A preliminary study to optimise safety conditions on a freight urban robotic vehicle

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Abstract: The paper presents a new concept architecture of light duty fully electric vehicle for efficient sustainable urban freight transport which allows the movement of two Euro Pallets 800 × 1200 mm (or boxes with similar bottom part). Active suspensions of the vehicle have been designed in order to adapt their stiffness to the payload on board and to modify the chassis height during loading-unloading tasks. In this paper, a preliminary study to optimise safety conditions on goods on board of the vehicle, and on people near the vehicle is presented. In order to guarantee safety conditions for the vehicle’s driver and city areas where the vehicle should be moved, design optimisations on the chassis have been developed. These optimisations have been compared using computational analysis. Two alternative solutions have been proposed and one of the presented results has been included on the real vehicle.

Keywords: safety; freight transport; robotic vehicle; computational analysis.


1 Introduction

Thompson (2015) outlines a range of technologies and city logistics schemes that can improve the environmental performance and safety of urban freight systems. Kant et al. (2016) present the challenges, failures and successes on urban freight safety and transportation. Vieira and Fransoo (2015) proposed a model empirically tested with 119 freight operators. According to the effects shown by the proposed model, regulation, along with lack of collaboration, appear to be the Achilles’ heel of freight distributors, in that both factors contribute (directly and indirectly) to detour, which results in less efficient logistical performance.
In industrialised countries, the number of studies and surveys in the field of urban goods movement (UGM) has increased considerably over recent years. Ambrosini and Routhier (2004) compare the objectives, methods and results in this sector and focuses on nine industrialised countries of Europe, America and Asia. Cooperative action seems to bear fruit providing that information and dialogue take place in the long-term with all the operators involved. The development of intelligent transport systems (ITS) and better management of urban facilities may improve these attempts.

De Jong et al. (2004) present a review of the literature on freight transport models, focusing on the types of models that have been developed since the 1990s for forecasting, policy simulation and project evaluation at the national and international levels.

Dablanc (2007) presents three characteristics of urban goods movements in major European cities: (1) Goods movements are largely indifferent to the internal structure of cities. (2) Urban policies targeted on freight mobility appear to be quite inefficient. (3) The provision of appropriate urban logistic services is slow in emerging despite growing needs. These features have been observed around from 2001 to 2006 through working with large metropolitan transport authorities, as well as with the French national research program on “Goods in Cities” and the “Best Urban Freight Solutions” European network. These observations draw a picture of the urban freight industry, which can appear quite critical.

Browne et al. (2010) provide a review of the light goods vehicle (LGV) fleet and its activity, with specific reference to operations in urban areas, and sustainability issues associated with the ever-growing use of LGVs. Traditionally these vehicles have received little attention but are becoming an ever-more important element of urban freight transport both for goods collection and delivery and for the provision of a wide range of critical services.

Freight transport is a critical issue for urban areas: the population is becoming more and more concentrated in cities and therefore the bulk of industrial production is dispatched to these areas. Moreover, the demand for freight transport is growing at a fast rate due to changes in industry logistics and consumer purchasing patterns.

As urban freight transport deals primarily with the distribution of goods at the end of the supply chain (Power, 2005), many deliveries tend to be made in small loads and in frequent trips, thus resulting in many vehicle kilometres (Cepolina and Farina, 2013).

Many transport companies are reluctant to serve householders: they consider home deliveries to be a difficult market, because of the high dispersal of delivery points, a high proportion of missed appointments, difficult delivery schedules and a large number of upper floor deliveries (Dablanc, 2014).

As a result the scope of urban freight focuses on vehicles that visit many destinations, picking up and delivering many separate consignments (Muñuzuri et al., 2009).

These urban freight movements cause problems within cities, e.g. due to: the lack of suitable infrastructure for deliveries, the conflicts with other users during freight delivery operations, the accessibility of these vehicles to pedestrian areas and historic city centres, environmental and noise pollution, generation of accidents in the urban areas and compromising the mobility of citizens.

The primary focus of urban transport planners in recent years has been to address the demand for people movement, and more specifically, to reduce the collective dependence on motorcars and on fossil fuels. As a result, we have seen the gradual conversion of road and street networks towards the inclusion of bus lanes, larger footpaths, cycle lanes, etc. and the reduction of road space available for cars. So the road space available for the
freight distribution, both in terms of available road lanes and loading space has been reduced (Crainic et al., 2004).

Novel design of freight vehicles should be proposed in order to overcome these limitations. The current technology does not satisfy the needs of this specific context also for what concerns the vehicles and the transportation process. In this context, the FURBOT vehicle was developed, as a result of the FURBOT (Freight Urban RoBOTic vehicle) project (Muscolo et al., 2014; Muscolo et al., 2015; Pollard et al., 2014; Molfino et al., 2015; Molfino et al., 2014), funded within the Seventh Framework Programme of the European Commission, which aim was to develop a new vehicle to improve the urban freight transport. The main goal of the project was to design a vehicle that redefines the paradigms of freight transportation focusing on energy efficiency, sustainability, mobility dexterity and safety, modularity, intelligent automated driving and freight handling robotisation.

The obtained vehicle is well in line with the position of ERTRAC expressed in the “ERTRAC Road Transport Scenario 2030” (October 2009); the position of OECD delivered in “Freight transport demand-outlook from OECD” (12 November 2013); as well as the position of UITP European Union expressed in the position paper of January 2014 “The future of urban mobility” and with the position about the mobility modelling disseminated by the International Energy Agency in “Informed analysis of sustainable transportation” and with all the recent documents on sustainable transport edited by most of the countries (Japan, USA and Europe).

With the change in transport paradigm, it becomes clear the need of lean, agile and sustainable freight transport systems for urban environments; this necessity will surely grow in next years, ensuring a place in the market for solutions such as the one proposed in the FURBOT project.

In this paper a design optimisation of the FURBOT robotic vehicle is presented including computational studies on its chassis. A critical analysis of the vehicle is presented underlining the novelty of the vehicle and the risks for safety during its use in a real environment. In order to guarantee safety conditions at the vehicle’s driver and urban areas where the vehicle should be moved, design optimisations on the chassis have been developed and compared through computational analysis. Two alternative solutions have been proposed and one of these has been included on the realised vehicle.

The paper is so structured: Section 2 shows a brief description on the FURBOT prototype: the vehicle working conditions, the freight handling functional parameters, the realised prototype, the power supply, and the freight handling device design; Section 3 shows the computational tests to optimise the vehicle, results and discussion: a preliminary analysis, a structural analysis of the chassis, the critical conditions, results and discussion. The paper ends with conclusions and future works.

2 FURBOT prototype

2.1 Vehicle working conditions

The FURBOT vehicle is designed for urban freight transportation, and it is assumed to work within urban areas and streets. The maximum speed of the vehicle is 40 km/h and the maximum slope is considered to be 11%. These considerations were very useful while designing the vehicle and are still a good starting point for analysing the possible
configurations of the vehicle and the load. The autonomy of the vehicle would be enough to produce four trips of 50 minutes each. The power of the vehicle has been indicated to be 16 kW (8kW/motorised wheel). No assumptions were made about the type of freights to be carried so it cannot be excluded a priori that the content of a load is fragile or delicate. Anyway, as in most freight transportation solutions, it is assumed that if a load is fragile it will be properly packaged so that all freights can be treated equally. To prevent the loads from being damaged it is important to assure small, smooth accelerations of the load, especially along the vertical axis, and to avoid rotations around the horizontal axis, regardless of the type of load.

Another fundamental feature of the vehicle is its active suspensions system, which allows it to control the chassis height, ranging from 0 to 120 mm, and to change the vehicle’s roll and pitch. Even though the type of freight is assumed to be pallets or pallet-like boxes, there were no requirements or assumptions on the maximum height of the loads. This data was obtained consulting freight transportation and packaging companies that stated that a height of 1800 mm would be more than sufficient for palletised goods. These assumptions and considerations gave the guidelines for the chassis dimensions, reported in Figure 1. More details on the vehicle and its handling device are presented in Muscolo et al. (2014, 2015).

Figure 1 Internal dimensions of the FURBOT vehicle’s chassis (a), Initial state of the chassis of the vehicle (b) and digital mock-up of the vehicle with (c) and without boxes (d)
2.2  Freight handling functional parameters

At the base of the design and development of the FURBOT handling device stand a few key constraints (Muscolo et al., 2014; Muscolo et al., 2015; Pollard et al., 2014; Molfino et al., 2015):

- The loading is realised from the sides of the vehicle in order to minimise the manoeuvres, as well as loading/unloading time and effort in urban areas.

- The loading capacity of FURBOT vehicle is equal to two Euro-pallets (800 mm × 1200 mm) (Figure 2), or two dedicated boxes with the same dimensions. A loaded configuration of the vehicle is presented in Figure 2.

- The loading bay is able to support a payload of maximum 1000 kg. We suppose that the weight is equally distributed between the two pallets (or boxes), so 500 kg each.

- The loading of the pallets or boxes is done from the 800 mm side with a maximum height of 150 mm at a maximum distance of 300 mm from the vehicle’s side.

Figure 2  (a) scheme of standard EURO-Pallet; (b) Sketch of the FURBOT vehicle (first version)
These constraints by themselves constituted the guidelines of the design process. In order to clearly define the working conditions of the freight-handling device further assumptions have to be made on the position of pallets. To correctly load the pallet it is necessary to verify that the following pre-conditions are satisfied:

- The pallet is placed on the street or low height pavement level,
- The pallet is positioned to be forked from the shortest side (hereafter it will be called operating side),
- The pallet is located in a horizontal position.

These functional parameters can be grouped into functional assumptions, schematised in Table 1, and functional requirements, described in Table 2. Given these basic constraints we can state that a minimum of 2 DoF is required to perform the loading and unloading procedures (vertical, to pick the pallet off the ground and transversal, to move it on the vehicle).

To increase efficiency and limit loading and unloading time these processes must be completely automated and not require any manpower or human intervention. The handling process can only happen after the correct positioning of the system with respect to the load is assured. This part of the procedure is human controlled to make sure that the handling device is perfectly aligned to the pallet slots and the freights or the device are not damaged during the process. The driver supervises the loading and unloading procedures from a tablet or control pad. Another factor to take into account during the design process is that it should be possible to load/unload independently at least two boxes or containers. For the unloading phase the human operator should start the procedure after making sure that the box will be deposited in an empty and safe area. Safety of the operations should be ensured by sensors and monitoring of the environment in case of error or distraction of the driver. Table 2 can be used as a benchmark to verify the worth of each system with respect to the FURBOT specific application.

### Table 1 Functional assumptions

<table>
<thead>
<tr>
<th>Type of loads</th>
<th>Standard Euro-pallets (800 mm × 1200 mm) dedicated boxes with equal dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading capacity</td>
<td>2 Euro-pallets or boxes</td>
</tr>
<tr>
<td>Distance from side of vehicle</td>
<td>200–300 mm</td>
</tr>
<tr>
<td>Height of load</td>
<td>0–150 mm</td>
</tr>
<tr>
<td>Loading Procedure</td>
<td>The pallet shall be loaded from its shortest side</td>
</tr>
<tr>
<td>Additional</td>
<td>Rotations around horizontal axis shall be avoided</td>
</tr>
</tbody>
</table>

### Table 2 Functional requirements

<table>
<thead>
<tr>
<th>Loading time</th>
<th>≤ 25 seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuation</td>
<td>Hydraulic</td>
</tr>
<tr>
<td>Mass of freight handling system</td>
<td>≤ 200 kg</td>
</tr>
<tr>
<td>Max. Payload</td>
<td>1000 kg to be equally distributed between the 2 pallets</td>
</tr>
<tr>
<td>Loading/Unloading side</td>
<td>The system must be able to load and unload from both sides</td>
</tr>
</tbody>
</table>
2.3 Realised prototype

Figure 3 shows the first prototype of the FURBOT vehicle. Figure 1b shows the initial state of the vehicle, and Figure 1c and Figure 1d show the digital mock-up of the vehicle respectively with and without boxes. The driver controls the vehicle with a joystick on the left of his position.

Figure 3  The structure of the Furbot vehicle prototype

2.4 Power supply

The power supply unit is in charge of storing and providing the energy required for the operation of the vehicle. The complete system is composed of cells, the battery management system, the balancing system, the power distributor, three voltage power supplies and the battery charger. The first step to design the power supply system was to calculate the amount of energy needed and the maximum power required. The power requirements come from the conditions of use. The main consumers are the power train, the handling device and the auxiliary service. The power train system is the responsible for moving the vehicle and has to overcome three main forces: rolling, aerodynamic and slope. According to calculations the force that has most influence in the power requirements is that related to the slope. As there was a restriction of 15 kW for the power train system, the power supply unit has to be able to provide this amount of power. The condition where this limit is reached is when driving on a 6% slope at 29 km/h or when driving on a 23% slope at 10 km/h. The maximum power required for the freight handling systems depends on load weight and the time of operation and has been around 3 kW. Finally, some estimation using standard components in the automotive and robotics industry have led to consider it around 2 kW.

Once the maximum power is calculated, estimation about the amount of energy that has to be stored in the battery system is needed. This has to take into account the power requirements and the conditions of use. For this purpose a simple model of the vehicle was developed, taking into account only the slope and aerodynamic forces. With this model the behaviour of the vehicle in some scenarios with different terrain sections, speed and hours of operation was simulated. With this information and the correction for the service handling system, the total amount of energy has been approximated by 17 kWh.
The battery is charged with a dedicated battery charger, connected to 220 V AC and can deliver up to 5.5 A. The main voltage of the battery is limited by the power train motors, which work at 96 V DC.

The driving estimated range of FURBOT operation will be around 60 km, with a total amount of 12 kWh for traction, 3 kWh for forklift handling system and 2 kWh for service.

2.5 Freight handling device

The current robotic handling device is composed of a sliding frame providing one DoF (Figure 4) on which the forklift is mounted adding the second DoF. Such frame features two pairs of linear guides located one on top of the other on each side of the frame. A steel plate works as a housing for the linear guides and connects parts A, B, and C together. The motion along the horizontal axis (Z direction, see Figure 4) is provided by hydraulic cylinders, mounted on the sides of the system (actuators 1 and 2). The system has only one non-moving part, part C, which is the fixed area of contact between the handling device and the vehicle’s chassis. The fork’s moving parts, parts A and B, are actuated by the hydraulic cylinders allowing the translation (Z direction) of the handling device in two independent stages. Actuator 1 allows the motion of part B with respect to the fixed part C; then actuator 2 allows the motion of part A thanks to the linkage between the actuator and the forklift. Part A is connected to the backside of the forklift while the piston shaft of the 2nd actuator is located in the front. Such 2-depth fork system permits the handling device to translate well beyond the minimum requirement of 1500 mm. The motion in the Y direction, i.e. the second DoF of the handling device, is given by a third hydraulic cylinder, located in the back of the forklift.

Figure 4  Robotic handling device frame

The complete robotic handling device is shown in a digital mock-up in Figure 5a. The shown configuration represents the idle state of the device when all the actuators are retracted and the device is inside the loading bay of the vehicle with the exception of the front rollers that in any case are within the total width of the vehicle including the wheels and body. Figure 5b shows the relative motion of each part of the handling device as it would happen during the loading or unloading.
The active suspension system of the FURBOT vehicle plays a key role in the vehicle positioning right before the pickup of the pallet. In fact, controlling independently the four suspensions’ cylinders it is possible to control the vehicle’s height, roll, and pitch.

Figure 5  Robotic handling device digital mock-up: (a) closed configuration, (b) open and lifted configuration

3 Computational tests: results and discussion

In order to optimise the safety, the functional conditions of the vehicle in a real environment have been considered optimising the design for commercial freight vehicles. Two functional conditions have been analysed:

- **Functional Condition 1**: the vehicle is steady changing the composition of goods on board.
- **Functional Condition 2**: the vehicle is in motion at its maximum speed with goods on board.

A preliminary study on the structural optimisation of the chassis, reducing slipping and unbalancing of goods during acceleration, deceleration, turn left, and turn right, are presented in this section.

Many tests have been performed considering different positions of the three goods designed for the FURBOT vehicle (see Figure 6): multibox, isolatedbox, and solidbox.

The functional condition 1 has been analysed using two multibox, or two isolatedbox, or two solidbox on board of the vehicle (see Figure 7), considering the same maximum weight of 500 kg for each good package. The functional condition 2 has been analysed using the most critical condition constituted of two multibox during acceleration, deceleration, turn left, and turn right.

In order to solve these two functional conditions, two different analyses have been performed and a unique solution that solves the two conditions has been proposed.

In following, starting from the initial condition of the FURBOT vehicle, two alternative solutions (alternative solution 1 and alternative solution 2), and the
implemented solution on the real vehicle are shown. The two alternative solutions are conceived with the final aim to optimise the structural stiffness of the chassis including also advantages for good’s transportation. A Finite Element Analysis (FEA) using ANSYS 14 is also presented.

**Figure 6** multibox (a), isolatedbox (b), and solidbox (c) used in the furbot vehicle (courtesy of ZTS)

![Figure 6](image)

**Figure 7** Chassis of the Furbot vehicle with robotic handling device on board

![Figure 7](image)

### 3.1 Preliminary analysis of the vehicle

Figure 7 shows the position of the Centre of Mass (CoM) of the complete vehicle calculated respect to the reference frame system shown in the figure (the CoM is indicated with G in Figure 7). In the preliminary analysis here presented, all weights of the vehicle (as battery, robotic handling device, pumps, etc.) were included, except the
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cover, console of the driver and driver’s seat, and wheels. In the following discussions, only multibox and solidbox are shown because isolatedbox and solidbox have small differences in dimensions and, in our analysis, each good is considered with the same weight. Figure 8 shows a simplified sketch of the chassis with the resultant forces concentrated on the CoM (indicated with G). Varying the composition of the goods on the vehicle (e.g. with two multiboxes, with one multibox and one solidbox, without goods, etc.), the global coordinates of the total CoM are modified and the reaction forces on the active suspensions A, B, C, and D, shown in the figure are modified. Table 3 shows the numerical value of the parameters shown in the Figure 8. Table 4 shows the numerical value of the reaction forces on the frontal \((V_D, V_C)\) and rear \((V_A, V_B)\) suspensions of the vehicle and the position of the CoM for each configuration with and without goods. The numerical values of the Table 4 are obtained assuming all external forces and moments on the vehicle (e.g. inertia, drag forces, etc.) equal to zero \((\Sigma F_{external} = 0; \Sigma M_{external} = 0)\), and assuming the equilibrium of all internal forces and moments. In order to simplify the calculation, only the ZX plane, as shown in the Figure 8, is considered:

\[
P - (V_D + V_C) = V_A + V_B; \quad \frac{P \cdot (a + b)}{(a + b + c)} = V_D + V_C;
\]

where \(P\) is the force generated by the weight; \(V_A\) and \(V_B\) are the reaction forces on the rear suspensions of the vehicle; \(V_D\) and \(V_C\) are the reaction forces on the frontal suspensions of the vehicle; \(a, b, c\) are the distances shown in Table 3.

**Figure 8** Sketch of the chassis of the FURBOT vehicle in the ZX plane
Table 3  Numerical values of the parameters shown in the Figure 8

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>a [mm]</td>
<td>b [mm]</td>
<td>c [mm]</td>
<td>(l = a + b + c) [mm]</td>
<td>h [mm]</td>
</tr>
<tr>
<td>351</td>
<td></td>
<td></td>
<td>2675</td>
<td>1970</td>
</tr>
<tr>
<td>Xg</td>
<td></td>
<td></td>
<td>1039</td>
<td>733</td>
</tr>
</tbody>
</table>

Table 4  Reaction forces on the active suspensions and position of the Centre of Mass (CoM) with and without goods

<table>
<thead>
<tr>
<th>Composition on board of the vehicle</th>
<th>Xg [mm]</th>
<th>Yg [mm]</th>
<th>Zg [mm]</th>
<th>P [N]</th>
<th>Vg + Vp [N]</th>
<th>Vg + Vc [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>With handling device and without goods</td>
<td>716.7</td>
<td>747.4</td>
<td>509.7</td>
<td>7200.5</td>
<td>4326.5</td>
<td>2874.0</td>
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<tr>
<td>Multibox on the first handling</td>
<td>1020.2</td>
<td>639.2</td>
<td>713.4</td>
<td>12,105.5</td>
<td>5900.3</td>
<td>6205.3</td>
</tr>
<tr>
<td>Multibox on the second handling</td>
<td>627.1</td>
<td>666.5</td>
<td>713.4</td>
<td>12,105.5</td>
<td>7679.6</td>
<td>4425.9</td>
</tr>
<tr>
<td>Solidbox on the first handling</td>
<td>1014.1</td>
<td>653.2</td>
<td>472.7</td>
<td>12,105.5</td>
<td>5927.9</td>
<td>6177.6</td>
</tr>
<tr>
<td>Solidbox on the second handling</td>
<td>633.2</td>
<td>653.7</td>
<td>472.7</td>
<td>12,105.5</td>
<td>7651.6</td>
<td>4453.9</td>
</tr>
<tr>
<td>Solidbox on the first handling, Multibox on the second handling</td>
<td>867.5</td>
<td>637.7</td>
<td>651.7</td>
<td>17,010.5</td>
<td>6262</td>
<td>7748.5</td>
</tr>
<tr>
<td>Multibox on the first handling, Solidbox on the second handling</td>
<td>873.3</td>
<td>603.7</td>
<td>628.3</td>
<td>17,010.5</td>
<td>9225.1</td>
<td>7785.4</td>
</tr>
<tr>
<td>Two multibox</td>
<td>869.1</td>
<td>611.5</td>
<td>799.6</td>
<td>17,010.5</td>
<td>11,483.9</td>
<td>5526.7</td>
</tr>
<tr>
<td>Two solidbox</td>
<td>707.7</td>
<td>701.6</td>
<td>443.7</td>
<td>17,010.5</td>
<td>10,278.2</td>
<td>6732.4</td>
</tr>
</tbody>
</table>

Notes:  

a Handling device near the driver.  
b Handling device near the battery.

3.2  Safety conditions in static position

In this section a Finite Element Analysis (FEA) using ANSYS 14 is shown. Figure 9 shows the GUI of the ANSYS software with the chassis of the FURBOT vehicle. The fixed supports A, B, C, D of the figure are the same as shown in the Figure 8. The remote forces E, F, G, H, I, in Figure 9, represent respectively the weight of battery, pumps, circuitry, and the robotic handling devices.

The frame is constituted by welded stainless steel tubes with square and rectangular section. The main frame is constituted by four tubes of rectangular section 100 mm × 40 mm with thickness of 2 mm. The material used for the frame is stainless steel EN 1.4301 (or AISI 304). The mechanical performance of stainless steels allows the creation of light frames. In general, a material AISI 304 has a breaking load of 500–700 MPa and yield strength of 190 MPa with some variation depending on the treatment of the material.
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Figure 10a shows the total maximum deformation of the chassis of the vehicle 5.1789 mm when two multiboxes are positioned on the frame of the Figure 9. Figure 10b shows the equivalent (von-Mises) stress of the chassis underlining that the critical points have a stress value 459.27 MPa major of the yield strength of the material.

Figure 11a shows the total deformation of the implemented solution on the actual version of the FURBOT vehicle (see Figure 3) and Figure 11b shows the equivalent (von-Mises) stress with a maximum value of the stress 442.79 MPa and a maximum deformation 4.7963 mm, minus than the solution proposed on the Figure 10.

Figure 12a shows the total deformation 3.3845 mm and Figure 12b shows the maximum stress 304.48 MPa of the proposed solution 1. Figure 13a shows the total deformation 3.1099 mm and Figure 13b shows the maximum stress 412.12 MPa of the proposed solution 2.

Table 5 shows a comparison among the initial solution, the implemented solution, and the novel alternative solutions 1 and 2. The alternative solution 1 is preferred respect to the other presented because the total deformation is limited to 3.4 mm, and a max equivalent stress noted on the chassis is 304 MPa. The alternative solution 1 is used to solve the two critical conditions underlined by a static deformation of the chassis and slipping and unbalancing of goods during motion. Solution number 1 allows to reduce deformation in its critical central point at 2.6 mm and avoids slipping and unbalance of multiboxes with a simple separation of the two zones of the two pallets or boxes in case of emergency break. In any case some protections activated after loading/unloading of goods should be implemented for more safety.

Figure 9  Definition of the forces (battery (E), pumps (F), circuitry (G), and robotic handling devices (I, H), and constraints (A, B, C, D) on the chassis
Figure 10  Chassis with two multiboxes on board (Initial solution): (a) total deformation; (b) equivalent (von-Mises) stress
Figure 11  Chassis with two multiboxes on board (implemented solution): (a) total deformation; (b) equivalent (von-Mises) stress
Figure 12  Chassis with two multiboxes on board (alternative solution 1): (a) total deformation; (b) equivalent (von-Mises) stress.
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Figure 13  Chassis with two multiboxes on board (alternative solution 2): (a) total deformation; (b) equivalent (von-Mises) stress
Table 5  Total deformation and maximum equivalent (von-Mises) stress for each proposed solution

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Total deformation [mm]</th>
<th>Maximum equivalent (von-Mises) stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial solution (Figure 10)</td>
<td>5.18</td>
<td>459.3</td>
</tr>
<tr>
<td>Implemented solution (Figure 11)</td>
<td>4.80</td>
<td>442.8</td>
</tr>
<tr>
<td>Alternative solution 1 (Figure 12)</td>
<td>3.39</td>
<td>304.5</td>
</tr>
<tr>
<td>Alternative solution 2 (Figure 13)</td>
<td>3.10</td>
<td>412.1</td>
</tr>
</tbody>
</table>

3.3 Safety conditions during motion of the vehicle

If a vehicle is moving in a real environment (Venture et al., 2006), many inertial influences relative to its motion and external perturbations can be noted: e.g. vertical accelerations with respect to the ground, caused by small rocks, or other external causes, on the road; longitudinal acceleration/decelerations during acceleration/deceleration of the vehicle; centrifugal accelerations during a turn. The dynamic inertial forces are generated by:

- Vertical symmetric forces: two wheels (two frontal or two rear wheels) are obliged by external causes to go at the same altitude with respect to the ground;
- Vertical asymmetric forces: one wheel is obliged to change its altitude from the ground;
- Longitudinal forces: caused by acceleration/deceleration of the vehicle;
- Lateral centrifugal forces: during a turn.

Figure 14 shows the vehicle motion terminology.
The boxes on the FURBOT vehicle are not locked and, during normal functional conditions, unbalancing of the goods could be generated reducing safety for the environment near to the vehicle. Figure 15 shows a sketch of the vehicle in two critical conditions: during turning (Figure 15a) and stopping (Figure 15b).

In the case of a turn left of the FURBOT vehicle (the side of the vehicle used for the loading/unloading goods is on the right of the driver during motion), the goods could be moved on the right of the vehicle by the centrifugal inertial force \( (F_c) \). No protections of the good are installed on the FURBOT and only the weight of the good can avoid the unbalance. If a vehicle goes at its maximum speed during a turn left, assuming that the road is horizontal, the suspensions are rigid, and the degree of turning is constant, the centrifugal force depend on \( m \), the mass of a good box, \( v \), the speed of the vehicle, and the turn radius \( R \). In all the calculation the position of the centre of mass of the good boxes \((x_1, y_1, z_1)\) is assumed not variable. It’s means that all materials inside the good boxes are fixed and not free to move.

**Figure 15** Sketch of a vehicle during turning (left) (a) or stopping (b)

Assuming the equilibrium of forces on the good box, two conditions should be verified in order to avoid the slipping and unbalancing for each configuration of boxes during turning or stopping. Considering the Figure 15a, one condition is relative to the slipping of the good and it can be controlled varying the weight of the good and it is underlined by the following equation \((\theta = 0)\):

\[
F_{cS} = \mu \cdot S_1 = \mu \cdot P = \mu \cdot m \cdot g; \tag{2}
\]

The second condition is relative to the unbalancing of the good and can be controlled by the dimensions of the good box. Assuming the equilibrium of the moment respect to the point O of the Figure 15a:

\[
F_{ck} = \frac{v_1 \cdot P}{z_1} = \frac{v_1 \cdot m \cdot g}{z_1}; \tag{3}
\]
where $S_1$ is the resultant force of the vertical reaction of the frame of the vehicle; $\mu$ is the coefficient of friction; $z_1$, $y_1$ are the dimensions of the good box; $P$ is the weight in Newton; $m$ is the mass of the good; $g$ is the gravity.

Posing the speed at 40 km/h (FURBOT maximum speed is 40 km/h = 11.11 m/s), and considering that the bottom part of the boxes is of stainless steel, like the frame of the chassis, the minimum radius of a turn left without a slipping and unbalancing can be calculated. The minimum value of $R$ ($R_m$) can be obtained using the maximum value between $R_{m1}$ and $R_{m2}$ obtained respectively from (2) and (3), as shown in (4):

$$R_m = \max \{ R_{m1}, R_{m2} \}; \quad R_{m1} = \frac{v^2}{\mu \cdot g}; \quad R_{m2} = \frac{z_1 \cdot v^2}{y_1 \cdot g};$$  \hspace{1cm} (4)

Table 6 shows $x_1$, $z_1$, $y_1$, $R_{m1}$, $R_{m2}$, and $R_m$, for isolated box, multibox, and solid box obtained using equation (4) and using: $m = 500$ kg; $v = 11.11$ m/s; $\mu = 0.8$; $g = 9.81$ m/s$^2$.

For a value of $R < R_m$, the good box will exit from the FURBOT vehicle reducing safety near the vehicle. This value is obtained performing some ideal assumptions as planar street, etc.; in normal conditions, this value could be higher. In order to have higher safety margin, some mechanisms should be considered and added to avoid the movement of goods during the motion of the vehicle and that can be removed during loading/unloading functions.

During the turn right, the slipping or unbalancing of the goods is avoided because handling devices are mounted on the vehicle, as shown in the Figure 7. Optimisation in design considering cyclic perturbation during motion on the handling device by unbalancing of the boxes should be considered for safety margin improvement.

Another critical functional condition is the emergency brake that can be generated in urban environments. Assuming that the vehicle is moving at 40 km/h, that it will be stopped in 5 seconds and that no external lateral forces caused by wind or other causes are present, the definition of the forces on the good boxes can be calculated. Other assumptions are that: the suspensions are rigid; no pitch of the vehicle is present during deceleration; the vehicle is considered as a rigid body; all the same conditions are imposed to the wheels. If the vehicle passes from 40 km/h to 0 km/h in 5 seconds, the deceleration is 2.2 m/s$^2$. With the hypothesis that the inertial force ($F_i$) will be transferred completely to the good, it will be invested by 1100 N. Figure 15b shows the condition of a deceleration. In this case, posing the equilibrium of the system, two values (one for slipping and one for unbalancing) of the $F_i$ can be generated by the following equations:

$$F_i = \mu \cdot S_i = \mu \cdot P = \mu \cdot m \cdot g; \hspace{1cm} (5)$$

$$F_{iu} = \frac{x_1 \cdot P}{z_1} = \frac{x_1 \cdot m \cdot g}{z_1}; \hspace{1cm} (6)$$

Equation (5) is relative to the equilibrium of the horizontal forces parallel to the frame of the chassis and it is influenced only by the weight of the goods, as in equation (2). Equation (6) is relative to the equilibrium of the moment respect to the point $O_1$ of the Figure 15b, and it is influenced by the dimensions of the good. Table 7 shows the minimum value of $F_i$ that generate unbalancing ($F_{iu}$) or slipping ($F_{is}$) of the goods for each good. The values are calculated considering: $m = 500$ kg; $g = 9.81$ m/s$^2$; $\mu = 0.8$; and $x_1, z_1, y_1$ from the Table 6.
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From Table 7 it can be noted such as the multibox could be affected by unbalancing more than other goods.

The preliminary analysis above discussed introduces a procedure to calculate the limits of the good boxes criterion that FURBOT can handle in given operative conditions and offers a novel optimisation criterion in design. It is shown the necessity to include systems to fix the goods during the motion of the vehicle, but also permitting all the loading/unloading functions. Using belts manually positioned by the operator to fix the goods, the time necessary for a loading/unloading function could be increased. The energy-efficiency of the electric vehicle suggests to use passive systems in order to use the battery only for driving, stopping, and loading/unloading (opening/closing the hydraulic pumps of the robotic handling device). In this case, the alternative solutions 1 and 2 presented in this paper could be used to optimise the safety of the vehicle.

<table>
<thead>
<tr>
<th>Table 6</th>
<th>Values for each good box in turning</th>
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<tbody>
<tr>
<td></td>
<td>$R_m$ [m]</td>
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<tr>
<td>Solidbox</td>
<td>15.73</td>
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<tr>
<td>Isolatedbox</td>
<td>15.73</td>
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<tr>
<td>Multibox</td>
<td>28.38</td>
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<table>
<thead>
<tr>
<th>Table 7</th>
<th>Inertial forces to generate unbalancing and slipping of goods on board of the FURBOT vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_{iu}$ [N]</td>
</tr>
<tr>
<td>Isolatedbox</td>
<td>7326</td>
</tr>
</tbody>
</table>

4 Conclusion and future works

The paper addresses the main features of the FURBOT vehicle. This vehicle has been designed with the aim to offer an innovative platform for freight delivery in urban areas with full respect of the people and the local environment. The FURBOT prototype has been tested in real cities that requested its use. The paper presented an optimisation of the vehicle from a safety point of view. In particular, two critical conditions have been analysed and some solutions to solve every condition are proposed. The static payload of the goods on the chassis, the slipping and unbalancing of goods during motion are the critical conditions for a freight urban vehicle as FURBOT. Alternative solutions to avoid these two problems are found. Future works will be oriented to reduce weight of the vehicle and its dimensions including higher safety margins. More complex computational analyses and real tests on loading/unloading process are planned for the next future. The tyre characteristics will also receive more consideration.
References


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