Table 1
Position error by algorithm iteration, for the example depicted in Fig. 4.

Step	err_x/m	err_y/m
0	5	5
1	0.11843	0.1183
2	0.0003	0.0003

Fig. 5. The skilled 1000 autonomous forklift at the Euroimpianti testing facility in Schio.

3.1. The Skilled 1000 autonomous forklift

The experiments presented within this paper were conducted using the Skilled 1000 autonomous forklift, shown in Fig. 5. This is a next-generation prototype vehicle manufactured by Euro-impianti company. The vehicle has one steering wheel in the front and two support wheels at the rear, configured in a tricycle steering system. It is controlled by controlling the velocity and the angle of the front wheel. Fig. 6 shows the steering configuration of the vehicle.

The following equations describe the motion of the vehicle in its local coordinate system.

$$v_x = cos(\theta)\cdot v_1$$
$$v_y = 0$$
$$\dot{\psi} = sin(\theta)\cdot\frac{v_1}{a} \tag{15}$$

where v_x and v_y represent translational velocities in x and y direction, $\dot{\psi}$ is the vehicle yaw rate, v_1 is the linear velocity of the front wheel (traction), θ is the steering angle of the front wheel and a is the distance between passive wheels and driven wheel (see Fig. 6). The distance a is directly measurable from the vehicle's geometry, whereas v_1 and θ can be obtained from motor encoder values using the following equations:

$$v_1 = \omega_d\cdot s_1$$
$$\theta = (\alpha_s - s_2)\cdot s_3 \tag{16}$$

where ω_d is the rotational velocity of the traction motor, α_s is the angle travelled by the steering motor and s_1, s_2 and s_3 are scaling parameters obtained by vehicle calibration. Velocities transformed into the global coordinate system are expressed as:

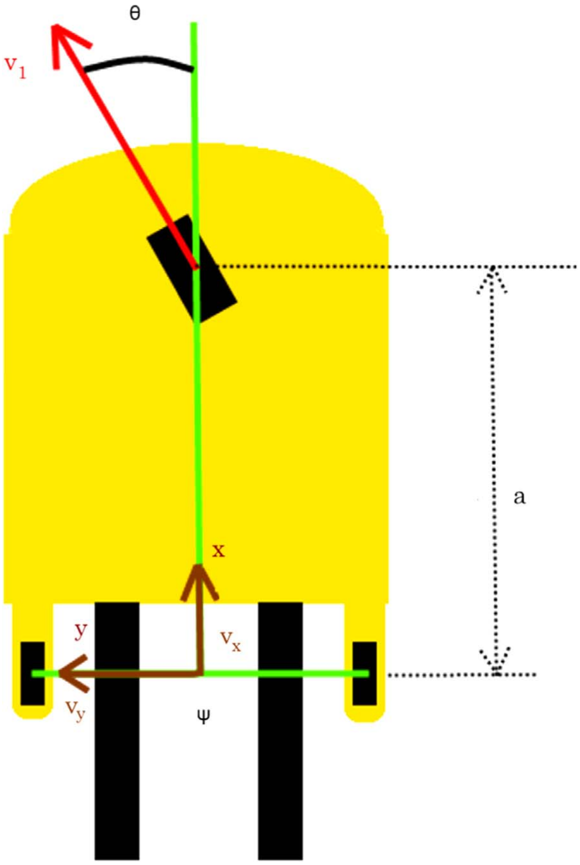

Fig. 6. The car-like kinematics of the LGV. The front wheel is used for both steering and traction. The unactuated rear wheels, located sideways from the forks, are for stabilization only.

$$v_{xg} = cos(\psi)\cdot v_x$$
$$v_{yg} = sin(\psi)\cdot v_x \tag{17}$$

where v_{xg}, v_{yg} are velocities in the global coordinate system in the x and y directions respectively. The odometry-based position estimate is obtained by integrating velocities. Since the controller operates on discrete time samples, integration is approximated by:

$$x_k = x_{k-1} + v_{xg}(k)\cdot T_s$$
$$y_k = y_{k-1} + v_{yg}(k)\cdot T_s$$
$$\psi_k = \psi_{k-1} + \dot{\psi}(k)\cdot T_s \tag{18}$$

where T_s is the sampling time and x_k, y_k and ψ_k represent the odometry-based pose of the vehicle at time step k.

The vehicle is equipped with four on-board lasers, three of those are safety lasers Sick S300 located at the ground level used to safely stop the vehicle if it comes too close to a moving or static obstacle. The fourth laser is the navigation laser Sick NAV350, a laser range scanner with the view angle of 360°. It provides the functionality of localizing the vehicle in 2-D space using reflective markers mounted in the environment. Range data from the navigation laser are used for the localization method presented within this paper.

Due to the prototype nature of the presented navigation and localization system, all of the algorithms were implemented on notebook PC that was interfaced to several systems of the vehicle (Fig. 7). Communication to the motor drives over CAN bus is used for gathering odometry data and for controlling vehicle motion. The ethernet interface was used for receiving range data from the NAV350 scanner. The ModbusTCP protocol was used for communicating with the system computer in order to enable and disable