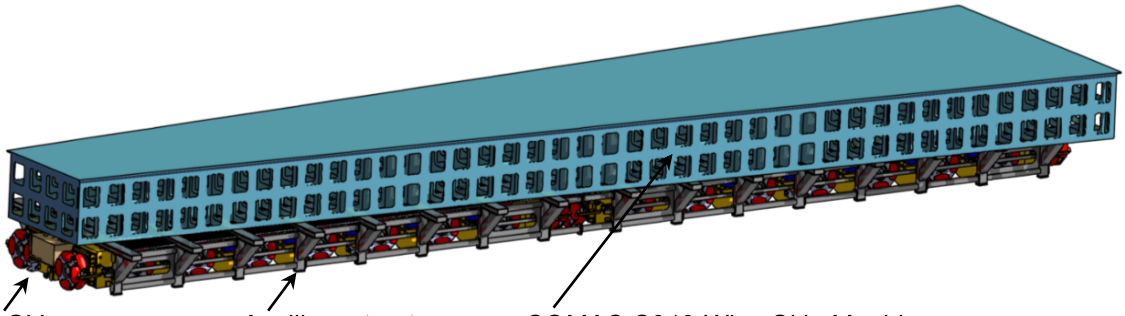


Figure 5.26 Wing skin mould being transported by double *SAGV*

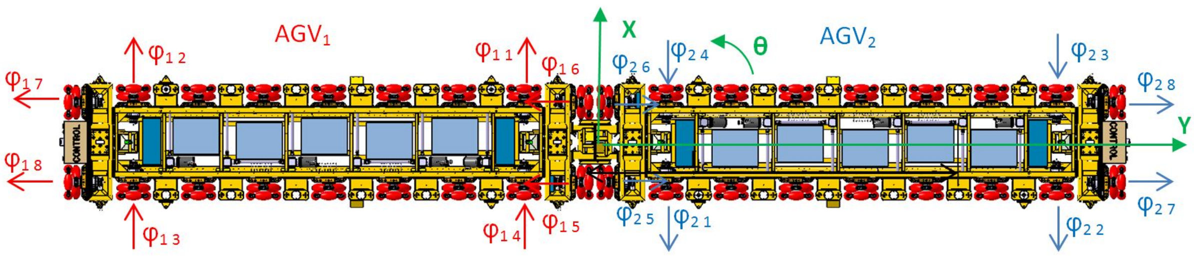


Figure 5.27 Top view of double *SAGV* variables

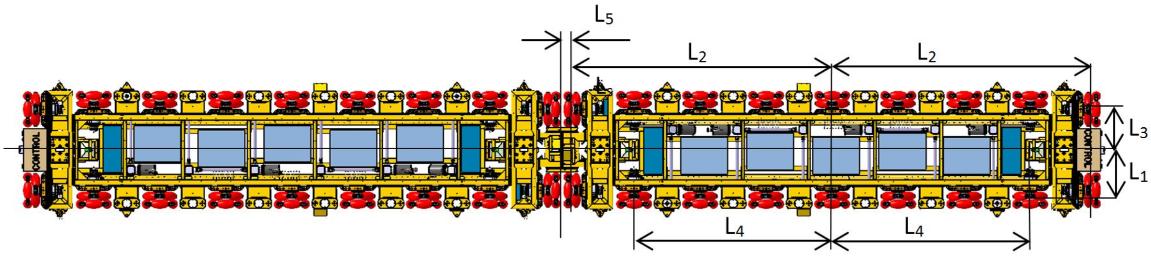


Figure 5.28 Top view of double *SAGV* parameters

5.9.3. Definition of variables and parameters

Figures 5.27 and 5.28 show the main variables and parameters. L_s is the distance between AGVs.

5.9.4. Formulation if AGV only can rotate from the origin P

$$\begin{bmatrix} \dot{\varphi}_{1\,1} \\ \dot{\varphi}_{1\,2} \\ \dot{\varphi}_{1\,3} \\ \dot{\varphi}_{1\,4} \\ \dot{\varphi}_{1\,5} \\ \dot{\varphi}_{1\,6} \\ \dot{\varphi}_{1\,7} \\ \dot{\varphi}_{1\,8} \\ \dot{\varphi}_{2\,1} \\ \dot{\varphi}_{2\,2} \\ \dot{\varphi}_{2\,3} \\ \dot{\varphi}_{2\,4} \\ \dot{\varphi}_{2\,5} \\ \dot{\varphi}_{2\,6} \\ \dot{\varphi}_{2\,7} \\ \dot{\varphi}_{2\,8} \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} 1 & 0 & -L_1 \\ 1 & 0 & -L_1 \\ 1 & 0 & L_1 \\ 1 & 0 & L_1 \\ 0 & 1 & -L_s \\ 0 & 1 & -L_s \\ 0 & 1 & -2L_2 - L_s \\ 0 & 1 & -2L_2 - L_s \\ -1 & 0 & -L_1 \\ -1 & 0 & -L_1 \\ -1 & 0 & L_1 \\ -1 & 0 & L_1 \\ 0 & -1 & -L_s \\ 0 & -1 & -L_s \\ 0 & -1 & -2L_2 - L_s \\ 0 & -1 & -2L_2 - L_s \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{5.28}$$

$$[\dot{\varphi}_{16x1}] = \frac{i}{r} \cdot [B_{16x3}] \cdot \dot{\xi}_R \tag{5.29}$$

5.9.5. Formulation if AGV can rotate from any point C

$$[\omega_{16x1}] = \frac{i}{r} \cdot [B_{16x3}] \cdot \dot{\xi}_R - \dot{\theta} \cdot \frac{i}{r} \cdot c_x \begin{bmatrix} 0_{4x1} \\ 1_{4x1} \\ 0_{4x1} \\ -1_{4x1} \end{bmatrix} - \dot{\theta} \cdot \frac{i}{r} \cdot c_y \begin{bmatrix} -1_{4x1} \\ 0_{4x1} \\ -1_{4x1} \\ 0_{4x1} \end{bmatrix} \tag{5.30}$$

5.10. AGVs with 4 motorized 45º Swedish wheels

5.10.1. AGV arrangement overview

An omnidirectional arrangement used successfully on several research robots consists of four 45º Swedish wheels, each one driven by an independent motor.
The wheels do not need a steering system to change the trajectory of the *AGV.*

The main characteristics of the vehicle are:

- The vehicle is able to move in any direction.
- The vehicle is able to rotate form any point.
- The degree of manoeuvrability is 3.
- The number of driving wheels is 4.
- The number of motors is 4.

The number of control motors installed is not the minimum as the wheel arrangement seen in Section 5.6 but the vehicle has improved stability. The shape of the *AGV* will be rectangular and it will be easier to adapt this geometry in order to use the vehicle to transport aeronautic structures.

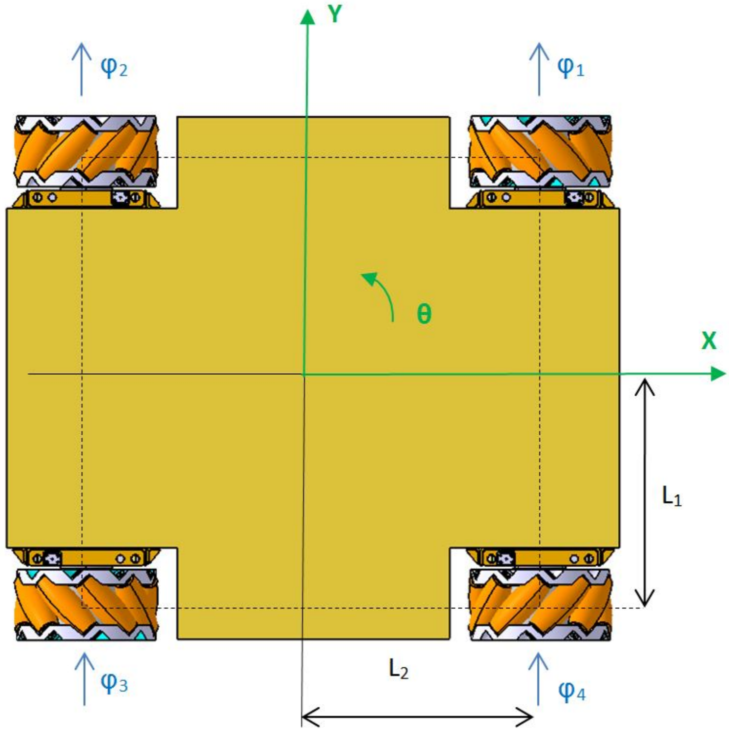


Figure 5.29 Top view of AGV with 4 45º Swedish

The vehicle has 4 wheels; it is hyperstatic and it is necessary to use shock absorbers in order to make sure that all the wheels are in contact with the ground. The correct contact of the wheels with the ground must be guaranteed in *AGVs* with Swedish wheels, contact with the ground is mandatory to avoid unpredictable trajectories.

5.10.2. Antecedents

5.10.2.1. MW and HTP moulds SAGV

Four 45º Swedish wheels where designed and manufactured by *ARITEX* in order to test an alternative design of wheel that could be very interesting in the aerospace sector.

These wheels where installed in the *AGV* designed to insert the *MW* mould and *HTP* mould in an autoclave. The main advantage of the new configuration is that the vehicle can be moved in any direction with only 4 driving motors instead of the 8 used in the previous design.

The results achieved where positive and the 45º Swedish wheels are going to be used in newer *AGVs*.

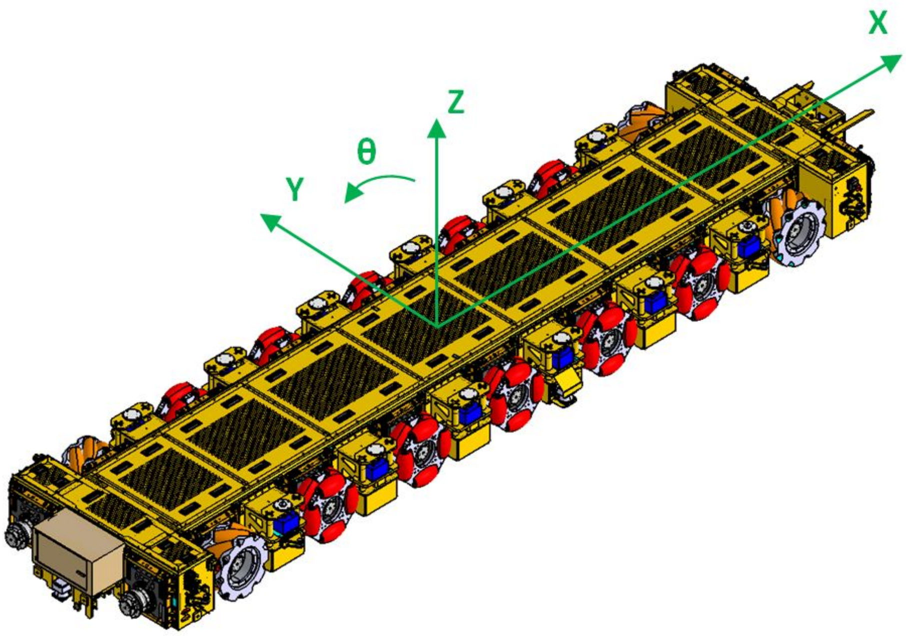


Figure 5.30 *MW* and *HTP* moulds *SAGV* with 4 45º Swedish wheels

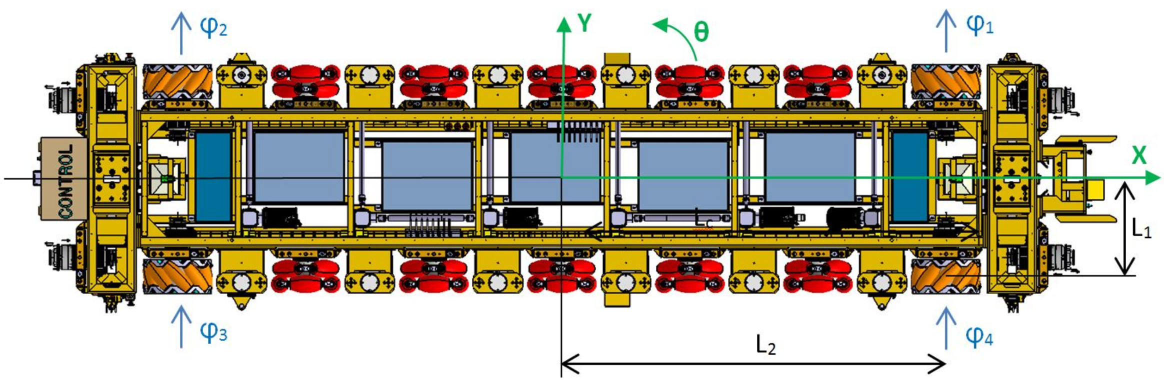


Figure 5.31 Top view of *MW* and *HTP* moulds *SAGV* with 4 45º Swedish wheels

5.10.2.2. VTP and Rudder extraction cart

COMAC purchased to *ARITEX* the assembly line of the Vertical Tail Plane, Section 19 and Tail Cone of the airplane C919. One auxiliary vehicle dedicated to extract the *VTP* and Rudder is part of this assembly line. The main functions of the vehicle are extracting the *VTP* from the assembly Jig and transferring it from the assembly area to the delivery zone.

The *VTP* is assembled inside a vertical assembly jig with the shape of a rectangular frame. This frame it is transferred between stations with an overhead transport system and once all the assembly process of the *VTP* is done the auxiliary vehicle extracts the *VTP* from the assembly frame and place it in the final delivery area. The *VTP* is extracted from the vehicle using slings. The process is exactly the same with the Rudder; the only differences are the interfaces.

In order to have a vehicle with high manoeuvrability 4 motorized 45º Swedish wheels were used. Combining the speed of the 4 wheels, the vehicle is able to move in any direction and rotate from any point.

The overall dimensions, mass and payload of the vehicle used to extract the *VTP* and the rudder are: L = 4,5 m, W = 3,6 m, H_b = 1 m, m = 8.500 kg, PL = 1.000 kg.

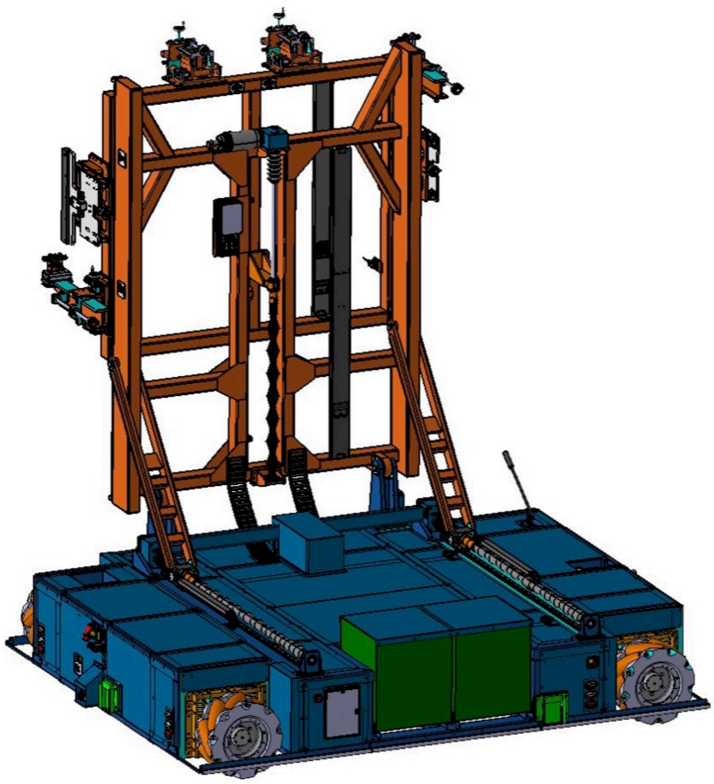


Figure 5.32 Isometric view of the VTP and rudder extraction cart

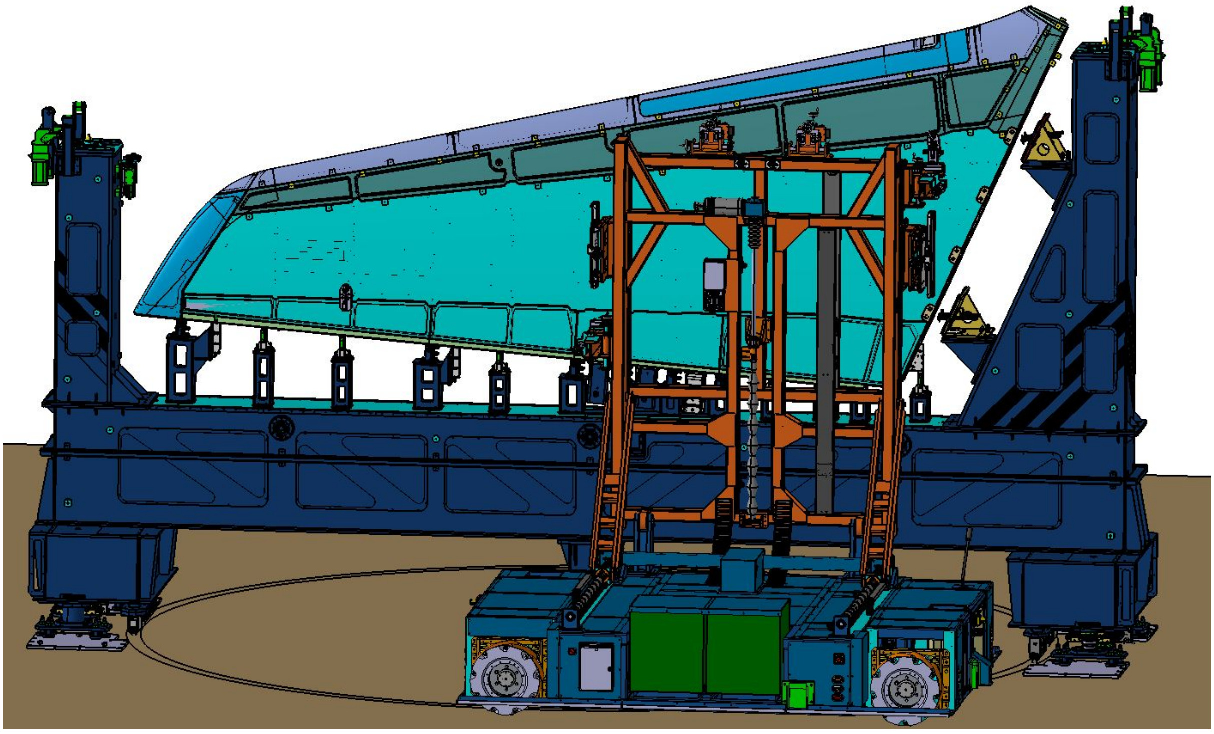


Figure 5.33 Extraction cart picking the *VTP* from the assembly jig

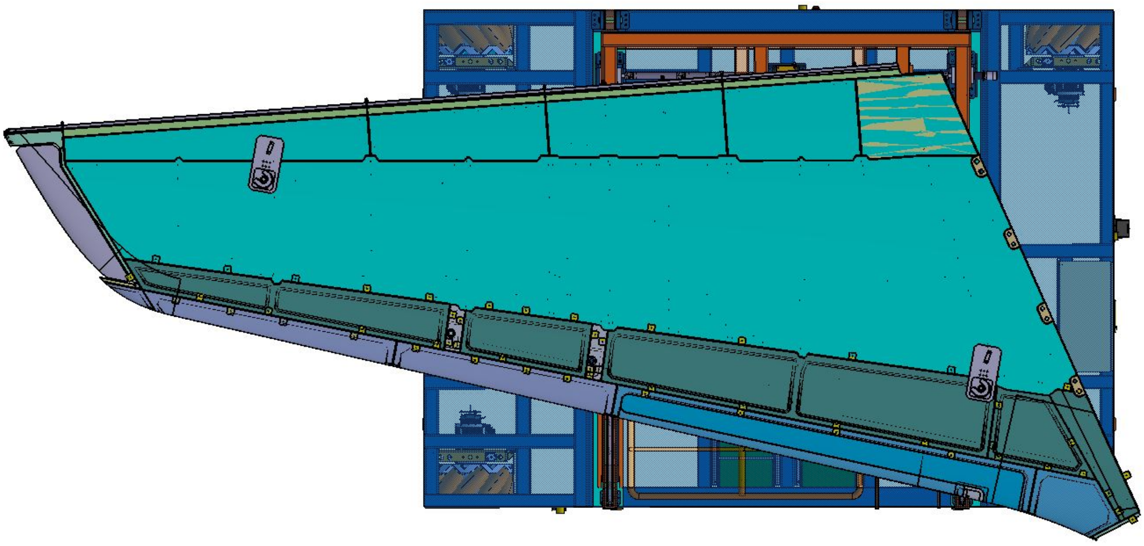


Figure 5.34 Top view of the extraction cart carrying the *VTP*

An operator controls the vehicle using a radio frequency remote control. The vehicle follows a line in the main corridors and stops in the right place using artificial vision cameras. The vehicle will be under construction in May 2015.

5.10.2.3. Junction cart

EMBRAER purchased to *ARITEX* a set of machines to be used in the Wing Final Assembly Line. Inside this set of machines there are 2 semi-automated vehicles dedicated to pick the wing from the last station of the Wing Final Assembly Line and install it in the fuselage in the Final Assembly Line. One vehicle will be dedicated to the left wing and the other to the right one.

The overall dimensions, mass and payload of the junction cart used to install the wings of the *E-Jets* are: L = 8 m, W = 3 m, H_b = 0,8 m, m = 8.500 kg, PL = 1.000 kg.

The vehicles have 8 45º Swedish wheels; 4 of these wheels are motorized and the other 4 are free. The vehicle is guided in the main corridors using cameras and lines painted in the floor. The operator must choose the speed and the sense of the movement using a radio frequency remote control. The vehicle is under construction in April 2015.

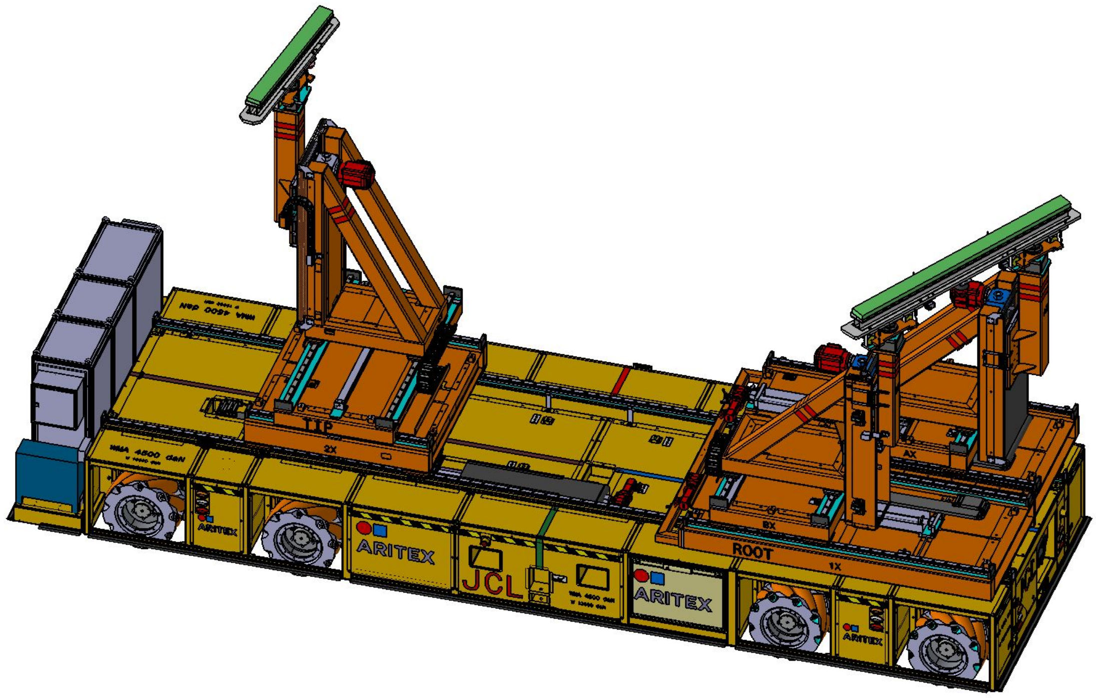


Figure 5.35 Isometric view of *WFA* junction cart

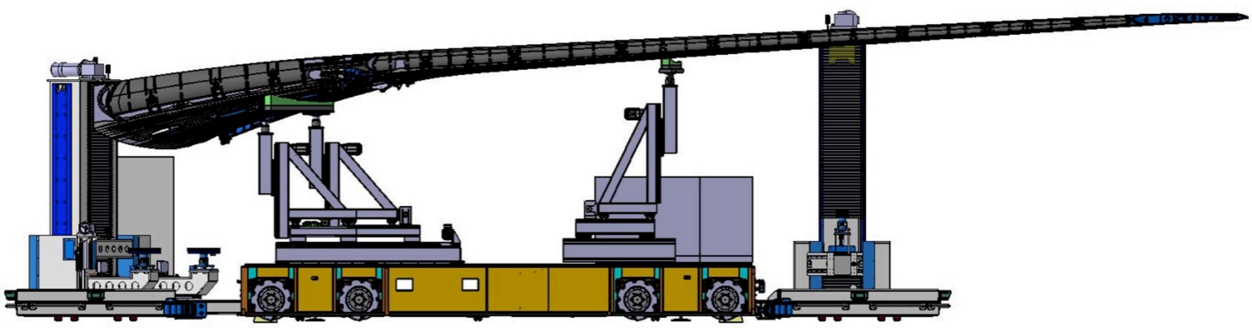


Figure 5.36 *WFA* junction cart picking the wing from the assembly station

5.10.3. Definition of variables and parameters

Figure 5.29 shows the main variables and parameters of the present wheel arrangement.

5.10.4. Formulation if AGV only can rotate from the origin P

$$\begin{bmatrix}\dot{\varphi}_1\\ \dot{\varphi}_2\\ \dot{\varphi}_3\\ \dot{\varphi}_4\end{bmatrix} = \frac{i}{r}\cdot\begin{bmatrix}1 & 1 & -(L_2+L_1)\\ 1 & -1 & -(L_2+L_1)\\ 1 & 1 & (L_2+L_1)\\ 1 & -1 & (L_2+L_1)\end{bmatrix}\cdot\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} \quad \textbf{(5.31)}$$

$$[\dot{\varphi}_{4x1}] = \frac{i}{r}\cdot[C_{4x3}]\cdot\dot{\xi}_R \quad \textbf{(5.32)}$$

5.10.5. Formulation if AGV can rotate from any point C

$$\begin{bmatrix}\dot{\varphi}_1\\ \dot{\varphi}_2\\ \dot{\varphi}_3\\ \dot{\varphi}_4\end{bmatrix} = \frac{i}{r}\cdot\begin{bmatrix}1 & 1 & -(L_2+L_1)\\ 1 & -1 & -(L_2+L_1)\\ 1 & 1 & (L_2+L_1)\\ 1 & -1 & (L_2+L_1)\end{bmatrix}\cdot\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} - \dot{\theta}\cdot\frac{i}{r}\cdot c_x\cdot\begin{bmatrix}-1\\ 1\\ -1\\ 1\end{bmatrix} - \dot{\theta}\cdot\frac{i}{r}\cdot c_y\cdot\begin{bmatrix}-1\\ -1\\ -1\\ -1\end{bmatrix} \quad \textbf{(5.33)}$$

$$[\dot{\varphi}_{4x1}] = \frac{i}{r}[C_{4x3}]\cdot\dot{\xi}_R - \dot{\theta}\cdot\frac{i}{r}\cdot c_x\begin{bmatrix}-1\\ 1\\ -1\\ 1\end{bmatrix} - \dot{\theta}\cdot\frac{i}{r}\cdot c_y[-1_{4x1}] \quad \textbf{(5.34)}$$

$$\begin{bmatrix}\dot{\varphi}_1\\ \dot{\varphi}_2\\ \dot{\varphi}_3\\ \dot{\varphi}_4\end{bmatrix} = \frac{i}{r}\cdot\begin{bmatrix}1 & 1 & -(L_2+L_1-c_x-c_y)\\ 1 & -1 & -(L_2+L_1+c_x-c_y)\\ 1 & 1 & (L_2+L_1+c_x+c_y)\\ 1 & -1 & (L_2+L_1-c_x+c_y)\end{bmatrix}\cdot\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} \quad \textbf{(5.35)}$$

5.11. AGVs with 8 motorized 45º Swedish wheels

5.11.1. AGV arrangement overview

It is possible to design infinite wheel arrangements using 90º Swedish wheels and 45º Swedish wheels. However the control matrices wont be easy if the wheel planes are oriented randomly. Another potential wheel arrangement that is interesting is to coordinate 2 *AGVs* with 4 Swedish wheels each; this approach is equivalent to a big *AGV* with 8 45º Swedish wheels.

The total number of driving wheels is 8; and there are 5 redundant control motors. As seen in the previous cases with Swedish wheels the vehicle is omnidirectional and the degree of manoeuvrability is 3.

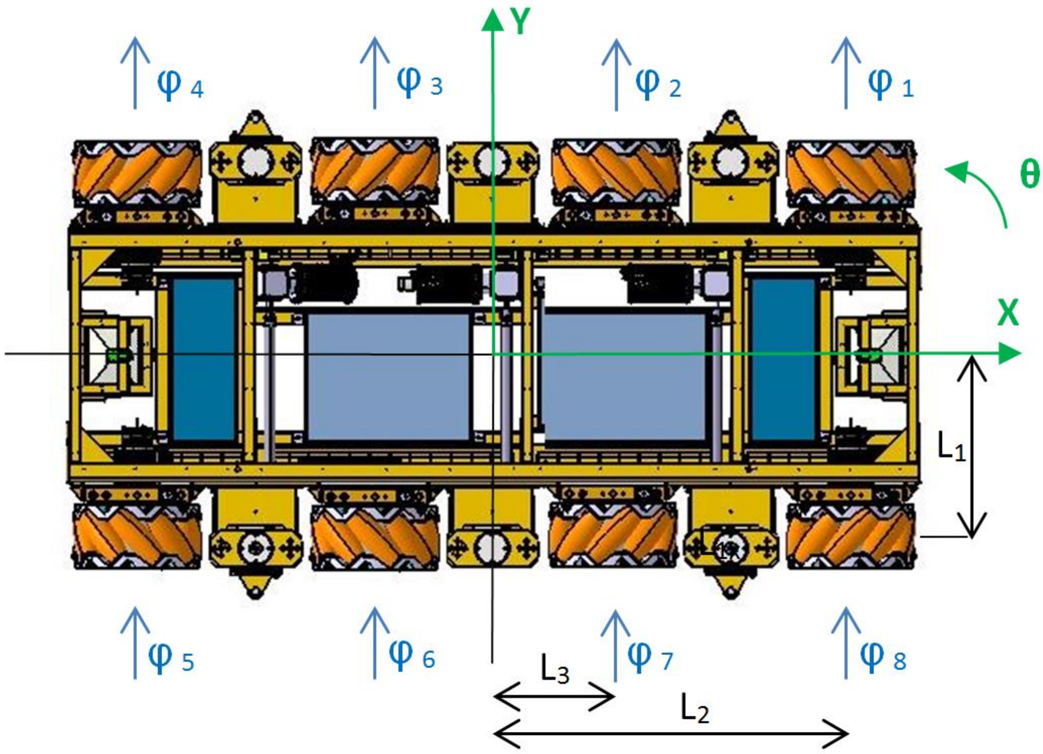


Figure 5.37 Top view of AGV with 8 motorized 90º Swedish wheel AGV

5.11.2. Definition of variables and parameters

Figure 5.37 shows the main variables and parameters of the *AGV.*

5.11.3. Formulation if AGV only can rotate from the origin P

$$\begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \\ \dot{\varphi}_4 \\ \dot{\varphi}_5 \\ \dot{\varphi}_6 \\ \dot{\varphi}_7 \\ \dot{\varphi}_8 \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} 1 & 1 & -(L_3 + L_1) \\ 1 & 1 & -(L_2 + L_1) \\ 1 & -1 & -(L_2 + L_1) \\ 1 & -1 & -(L_3 + L_1) \\ 1 & 1 & L_3 + L_1 \\ 1 & 1 & L_2 + L_1 \\ 1 & -1 & L_2 + L_1 \\ 1 & -1 & L_3 + L_1 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{5.36}$$

5.11.4. Formulation if AGV can rotate from any point C

$$\begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \\ \dot{\varphi}_4 \\ \dot{\varphi}_5 \\ \dot{\varphi}_6 \\ \dot{\varphi}_7 \\ \dot{\varphi}_8 \end{bmatrix} = \frac{i}{r} \cdot \begin{bmatrix} 1 & 1 & -(L_3 + L_1) \\ 1 & 1 & -(L_2 + L_1) \\ 1 & -1 & -(L_2 + L_1) \\ 1 & -1 & -(L_3 + L_1) \\ 1 & 1 & L_3 + L_1 \\ 1 & 1 & L_2 + L_1 \\ 1 & -1 & L_2 + L_1 \\ 1 & -1 & L_3 + L_1 \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} - \dot{\theta} \cdot \frac{i}{r} \cdot c_x \cdot \begin{bmatrix} -1 \\ -1 \\ 1 \\ 1 \\ -1 \\ -1 \\ 1 \\ 1 \end{bmatrix} - \dot{\theta} \cdot \frac{i}{r} \cdot c_y \cdot \begin{bmatrix} -1 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \end{bmatrix} \tag{5.37}$$

Chapter 6

ENVIRONMENTAL IMPACT

Making a strict evaluation of the environmental impact of an *AGV* is not easy. It is necessary to analyse the whole life cycle of the *AGV* to calculate the environmental impact. This chapter is a preliminary analysis of the environmental impact; a deep analysis is complicate enough to make another project and it is left as a future work.

Figure 6.1 shows the life cycle of an *AGV*. During all the five phases of the vehicle life there is an environmental impact that is examined in the following paragraphs. The quantitative analysis is left for future studies.

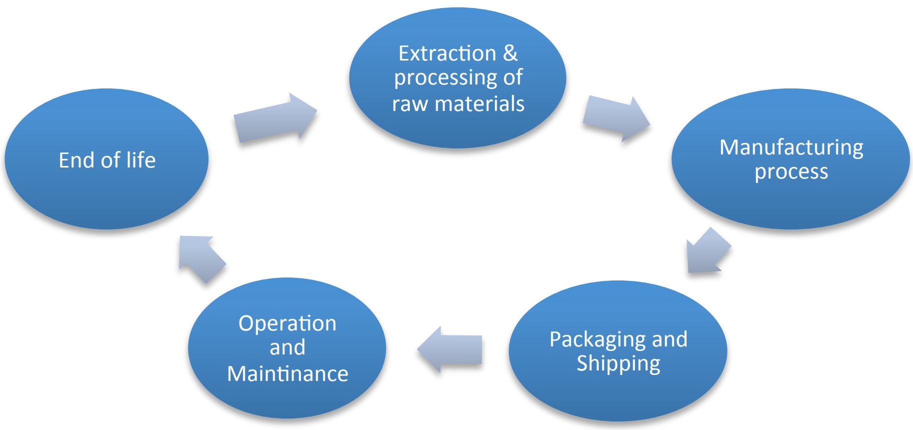


Figure 6.1 Life cycle of an *AGV*

The extraction and processing of the raw materials produce emissions of CO_2 and other contaminants. Also it reduces the natural resources. Each raw material has an associated amount of greenhouse gas emissions and an associate amount of energy consumption per kilogram. The main materials of an *AGV* are listed below.

- Steel: welded structures, mechanical components.
  Approximately 90% of total weight.
- Aluminium: wheel rims and parts that must be manipulated by operators.
  Approx. 2% in weight.
- Batteries: Lead-Acid, Ni-Cd.
  Approx. 4% in weight.
- Copper: Power transmission. Electric engines wiring.
  Approx. 2% in weight.
- Nylon: Product interfaces.
  Less than 1% in weight.
- Electronic components
  Less than 1% in weight.

The most important manufacturing procedures of the *AGVs* are:

- Welding of steel profiles to manufacture the structures.
- Machining of welded structures of steel to achieve the design tolerance.
- Machining of steel profiles and steel blocks to obtain mechanical parts.
- Cutting and bending of steel sheet to obtain the covers.
- Machining of aluminium blocks to obtain the wheel rims.
- Degreasing cleaning and painting the steel parts.

All manufacturing procedures consume energy and produce waste materials. The main waste materials are metallic parts that can be easily treated and recycled. Organic solvents are used during the degreasing, cleaning and painting processes; the gases produced by these solvents must be extracted and treated properly.

There is a consumption of energy and emissions in the atmosphere during all the transports of materials. A clear example is the shipping from the manufacturing site to the costumer site. However there are transports during the whole life cycle, from the extraction of the raw materials to the end of the life of the *AGV*.

Before the shipment it is necessary to package the *AGV.* Commonly the *AGVs* are shipped inside standard freight containers with a plastic bag and drying salts to avoid corrosion. Occasionally it is necessary to slit the vehicle to fit it inside the container. Then the *AGV* is divided in groups easy to reassemble. The material consumption for packaging is small because the freight containers are reused; however the container increases considerably the total freight weight and thus the energy consumption during transport.

During the operation of the *AGV* the main environmental impact is the energy consumption. The energy consumption is directly related with the vehicle weight, the speed and the efficiency of the engines. Another waste related with the operation and maintenance of the *AGV* is consumption of spare parts. The only spare parts that are expected to have a real consumption are the wheel rollers. Other possible replacement components are the engines (in case of failure) or the batteries (in case they are at the end of the life).

At the end of the life of the *AGV*, all the materials except the electronic components and the batteries are fully recyclable. The metals used in the *AGV* have a commercial value once the life of the AGV is finished. The Nylon is a polyamide easy to melt and process during recycling. There are factories that recycle the lead-acid batteries due the extended use of this type of batteries in the automobiles. Also there are recycling factories that treat the electronic components in order to separate the different materials and reuse them.

Chapter 7

CONCLUSIONS

Nowadays there are many industrial *AGVs* used in the intralogistics sector; the vehicles are dedicated to move and store goods in automatic warehouses or similar. Most of these AGVs however are simple and the degree of mobility is only 2. Consequently, they are not able to move sideways without manoeuvring and they are not able to rotate from any point in the plane. The *ICR* always must be in the same axis.

AGVs can have an important role in the aerospace industry. However, it is necessary to design *AGVs* with higher manoeuvrability and payload capabilities than those of other industrial sectors.

It is possible to design omnidirectional *AGVs* with spherical wheels, but these types of wheels have low load capacity, plus it is difficulty to design a motorized *spherical wheel*. It has been impossible to find any example of application of spherical wheels in the industry; there are examples of research robots like the *Tribolo* designed at *EPFL*[1].

Another alternative to design omnidirectional vehicles is to use castor wheels, however these wheels have the pivot point eccentric and force the vehicle frame to rotate around the wheel contact point to change the trajectory sharply. Moreover if the castor wheels are combined with the *Swedish wheels* or *driving and steering wheels* some of the wheels are forced to slip when the *AGV* trajectory is changed severely.

An alternative to design an *AGV* with degree of mobility 3 is to steer all the vehicle wheels; this solution allows to set the centre of rotation anywhere in the plane and to move in any direction. The weak point of this solution is that requires a lot of steering motors; also it is necessary to steer the wheel before changing the vehicle trajectory.

The Swedish wheels have rollers attached in the perimeter that introduce an additional degree of freedom (3DF in total). With these wheels it is possible to design omnidirectional *AGVs* and it is not necessary to steer the wheels. For this reason, the Swedish wheels are a good solution to design *AGVs* with high manoeuvrability.

An *AGV* with 3 90º Swedish wheels distributed in the 3 vertex of an equilateral triangle, each one at 120º from the other, has the minimum number of motors to control an omnidirectional *AGV*, the minimum number of wheels to have a stable vehicle and consequently is an optimal design of *AGV.* The weak point of this solution is that the vehicle has a very particular wheel arrangement. It is a good solution to transport parts with round or square base like a *CWB* but it is not appropriate to transport long parts like a wing, a *HTP* or a VTP.

The 45º Swedish wheels allow designing omnidirectional *AGVs* with rectangular shape. In the commercial aircraft manufacturing industry this wheel arrangement will be very useful and will have key role in the next future. The weak points of the Swedish wheels are the high manufacturing cost compared with a standard wheel; also the reduced payload compared with the wheel diameter and finally the impossibility to find commercial Swedish wheels with high payload.

Writing this Master Thesis I have learned the state of the art of *AGV* in the industry. Generally the industrial *AGVs* are small and very simple. Then it is necessary to find innovative *AGV* configurations in order to use this type of vehicles in the *CAMI.* For this reason I have proposed innovative wheel arrangements that can be used in the *CAMI.*

During the development of this project I have done a lot of practical work and I have been able to put in practice a lot of the theoretical fundamentals achieved. I have designed, manufactured and tested 2 types of omnidirectional wheels that can be used in *AGVs* with high payload. Also I have manufactured and tested semi-automated vehicles like the studied in the previous points.

- 5.6 *AGV* with 3 90º Swedish wheels
- 5.7 *AGV* with 4 90º Swedish wheels
- 5.8 *AGV* with 8 90º Swedish wheels
- 5.9 Two synchronized *AGV* with 8 90º Swedish wheels
- 5.10 *AGV* with 4 45º Swedish wheels

Future work

- Improve the design of the 45º Swedish wheel, the shock absorber and the wheel drive in order to reduce the high cost of the self-made wheels.

- Manufacture and test an *AGV* with 2 driving and steering wheels and 2 or more caster wheels in order to check the comportment of the caster wheels.

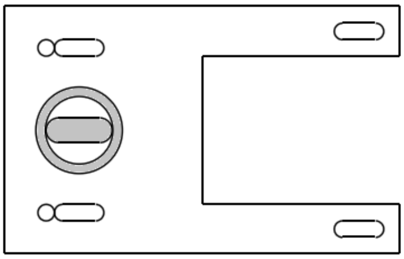
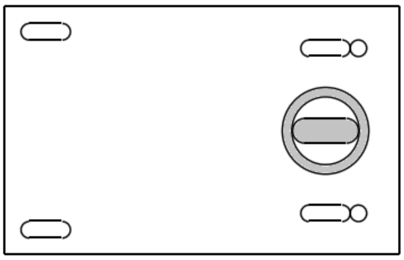
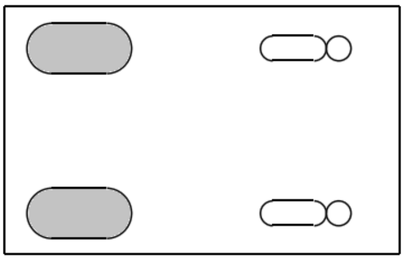
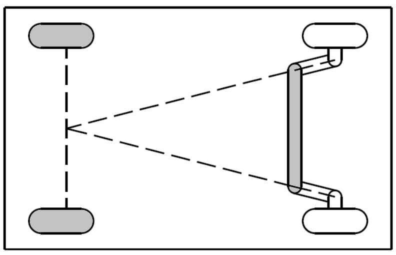
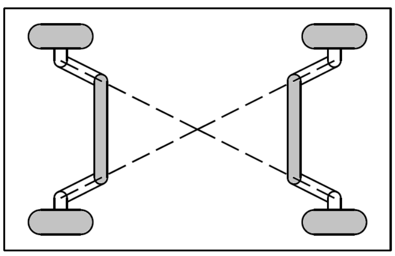
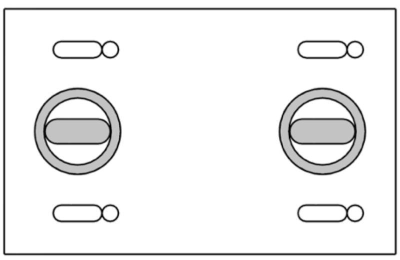
- Manufacture and test 2 independent *AGVs* working as a single one to move large payloads. A system to achieve good positioning between the *AGVs* must be developed.

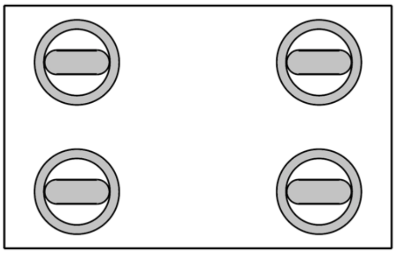
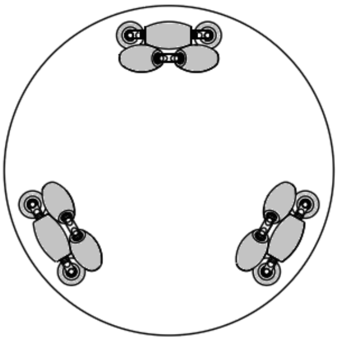
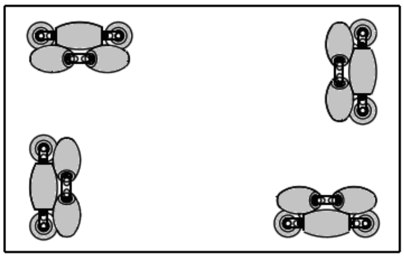
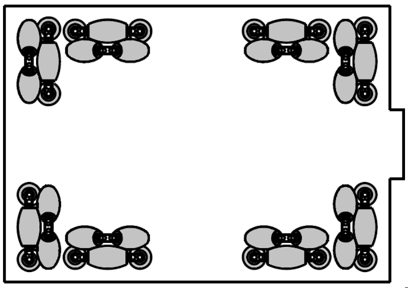
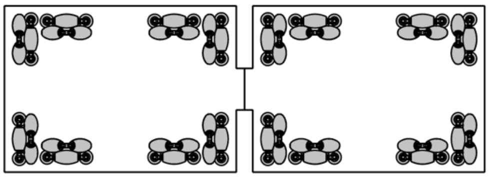
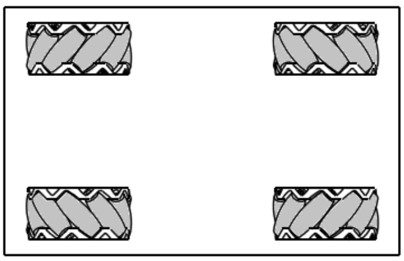
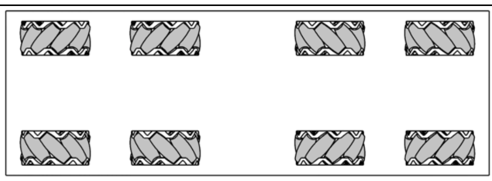
- Manufacture and test an *AGV* with 4 driving and steering wheels.

- Make a deep analysis of the environmental impact of an *AGV* and compared it with alternative systems.

Table 7.1 gives a fast overview of all the *AGV* configurations studied in the present thesis.

Table 7.1 Studied and proposed AGV arrangements.

	Arrangement	**Description**	
A		1 driving and steering wheel in the rear, 2 caster wheels in the rear and 2 free wheels in front.	$\delta_M = 2$ $\delta_m = 1$ $\delta_s = 1$ $n_{cm} = 2$
		Same configuration as above but opposite sense of advance.	
B		2 wheeled differential drive with 2 additional contact points. 2 motorized wheels in the rear and 2 caster wheels in the front.	$\delta_M = 2$ $\delta_m = 2$ $\delta_s = 0$ $n_{cm} = 2$
C		Single Ackermann Steering	$\delta_M = 2$ $\delta_m = 1$ $\delta_s = 1$
D		Double Ackermann Steering	$\delta_M = 2$ $\delta_m = 1$ $\delta_s = 1$ $n_{cm} = 2$
E		2 Driving and steering wheels with additional swivel caster wheels	$\delta_M = 3$ $\delta_m = 1$ $\delta_s = 2$ $n_{cm} = 4$

F		4 Driving and steering wheels	$\delta_M = 3$ $\delta_m = 1$ $\delta_s = 2$ $n_{cm} = 8$
G		3 90º Swedish wheels with independent motors	$\delta_M = 3$ $\delta_m = 3$ $\delta_s = 0$ $n_{cm} = 3$
H		4 90º Swedish wheels with independent motors	$\delta_M = 3$ $\delta_m = 3$ $\delta_s = 0$ $n_{cm} = 4$
I		8 90º Swedish wheels with independent motors	$\delta_M = 3$ $\delta_m = 3$ $\delta_s = 0$ $n_{cm} = 8$
J		2 AGV with 8 90º Swedish wheels with independent motors	$\delta_M = 3$ $\delta_m = 3$ $\delta_s = 0$ $n_{cm} = 16$
K		4 45º Swedish wheels with independent motors	$\delta_M = 3$ $\delta_m = 3$ $\delta_s = 0$ $n_{cm} = 4$
L		8 45º Swedish wheels with independent motors	$\delta_M = 3$ $\delta_m = 3$ $\delta_s = 0$ $n_{cm} = 8$

BIBLIOGRAPHY

[1] Siegwart R. and Nourbakhsh I.R., "C.2 Locomotion" and "C.3 Mobile Robot Kinematics", *Introduction to Autonomous Mobile Robots,* pp. 13-88, Edited by: The MIT Press, Cambridge, Massachusetts, USA (2004).

[2] Doroftei I., Grosu V. and Spinu V., "C.29 Omnidirectional Mobile Robot – Design and Implementation", *Bioinspiration and Robotics: Walking and Climbing Robots*, pp. 511-544, Edited by: Maki K. Habib, I-Tech, Vienna, Austria (2007). ISBN 978-3-902613-15-8

[3] Pin F.G. and Killough S.M., *A New Family of Omnidirectional and Holonomic Wheeled Platforms for Mobile Robots*. IEEE Transactions on robotics and automation. Vol. 10 No. 4. (August 1994).

[4] Pin F.G. and S.M. Killough, *Omnidirectional Holonomic Platforms.* Twelfth Symposium on Energy Engineering Sciences, Argonee, Illinois, USA (1994).

[5] Agulló J., *Les rodes omnidireccionals, el darrer pas evolutiu de la roda*. Edited by: Real academia de Ciència i Arts de Barcelona, Barcelona, Spain (2004). ISBN: 0368-8283

[6] Tlale N. and de Villiers M., *Kinematics and Dynamics Modelling of a Mecanum Wheeled Mobile Platform*. Council for Scientific and Industrial Research, Pretoria, South Africa (2008).

[7] 1001 CRASH. Accessed January 2015.
www.1001crash.com/index-page-composite-lg-2.html

[8] AIRBUS. Accessed January 2015.
www.airbus.com

[9] AIRBUS A350XWB. Accessed January 2015.
www.a350xwb.com/innovation

[10] Airways News. Accessed March 2015.
airwaysnews.com/blog/2013/06/09/inside-boeings-737-renton-factory-as-they-take-it-to-the-max-part-one

[11] ARITEX. Accessed February 2015.
www.aritex-es.com

[12] ATAB. AGV manufacturer. Accessed December 2014.
www.atab.se/index.php?page=automotive

[13] Autonomous Mobile Robots. Slides, exercises and complementary information of [1]. Accessed February 2014.
www.mobilerobots.ethz.ch

[14] Aviation News. Accessed February 2014.
www.aviationnews.eu/blog/wp-content/uploads/2011/06/Malaysia-Airlines-A380-final-assembly.jpg

[15] BOEING. Accessed January 2015.
www.boeing.com

[16] BOEING AERO Magazine. Accessed January 2015.
www.boeing.com/commercial/aeromagazine

[17] BT Forklifts. Toyota Forklifts partner. Accessed January 2015.
www.bt-forklifts.com

[18] C.F.R. Electric motors and driving wheels manufacturer. Accessed November 2014.
www.cfritaly.com

[19] COMAC. Chinese government owned Aircraft manufacturer. Accessed February 2015.
english.comac.cc/products

[20] CTI Systems. Integrated manufacturing solutions. Accessed February 2015.
www.ctisystems.com/

[21] DEMAG. Gantry crane manufacturer. Accessed March 2015.
www.demagcranes.de/cms/site/deutschland/Demag-Cranes-Airbus

[22] ECT Europe Container Terminals. Leading and most advanced container terminal operator in Europe; it handles a vast majority of all the containers passing through the port of Rotterdam. Accessed March 2015.
www.ect.nl/en/content/ect-orders-22-hybrid-agvs

[23] EGEMIN. Material handling solutions manufacturer. Accessed December 2014.
www.egeminusa.com/pages/agvs/agvs_general.html

[24] EPFL École polytechnique fédérale de Lausanne. Topics in autonomous robotics. Accessed March 2015.
moodle.epfl.ch/pluginfile.php/1439841/mod_resource/content

[25] EUROCRANE. Gantry crane manufacturer. Accessed March 2015.
www.eurocranelifting.com/profile/space-industry.html/138086/0

[26] FROG AGV SYSTEMS. AGV manufacturer. Accessed December 2014.
www.frog.nl/?newlang=en

[27] FLIGHT GLOBAL. Creating a Titan. Accessed January 2015.
www.flightglobal.com/news/articles/creating-a-titan-199071

[28] KIVA SYSTEMS. Automatic warehouse system. Company owned by AMAZON. Accessed December 2014.
www.kivasystems.com

[29] KUKA OMNIMOVE. Robotic systems and omnidirectional vehicles manufacturer. Accessed December 2014.
www.kuka-omnimove.com/en

[30] MASTERMOVER. Electric tug solutions. Accessed March 2014.
www.mastermover.com/news/airbus-creates-production-line-using-mastermover-electric-tugs#.VQR2DxCG8y4

[31] MIAG. Explosion-proof lift trucks and innovative transport systems. Accessed December 2014.
www.miag.eu/Produkte/OCS/HAB/hab.html

[32] MOTOTOK. Helicopter and Airplane tugs. Accessed March 2015.
www.mototok.com

[33] QATAR AIRWAYS. A350 Site. Accessed January 2015.
www.qatarairways.com/global/en/airbus-a350.page

[34] SOFT DESIGN. Material handling and vision systems. ATAB partner. Accessed December 2014.
www.softdesign.se/en/products

[35] SNOX. AGV manufacturer. Accessed December 2014.
snox.com/autoguided_cart_snoxcart_AGV

[36] SWISSLOG. Automation solutions for hospitals, warehouses and distribution centres. Accessed December 2014.
www.swisslog.com/en/Products/WDS/Automated-Guided-Vehicles

[37] TOYOTA FORKLIFTS. Material handling solutions. Accessed December 2014.
www.toyota-forklifts.co.uk/EN/Products/automated-trucks/Pages/Default.aspx

[38] VEX ROBOTIC. Manufacturer of robotic kits for education. Accessed Febraury 2015.
www.vexrobotics.com

[39] VDL CONTAINER SYSTEMEN. Container handling solutions. Accessed December 2014.
www.vdlcontainersystemen.com/?page/4496632/AGV.aspx

APPENDICES

A.1. Materials of new generation aircrafts

The images of this appendix show the materials used to build the airplanes *AIRBUS A350* (introduced in January 2015), BOEING *787* (introduced in October 2011) and *AIRBUS A380* (introduced in October 2007). All the main structures of the new *A350* are manufactured in *CFRP*.

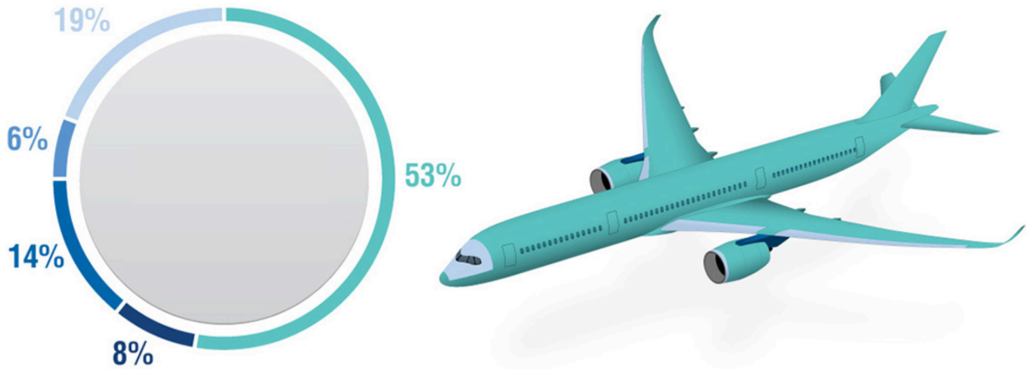


Figure A.1 *AIRBUS A350* Materials **[9]**

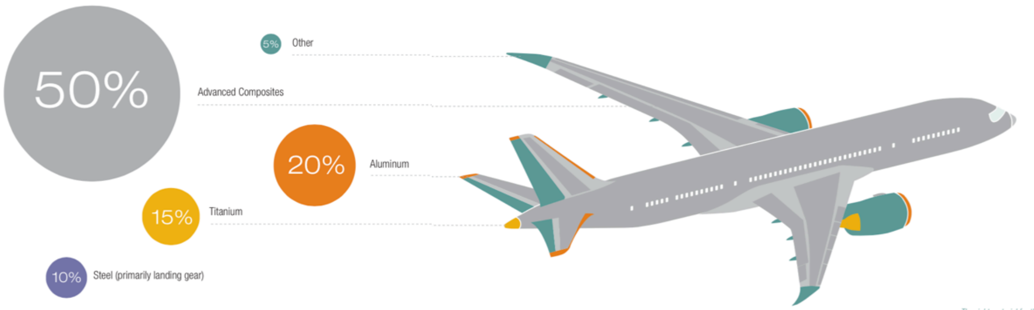


Figure A.2 *BOEING 787* Materials **[17]**

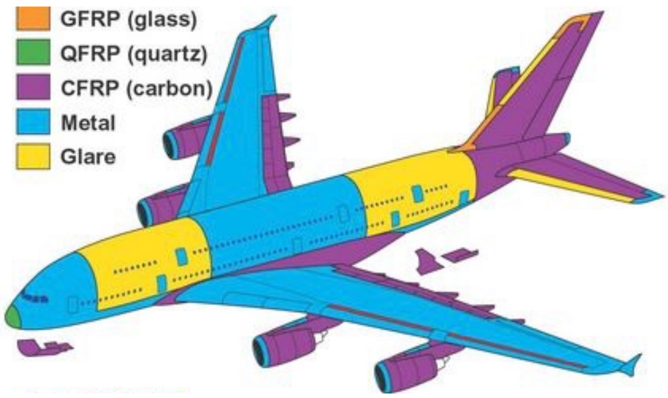


Figure A.3 *AIRBUS A380* Materials **[27]**

A.2. Commercial aircraft dimensions

Table A.1 shows the overall dimensions of some the commercial aircrafts that are mentioned in this master thesis. All these aircrafts are in production at present or are an improvement of a current model, as in the case of the 777X.

Table A.1 Airplane dimensions

	Dimensions (m)			
	Overall length L	**Cabin width Wc**	**Wing span WS**	**Height H**
AIRBUS A320neo	37,6	3,7	35,8	11,8
AIRBUS A330-300	63,7	5,3	60,3	17,2
AIRBUS A350-900	66,9	5,6	64,8	17,1
AIRBUS A380	72,7	6,5	79,8	24,1
BOEING 777-9X	76,6	6	71,8	19,7
BOEING 787-8	56,7	5,5	60,1	16,9
COMAC C919	38,9	3,9	35,8	12,0
EMBRAER E190-E2	36,2	2,7	33,7	11

A.3. Main characteristics of industrial AGVs

A.3.1. Forklifts

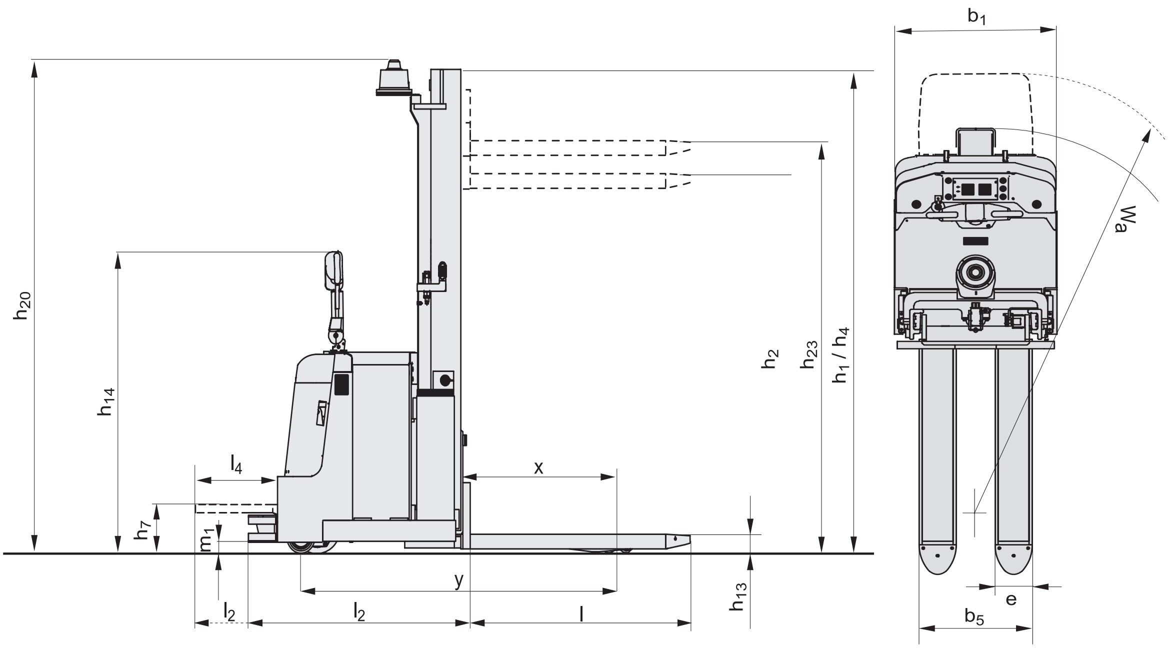


Figure A.4 *TOYOTA BT Autopilot SAE200* **[37]**

Table A.2 *TOYOTA BT Autopilot SAE200* Technical details **[37]**

Turning radius w_a	2 m with platform folded and 2,25 m with the platform down
Max. Speed	6 m/s
Length $l + l_2$	1,2m + 1,2m = 2,4m
Width b_1	0,79 m
Load capacity	2.000 kg
Weight with battery	1.500 kg
Safety	Laser bumpers proportional to speed and steering angle

Figure A.5 *SWISSLOG Standard AGV* **[36]**

Table A.3 *SWISSLOG Standard AGV* Technical details **[36]**

Max Speed	2 m/s
AGV dimensions	Customized
Load dimensions	Customized
Load capacity	4.000 kg
Navigation	Laser (inductive magnet as an option)
Safety	Laser bumpers

A.3.2. Paper reel AGVs

Figure A.6 *ATAB (MAX AGV) RX20 Paper reel AGV* **[12]**

Figure A.7 *CTI Systems* **[20]**

Figure A.8 *CTI Systems* **[20]**

A.3.3. Automatic warehouse AGVs

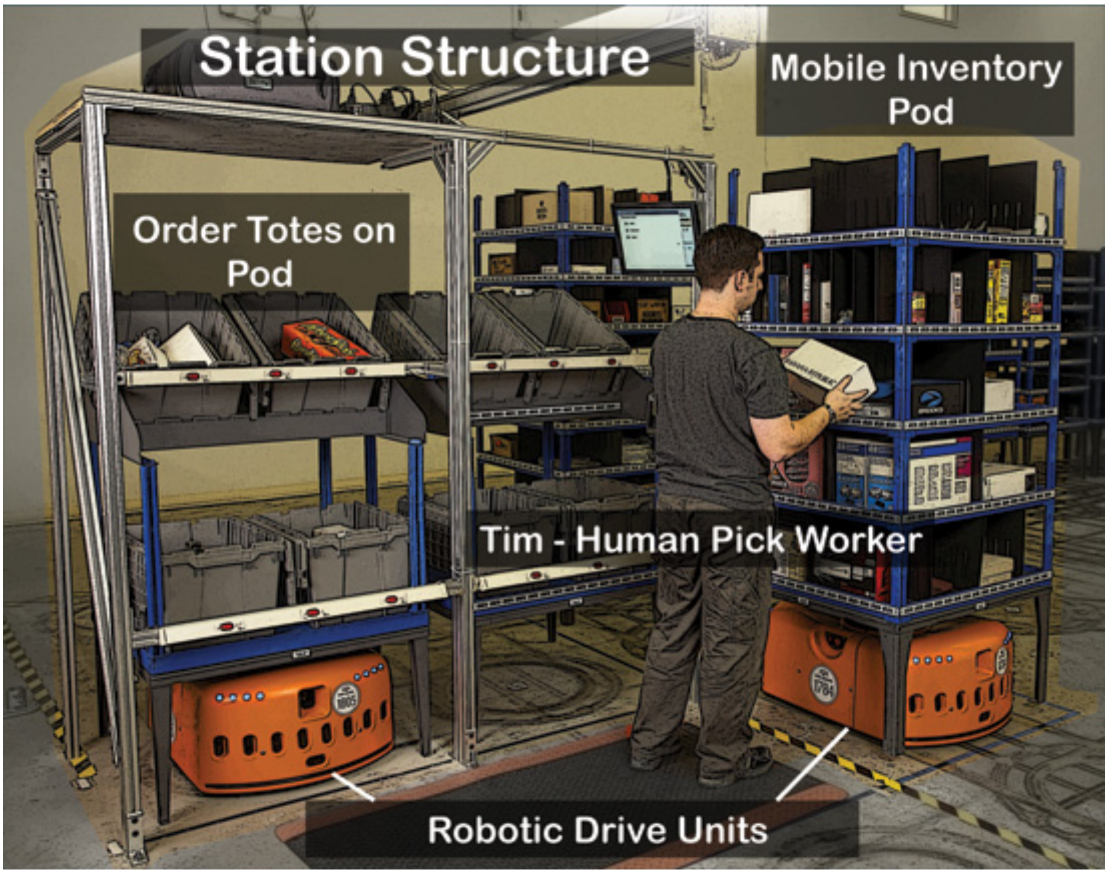


Figure A.9 KIVA station structure **[28]**

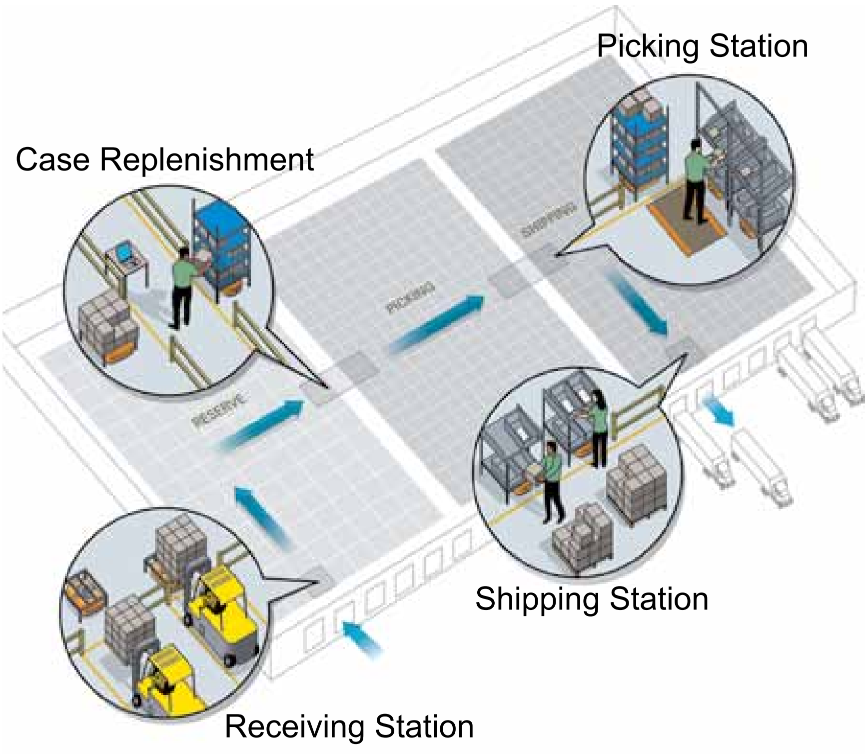


Figure A.10 KIVA system schema **[28]**

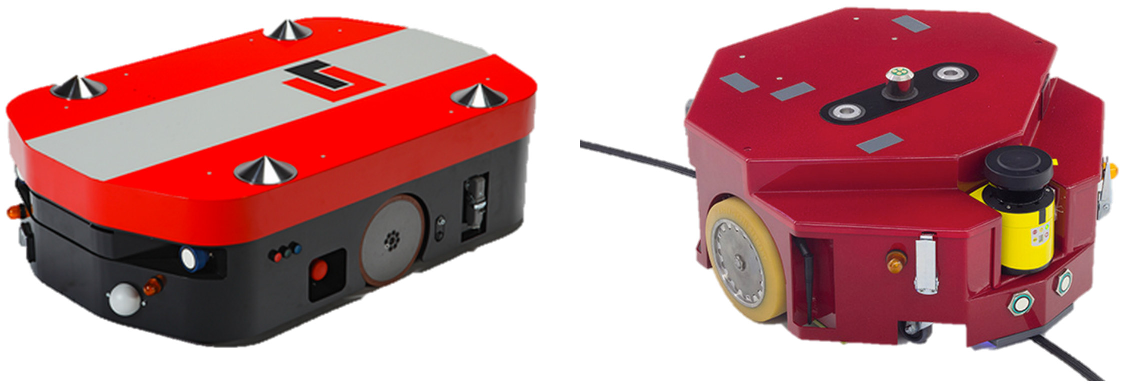


Figure A.11 Two different designs of *SWISSLOG CarryPro* **[36]**

Table A.4 *SWISSLOG CarryPro* Technical details **[36]**

Max Speed	1 m/s
AGV dimensions	Customized
Load dimensions	Customized
Load capacity	1.000 kg
Navigation	Optical (inductive magnet as an option)
Safety	Laser bumpers

A.3.4. Vehicle assembly AGVs

Figure A.12 *MAX AGV* Porsche Final Assembly Line AGV **[12]**

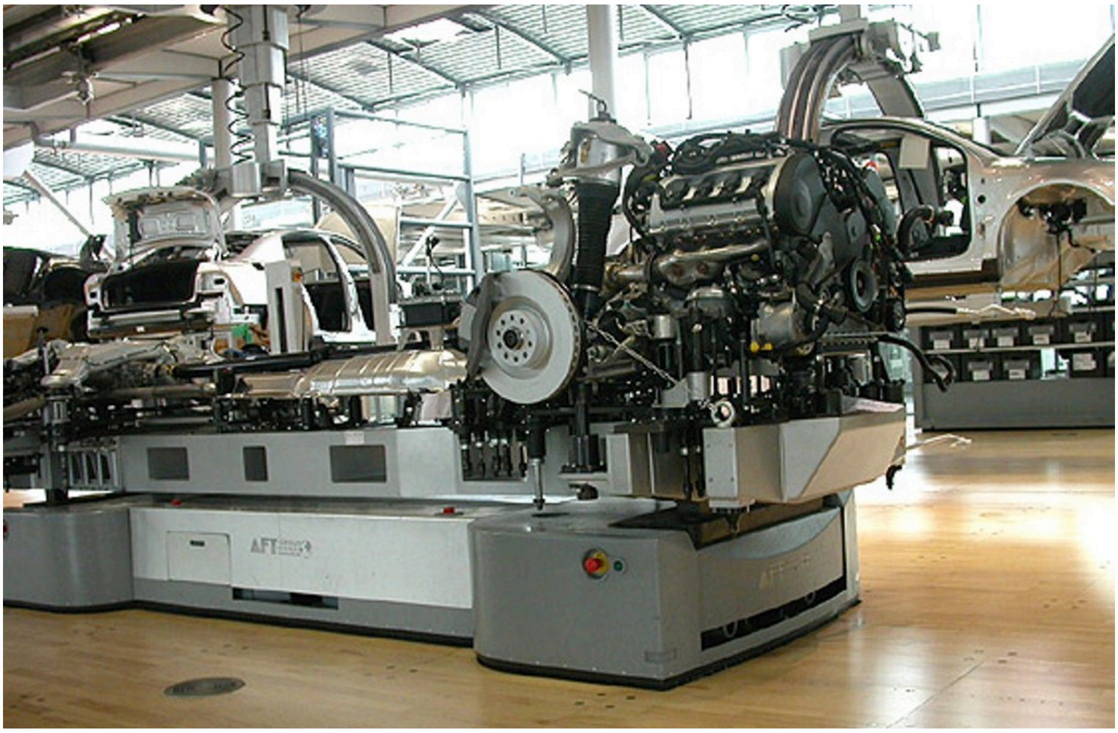


Figure A.13 *FROG AGV Systems* Volkswagen Phaeton Final Assembly Line **[25]**

A.3.5. Hospital AGVs

Figure A.14 *SWISSLOG TransCar AGV* with adapted carts **[36]**

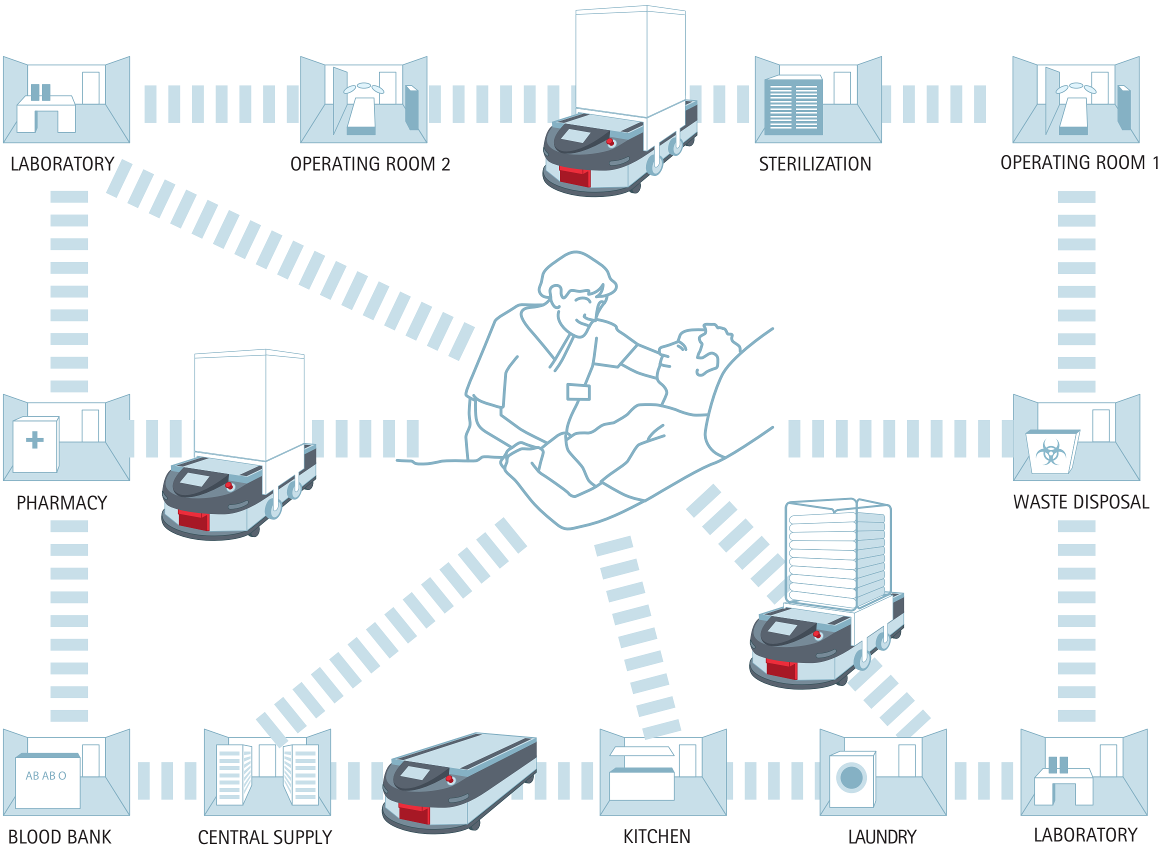


Figure A.15 *SWISSLOG TransCar AGV* operating schema **[36]**

Table A.5 *TransCar AGV* Technical details **[36]**

Max Speed	1,8 m/s
AGV dimensions	length 1706 mm, width 580 mm, height 330 mm
Load capacity	600 kg
Maximum ramp & weight	Up to 7% grade (at reduced speed) 320 kg
Safety	Laser bumpers. Object detection at 30m. Force impact absorption with twin shock absorption
Engine	Brushless DC 55 dB
Batteries	Lead acid 48 volt-82 amp hour batteries. (NiCad and Lithium Ion options available)
Positioning accuracy	Lateral ±15 mm. Longitudinal ± 26 mm.
Ingress Protection Rating	IP 54, protects from dust and splashing water
Sensors	
Dual-Range Laser Scanner	Slows down and stops vehicles when obstacles are encountered.
Ultrasonic Sensors	Detects obstacles above laser scanner for additional safety.
Side Tape Switches	Stop vehicle immediately upon contact with an obstacle.
Cart Sensor	Detects the frame of the front cart to facilitate dense storage of carts in lanes and ensures accurate cart pick up.
Floor Detection Sensor	Prevents vehicle from driving off docks or stairs.
Inclination Sensor	Prevents vehicle from dropping off carts on sloped ramps.
RFID or Barcode Reader	Positively identifies each unique cart and cart type for tracking, automatic order entry and to prevent delivery to undesired locations.

A.3.6. Container terminal AGVs

Table A.6 *VDL Container System* Technical details **[37]**

Max Speed	6 m/s
AGV dimensions	Customized
AGV weight	26.000 kg
Load dimensions	Standard containers 20´ 2x20´ 30´ 40´ 45´
Load capacity	70.000 kg
Positioning accuracy	± 2,5 cm
Safety	Laser bumpers. Object detection at 30m. Force impact absorption with twin shock absorption
Diesel Engine	152 kW 4,8l/h
Fuel Capacity	1.000 l
Steering and braking by independent hydraulic system	
Built in accordance with the highest environmental standards	

A.3.7. Helicopter and airplane AGVs

Figure A.17 shows 2 different options of interface of the *MOTOTOK AGV* with the airplane fuselage.

Option 1
Interface mounted on the AGV

Option 2
AGV tows a cart

Figure A.16 *MOTOTOK AGV* during airplane production **[32]**

Table A.7 *MOTOTOK AGV* Technical details **[32]**

Max Speed	6 km/h = 1,7 m/s
AGV dimensions	
Load dimensions	Customized
Weight	1.700 kg
Towing capacity	50.000 kg
Load capacity	6.000 kg
Navigation	Remote control Optical; guiding camera (possibility to identify barcodes)
Batteries	4x 200Ah 48V High-performance maintenance-free GEL batteries
Motors	Extremely powerful electrical motors
Safety	Laser bumpers

A.4. Tasks done during AGV design

I have been the Design Leader of all the *AGVs* and *SAGV* with Swedish wheels designed in *ARITEX.*

Now I am the head of the special machines department in *ARITEX.*

The following list shows the tasks that I have done during the development of the *AGVs* manufactured in *ARITEX*:

- Predesign of the *AGV* main dimensions, wheel arrangement and configuration of all the *AGV* subsystems.
- Design of the Swedish wheels (45º and 90º).
    - Preliminary design of the wheel geometry.
    - Selection of row materials.
    - Selection of bearings and garter seals.
    - Selection of lubrication.
    - Final 3D design of the wheel.
    - Supervision of manufacturing drawings.
- Design of wheel drive.
    - Dimensioning: output speed, reduction ration and required power.
    - Selection of gearbox.
- Design of the shock absorber:
    - Preliminary design of the shock absorber.
    - Selection of row materials.
    - Selection of bearings, garter seals and lubrication.
    - Supervision of design development.
    - Supervision of manufacturing drawings.
- Design of the *AGV* structure.
    - Preliminary design of the structure.
    - Selection of structural profiles and steel grade.
    - FEM analysis.
    - Supervision of design development.
    - Supervision of the manufacturing drawings.
- Design of *AGV* secondary function. Lifting system or Turing and Lifting system.
    - Preliminary design of the *AGV* secondary function.
    - Define and optimize the geometry of the mechanism.
    - Selection of row materials.
    - Selection of commercial parts.
    - FEM analysis.
    - Supervision of design development.
    - Supervision of the manufacturing drawings.
- Calculation of power consumption.
- Calculation of standard working cycle and expected life.
- Formulation of *AGV* kinematics.
- Formulation of Best-Fit kinematics for the *Junction cart* described in Section 5.10.2.3.

The 3D design and the drawings are made using *CATIA V5* software.

The mechanisms are optimized using the solver of an *EXCEL* sheet.

The *FEM* calculations are made using the package *Generative Assembly Structural Analysis* from *CATIA V5.*

Commonly two or three engineers from *ARITEX* or from outsourcing companies give me support during the development of the *AGVs.* The main function of these engineers are to detail the 3D.

Usually the *AGV* drawings are outsourced to engineering companies of India or to the filial company *ARITEX* Mexico.