

Effect of kinematic parameters on MPC based on-line motion planning for an articulated vehicle



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HIGHLIGHTS

- A motion planning scheme for an articulated vehicle based on a modified bug like algorithm and MPC has been presented.
- The motion planning scheme has been developed based on the real non linear kinematic equations of the articulated vehicle.
- An extended sensitivity analysis of the motion planning scheme has been performed.

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ABSTRACT

The aim of this article is to analyze the effect of kinematic parameters on a novel proposed on-line motion planning algorithm for an articulated vehicle based on Model Predictive Control. The kinematic parameters that are going to be investigated are the vehicle's velocity, the maximum allowable change in the articulated steering angle, the safety distance from the obstacles and the total number of obstacles in the operating arena. The proposed modified path planning algorithm for the articulated vehicle belongs to the family of Bug-Like algorithms and is able to take under consideration, the mechanical and physical constraints of the articulated vehicle, as well as its full kinematic model. During the on-line motion planning algorithm, the MPC controller controls the lateral motion of the vehicle, through the rate of the articulation angle, while driving it accurately and safely over the on-line formulated desired path. The efficiency of the proposed combined path planning and control scheme is being evaluated under numerous simulated test cases, while exhaustive simulations have been made for analyzing the dependency of the proposed framework on the kinematic parameters.

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1. Introduction

In general path planning and obstacle avoidance algorithms, coupled with control schemes, are one of the major areas of focus in the field of autonomous vehicles [1]. Regarding the specific area of Articulated Vehicles (AV) as the one depicted in Fig. 1, their autonomous operation has received considerable attention from researchers lately such as in [2]. However, in most of the existing research approaches, the focus has been in the remote operation of the AVs rather than embedding autonomy into the vehicles for accomplishing specific missions in controlled environments [3]. Currently, there is a continuous trend for increasing the overall levels of AVs' autonomy, especially in the field of on-line path planning and in related control schemes.

The specific geometry of the AV is more suitable to a free space constrained environment, than a car-like vehicle [4]. Furthermore, an articulated vehicle is able to perform sharper turns from an Ackerman vehicle of a similar length, while it is being characterized in general by a higher maneuverability [5] and thus AVs are commonly found in multiple applications in the fields of mining and construction sites [6].

Regarding the area of path planning, one of the major challenges is to satisfy the vehicle's kinematic constraints, while applying the generated planned path, a problem that to the authors best knowledge is still an open research issue. Towards this direction, common and rather oversimplified and non-realistic approaches have been the cases where the vehicle has been considered as a unit point, with the major kinematics of the vehicle neglected for simplicity reasons, while the AV has been considered of having full translation capabilities with a general state space representation of $\dot{x} = u$, with u the actuating control signal.

For a path planning approach compatible with the vehicle's constraints, a non-holonomic path planning method, for minimizing

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Fig. 1. Type of an articulated vehicle.

the traveling length and curvature constraints, has been presented in [7], while in [8] it has been investigated the utilization of polar polynomial curves to produce a continuous path changing, under specific curvature constraints. In [9–11] extensive work focusing on the systematic error to achieve minimal path planning errors has been evaluated, while in [12] an algorithm for minimizing the maximum path length in real time has been presented. Furthermore, in [13], a new scheme based on calibration equations, introducing fewer approximation errors in order to reduce kinematic modeling errors, was proposed.

From a control point of view, there have been proposed many traditional techniques for nonholonomic vehicles, based on error dynamics models without the presence of slip angles. A control scheme that combines a kinematic and a sliding mode controller for wheeled mobile robots has been presented in [14,15]. In [16] a general kinematic model of an articulated vehicle has been proposed that described how heading angle evolved with time as a function of steering angle and velocity. In [17] a Lyapunov based approach has been presented that addressed the problem of asymptotic stabilization for backward motion. A nonlinear control law based on partial state feedback linearization and a Lyapunov method for the closed-loop path following problem of a nonholonomic mobile robot has been appeared in [18,19]. Finally, a control scheme based on linear matrix inequalities has been presented in [20] and in [21] a pole placement technique has been applied.

The main contributions of this article are the following ones. Firstly, a modified novel Bug like algorithm will be coupled with the MPC in order to establish a smooth and efficient path planning scheme for an AV. The proposed scheme is based on a partial sensory-based awareness of the AV's surrounding environment and a priori knowledge about the current goal points. Secondly, the full kinematics of the vehicle and especially its non-linearities will be considered in the proposed online path planning algorithm. Thirdly, a sensitivity analysis of the proposed combined online path planning and MPC scheme will be presented.

The rest of the article is organized as follows. In Section 2, the AV kinematic and error dynamics models are being presented, while in Section 3, the proposed on-line path planning is being demonstrated in combination to the utilized MPC scheme. In Section 4, multiple simulation results, subjected to various conditions, are being analyzed examining the sensitivity of the proposed scheme, while proving the overall efficacy in different arenas and in different configurations. Finally, the concluding remarks are provided in Section 5.

2. Articulated vehicle and error dynamic models

The AV's geometry is represented in Fig. 2. It consists of two parts, a front and a rear, with lengths l_1 and l_2 respectively, linked by a rigid free joint, while the overall vehicle's width is denoted by w . Each body has a single axle and all wheels are non-steerable. The centers of gravity for these parts are being denoted as $P_1 = (x_1, y_1)$ and $P_2 = (x_2, y_2)$. The steering action is being performed on the center joint, by changing the corresponding articulated angle γ . Furthermore, the velocities v_1 and v_2 are considered to have the same change, with respect to the velocity of the rigid free joint of the vehicle, while C is the instantaneous center velocity of the

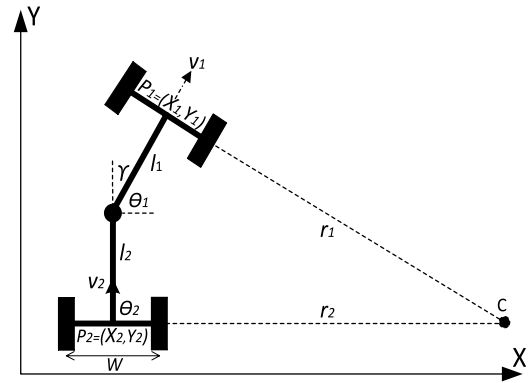


Fig. 2. Articulated vehicle's geometry.

front and rear parts with different radiuses (r_1, r_2). For the described non-holonomic AV, the kinematic model, including the vehicle's configuration has been extendedly introduced and analyzed in [22].

This kinematic model deals with the geometric relationships between the control parameters and the overall behavior of the vehicle, while it has been assumed that the vehicle is traveling forward without slip, by controlling the rate change of the steering angle $\dot{\gamma}$. The non-holonomic constraints acting on the front and rear axles, can be expressed as it follows:

$$\dot{x}_1 \sin \theta_1 - \dot{y}_1 \cos \theta_1 = 0 \quad (1)$$

$$\dot{x}_2 \sin \theta_2 - \dot{y}_2 \cos \theta_2 = 0. \quad (2)$$

For deriving the vehicle's kinematic equations, it is assumed that (a) the steering angle γ remains constant under small displacements, (b) the dynamical effects due to low speed (like tire characteristic, friction, load and breaking force) are being neglected, (c) each axle is being composed of two wheels that can be replaced by a unique wheel, and (d) the vehicle moves on a plane without slipping effects. Furthermore, it is assumed that the vehicle's velocity is bounded within the maximum allowed velocity, which prevents the vehicle from slipping. From the geometrical characteristics of the vehicle it can be easily derived that the equations describing the translation of the articulated front part are:

$$\dot{x}_1 = v_1 \cos \theta_1 \quad (3)$$

$$\dot{y}_1 = v_1 \sin \theta_1. \quad (4)$$

The velocities v_1 and v_2 are considered to have the same changing with respect to the velocity of the rigid free joint of the vehicle and thus the relative velocity vector equations can be defined as:

$$v_1 = v_2 \cos \gamma + \dot{\theta}_2 l_2 \sin \gamma \quad (5)$$

$$v_2 \sin \gamma = \dot{\theta}_1 l_1 + \dot{\theta}_2 l_2 \cos \gamma \quad (6)$$

where $\dot{\theta}_1$ and $\dot{\theta}_2$ are the angular velocities of the front and rear parts respectively. Combining Eqs. (5) and (6) yields:

$$\dot{\theta}_1 = \frac{v_1 \sin \gamma + l_2 \dot{\gamma}}{l_1 \cos \gamma + l_2}. \quad (7)$$

For the case that there is a steering limitation for driving the rear part according to the coordinates of the point (x_2, y_2) , the relationship between front and rear coordinates is provided by:

$$x_2 = x_1 - l_1 \cos \theta_1 - l_2 \cos \theta_2 \quad (8)$$

$$y_2 = y_1 - l_1 \sin \theta_1 - l_2 \sin \theta_2. \quad (9)$$

Based on the full modeling approach presented in [22] and from (3), (4), and (7) the state space vector for the AV is defined as

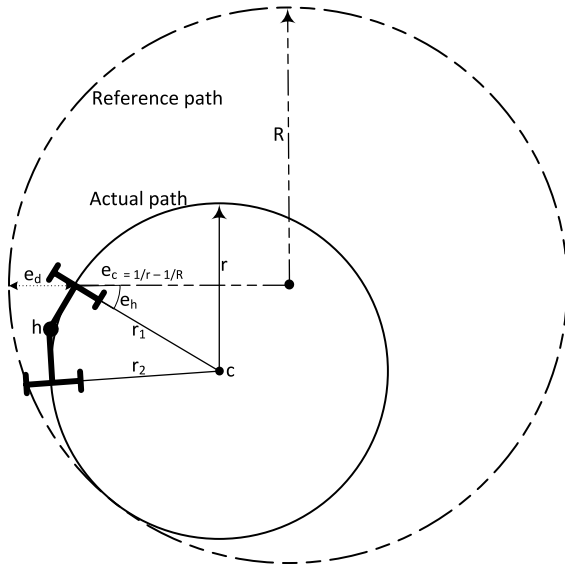


Fig. 3. A graphical representation of the error dynamics transformation.

$\mathbf{x} = [x_1 \ y_1 \ \theta_1 \ \gamma]^T$, with the following kinematic model representation for the front part:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{\theta}_1 \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} \cos \theta_1 & 0 \\ \sin \theta_1 & 0 \\ \sin \gamma & l_2 \\ \frac{l_1 \cos \gamma + l_2}{l_1 \cos \gamma + l_2} & \frac{l_2}{l_1 \cos \gamma + l_2} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \dot{\gamma} \end{bmatrix} \quad (10)$$

where $\dot{\gamma}$ is the rate of change for the articulated angle, denoted also as $\dot{\gamma}$. As it has been extensively presented in [23], the system representation can be formulated as a set of error dynamic equations. These error dynamics are described by the following parameters depicted in Fig. 3, which are the curvature e_c , the heading e_h , and the displacement e_d errors. In the presented error dynamics approach, the e_c is the difference between the curvature of the desired and the actual path. The e_h is the angle between the centers of the desired and actual path, when considering the front center of the vehicle. Finally, the e_d is the difference between the two paths with respect to the vehicle's location.

The curvature error can be presented using the equation $e_c = (1/r - 1/R)$. By assuming that the vehicle velocity v and the radius of the reference path R are constant, then; $\dot{e}_c = d(\frac{v \sin \gamma + l_2 \dot{\gamma}}{v(l_1 \cos \gamma + l_2)})/dt$. Furthermore, the rate of the curvature error is being defined as:

$$\begin{aligned} \dot{e}_c = & \dot{\gamma} \frac{l_2 \cos \gamma + l_1}{(l_1 \cos \gamma + l_2)^2} + \ddot{\gamma} \frac{l_2 (l_1 \cos \gamma + l_2)}{v(l_1 \cos \gamma + l_2)^2} \\ & - \dot{\gamma}^2 \frac{l_1 l_2 \sin \gamma}{v(l_1 \cos \gamma + l_2)^2}. \end{aligned} \quad (11)$$

As defined in Fig. 3, the change of heading error is: $e_h = \theta_1(1 - \frac{r}{R})$, by utilizing the relations ($r = \frac{v}{\dot{\theta}}$) and $e_c = (\frac{1}{r} - \frac{1}{R})$, the rate of heading error is being calculated as:

$$\dot{e}_h = v e_c + \dot{\gamma} \frac{l_2}{l_1 \cos \gamma + l_2}. \quad (12)$$

The displacement error is being defined as: $e_d = r \theta e_h - l_1 \cos \gamma$ and by taking the time derivative of this equation it can be derived that:

$$\dot{e}_d = v e_h + \dot{\gamma} l_1 \sin \gamma. \quad (13)$$

By linearizing the error dynamics in Eqs. (11)–(13) around the reference path and by considering small changes in the articulated

angle, measured in radians, and by redefining the state variables into a form containing a single control input (the rate of the articulation angle) it yields into [23]:

$$\begin{bmatrix} \dot{e}_c \\ \dot{e}_h \\ \dot{e}_d \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ v & 0 & 0 \\ 0 & v & 0 \end{bmatrix} \begin{bmatrix} e_c \\ e_h \\ e_d \end{bmatrix} + \begin{bmatrix} k_1 \\ k_2 \\ 0 \end{bmatrix} \dot{\gamma} \quad (14)$$

where $k_1 = \frac{1}{l_1 + l_2}$ and $k_2 = \frac{l_2}{l_1 + l_2}$ are constants and the derivative of the error states vector can be further denoted by $\dot{\mathbf{x}}_e = [\dot{e}_c \ \dot{e}_h \ \dot{e}_d]^T$. This error dynamics model in Eq. (14) is going to be utilized in the sequel for developing the proposed path planning algorithm and the corresponding MPC scheme for the AV's motion planning.

3. Path planning and motion control

As it has been mentioned before, in the related literature of AV's and especially in the area of path planning, the vehicle is being modeled as a unit dynamics point and this approach is mainly due to simplicity and for avoiding the non-linearities of the AV model. However, one of the contributions of this article is to present an overall and complete motion planning approach for an AV, based on the full kinematics of the vehicle, combine it with a MPC scheme, evaluate the performance of the motion planning algorithm in more realistic scenarios and present an extended analysis of the algorithms sensitivity based on numerous simulation results, while extending and strengthening the results presented in [24]. The sensitivity analysis, which will be presented in the next section is considered as the most important contribution of this article since instead of providing a couple of simulation results, it evaluates the presented scheme from an extended point of view based on multiple simulation results and based on significant algorithmic parameters that dramatically effect the performance of the proposed scheme, while providing direct insights and discussions. However, before the sensitivity analysis, the complete and extended approach on the motion planning, which includes the steps of path planning and path tracking will be presented in this section.

3.1. Modified path planning

The proposed online path planning algorithm can be applied for the objective of moving a vehicle from a starting point to the goal point, while detecting and avoiding identified obstacles based on the real vehicle's dynamic equations of motion and the Model Predictive Controller. As a common property of the Bug like algorithms, the proposed scheme initially faces the vehicle towards the assumed constantly known goal point. In the presented algorithm, it has also been assumed that the vehicle is able to on-line sense the surrounding environment, included in a sensing radius of r_{obs} . During translation, the path planner is on-line generating future way points that act as a reference path for the utilized MP-controller. Before feeding the MPC with the reference coordinates, a proper conversion is taking place from the Cartesian space to the curvature, heading and distance space, which consist the states of the vehicle's error dynamic model [23]. The overall proposed concept of path planning and MPC control is depicted in Fig. 4.

As it can be observed from this diagram, the algorithm starts by defining the current position and orientation of the vehicle, denoted by $[X_r, Y_r, \theta_r]$ and the final goal position denoted by $[X_g, Y_g, \theta_g]$. Based on the onboard sensory system, the vehicle identifies the surrounding environment and obstacles and generates on-line the way points for reaching the goal destination, by solving the local and by definition sub-optimal, path planning problem. In the sequel the way points are been translated to references for the error dynamics based MP controller. The control scheme generates the rate of articulated angle, which is the control

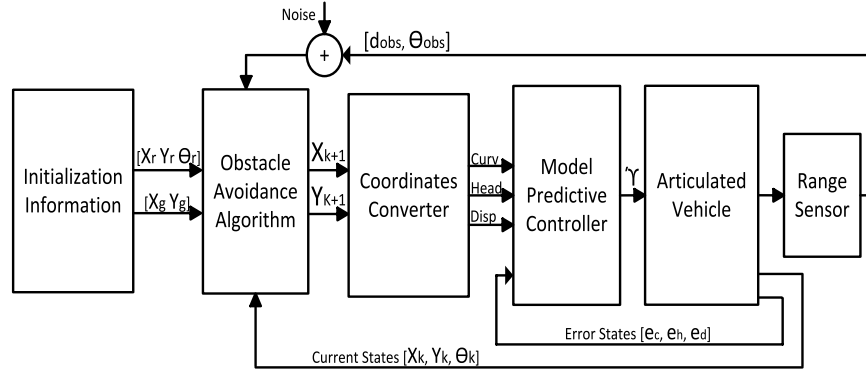


Fig. 4. The combined on-line path planning and MPC for the AV.

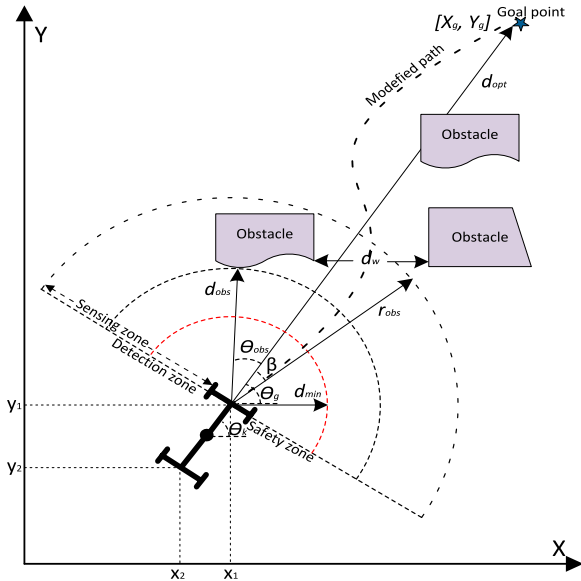


Fig. 5. Notations and overall concept of the proposed online path planning algorithm.

signal for the vehicle. In the presented architecture, it is assumed that accurate and continuous position and orientation measurements as well as corresponding updates are being provided, without any loss of generality.

The assumed sensory system is able to provide a partially bounded information on the surrounding environment due to the assumption of a limited sensing range $r_{obs} \in \mathbb{R}$, while these measurements are being transformed to relative distances and angles from the articulated robot to the identified surroundings or obstacles, defined as $d_{obs} \in \mathbb{R}$ and $\theta_{obs} \in \mathbb{R}$ correspondingly. It should be noted that in the presented approach all the obstacles and the surrounding environment are being considered as point clouds in a 2-dimensional space, while overlapping obstacles are being merged and represented by a single and unified obstacle. In the path derivation a safety distance has been also considered, denoted as $r_{min} \in \mathbb{R}$, for protecting the vehicle from approaching close to the obstacles. In the consideration of this safety distance, the algorithm calculates the related distance and angle from the identified obstacle, denoted as $d_{min} \in \mathbb{R}$ and $\theta_{min} \in \mathbb{R}$, while tuning the path planning accordingly. The notations utilized and the overall concept of the proposed path planning algorithm are depicted in Fig. 5.

The operation and the sequential execution of the proposed path planning and control scheme can be summarized as it is depicted in the following table, while in [24] a full analysis of the presented approach can be found:

Path Planning Algorithm

Initialization

- Set parameters: $[X_k Y_k \theta_k]$, $[X_g Y_g]$ and $[v, \dot{\gamma}, d_{min}, \theta_{min}, r_{min}, d_{obs}, \theta_{obs}, T]$.

Path Update

- Calculate orientation to the goal $\theta_g(k) = \arctan \frac{Y_g - Y_k}{X_g - X_k}$ and the difference angle $\beta(k) = \theta_g(k) - \theta_k$

Goal Update

- Update, $x(k) = v \cos(\theta(k) + \beta(k))$, $y(k) = v \sin(\theta(k) + \beta(k))$, and $\theta(k) = \beta(k)$

Scan Area

- Compute smallest distance, $d_{obs} = \sqrt{(X_{k+1} - X_{obs})^2 + (Y_{k+1} - Y_{obs})^2}$
- Compute angle to the obstacle, $\theta_{obs} = \arctan \frac{Y_{k+1} - Y_{obs}}{X_{k+1} - X_{obs}}$
- Compute angle between the obstacle and the goal, $\theta_{obs,g} = \theta_{obs} - \theta_g$

Obstacle Detection

- Evaluate the risk of collision, $(d_{obs} < d_{min})$ AND $(\theta_{obs,g} < \theta_{min})$
- Evaluate the angle to the obstacle, $(d_{obs} < d_{min})$ AND $(\theta_{obs} < -\theta_{min}, \theta_{obs} > \theta_{min})$

Obstacle Avoidance Conditions

- If being satisfied, $\theta_{obs,g} > 0$: $\beta(k+1) = \beta(k) + \Delta\beta(k)$, and if, $\theta_{obs,g} < 0$: $\beta(k+1) = \beta(k) - \Delta\beta(k)$

Update Reference Path for MPC

- Update, $x(k+1) = x(k) + v \cos(\beta(k+1))$, and update, $y(k+1) = y(k) + v \sin(\beta(k+1))$

Algorithm Termination

- If, $x(k+1) \in X_g \pm T$ AND $y(k+1) > Y_g \pm T$
- Go To Step "Path Update"

Otherwise

- Vehicle Reaches Goal and Velocity = 0

3.2. Model predictive control

The proposed MPC is utilizing the state space representation (14) for generating the proper rate of articulation angle for controlling the articulated vehicle. In order to design the MPC controller for path following, the linearized system (14) will be discretized as:

$$\mathbf{x}_e(k+1) = \mathbf{A}\mathbf{x}_e(k) + \mathbf{B}u_e(k) \quad (15)$$

where $\mathbf{A} \in \mathbb{R}^n \times \mathbb{R}^n$, n is the number of state variables and $\mathbf{B} \in \mathbb{R}^m \times \mathbb{R}^m$, m is the number of input control variable, x_e is the error dynamics state vector and with u_e is the control signal (the rate of the articulated angle). The overall aim of the MPC is to calculate a proper control signal that minimizes the quadratic objective

function of the states and control input with predictive horizon M , which is being described by:

$$J(k) = \sum_{j=1}^M (\mathbf{x}_e^T(k+j|k) \mathbf{Q} \mathbf{x}_e(k+j|k)) + \sum_{j=1}^N (\mathbf{u}_e^T(k+j-1|k) \mathbf{R} \mathbf{u}_e(k+j-1|k)) \quad (16)$$

where $\mathbf{Q} \in \mathbb{R}^n \times \mathbb{R}^n$ is the weighting matrix for predicted errors and $\mathbf{R} \in \mathbb{R}^m \times \mathbb{R}^m$ is the weighting matrix for control input. The \mathbf{Q} and \mathbf{R} weighting matrices are positive diagonal matrices with largest elements corresponding to the most important variables, while an increase in the values of weights tends to make the MPC controller more conservative. In the presented approach, the widely utilized ad-hoc tuning procedure for these weights have been followed in order to optimize the simulated results obtained. Finally, the control action is being obtained by solving on-line the optimization $J(k)$ with respect to the control variation Δu and the errors coordinates.

To handle the state and input constraints, let the bounds in the states variables as the following bounding inequality:

$$\mathbf{x}^{\min} = \mathbf{x} - \Delta_1 \leq \mathbf{x} \leq \mathbf{x} + \Delta_1 = \mathbf{x}^{\max} \quad (17)$$

where $\Delta_1 \in \mathbb{R}^n \times \mathbb{R}^n$ is the vector containing the selecting state boundary conditions, which are the maximum and minimum allowable limits for AV's error dynamics. Furthermore, the control input bounds could be derived by taking under consideration the mechanical and physical constraints of the articulated steering angle, while these constraints can be formulated as:

$$\mathbf{u}^{\min} = \mathbf{u} - \Delta_2 \leq \mathbf{u} \leq \mathbf{u} + \Delta_2 = \mathbf{u}^{\max} \quad (18)$$

where $\Delta_2 \in \mathbb{R}^m \times \mathbb{R}^m$ is the vector containing the selecting control boundary condition. These constraints are embedded in the MPC computing algorithm in order to compute an optimal controller that counts for the constraints that restrict the articulated vehicle's motion.

During the deviation of the MPC, special care should be provided in order to correctly tune the prediction M and the control N horizons. A long prediction horizon increases the predictive ability of the MPC controller but on the contrary it decreases the performance and demands more computations. The control horizon must also be fine-tuned since a short control horizon leads to a controller that tries to reach the setpoint with a few conservative motions, a method that might lead to significant overshoots. On the contrary, a long control horizon produces more aggressive changes in the control action that tend to lead to oscillations. Obviously the tuning of prediction and control horizon is a coupled process. For the aforementioned reasons the control horizon must be chosen short enough compared to the prediction horizon. Additionally, the response of the system can be also shaped using weight matrices on the system outputs, the control action and the control rates.

4. Simulation results

For simulating the efficacy of the proposed path planner and evaluating its sensitivity against the motion parameters, the following AV's characteristics have been considered as: $l_1 = l_2 = 0.61$ m, $w = 0.58$ m, while the vehicle's velocity for this part of simulation is in the range of $(0.5 \leq v \leq 2)$ m/s. Moreover, the constraints imposed on the articulated angle γ have been defined as: $-30^\circ \leq \gamma \leq +30^\circ$ and random measurement Gaussian noise with a fixed variance has been added to the measurements of the range sensor to simulate the real-life distortion.

The parameters of the MPC have been tuned as: (a) prediction horizon (number of predictions) $M = 10$, (b) control horizon

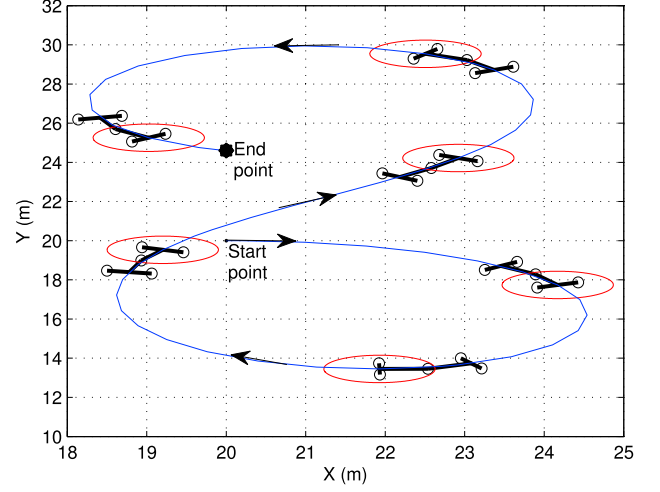


Fig. 6. Motion behavior of the AV (8-pattern).

(number of future control moves) $N = 5$, and (c) a time sampling period of 0.2 s. The constraints imposed on the input and control weighting matrices have been tuned according to the current active state space model as: weighting matrix for predicted errors $\mathbf{Q} = 0.3\mathbf{I}_{3 \times 3}$ and weighting matrix for control movement $\mathbf{R} = 0.1$ for suspending aggressive maneuvers. In the presented simulation results additional corrupting noise for the feedback range sensors signals has been considered to add more realistic behavior. This white noise has a uniform distribution and a gain of 0.01 to simulate the real life measurement distortion and has been tuned based on our real life experience and experimentation with the utilized range sensors (ultrasound sensors).

In Fig. 6, a typical example of the AV's motion behavior in an open-loop configuration is being presented. The simulation of the non-linear model has been performed by considering the AV to start translating from a start point of $[x = 20, y = 20, \theta = 0, \gamma = -10^\circ]$, while $\dot{\gamma}$ is changing with respect to time, in positive and negative orientations.

The case of movement from a starting point into two different goal points, in an arena with differently shaped obstacles, is being considered in Fig. 7. In this case, the AV's states initiate from $[0 \ 0 \ 45^\circ \ 7.5^\circ]$ and the multiple distinct goal points have been set as $[10, \ 35]$ and $[20, \ 25]$ respectively, with $r_{obs} = 4$ m and $d_{min} = 3$. In the depicted closed loop paths, the articulated kinematics of the vehicle are obvious due to the existing curvature of the vehicle during translation. Furthermore, in Fig. 8 the corresponding responses of the error dynamics states, as well as the articulated angle and the rate of the angle (control effort) are being depicted for both examined path tracking scenarios, (blue-lines for Goal point 1 and red-dashed lines for Goal point 2).

In the second scenario, the case of movement within a multiple bounding surrounding environment is being considered, as presented in Fig. 9, which mimics the operation in a mining environment or a construction site. In the examined case, the AV starts at $[0 \ 0 \ 15^\circ \ 7.5^\circ]$ with the goal points (1, 2, 3) at $[10 \ 15]$, $[40 \ 10]$, and $[10 \ -15]$, respectively, with $r_{obs} = 3$ m and $d_{min} = 2$. As in the previously examined case, the proposed scheme manages to provide smooth path generation and tracking for the vehicle. The existence of non-holonomic behavior, due to the articulated dynamics, is again obvious due to the curvature of the obtained path. The corresponding responses of the error dynamics states, as well, the articulated angle and the rate of the angle (control effort), which are being depicted for only the case of path generation and tracking to the second goal point are being presented in Fig. 10.

In the sequel the sensitivity of the proposed scheme will be evaluated with respect to the corresponding Kinematic Parameters

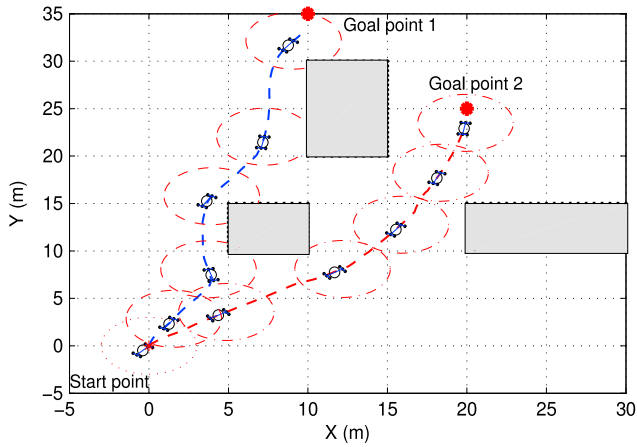


Fig. 7. Path tracking in an open arena with different shape obstacles.

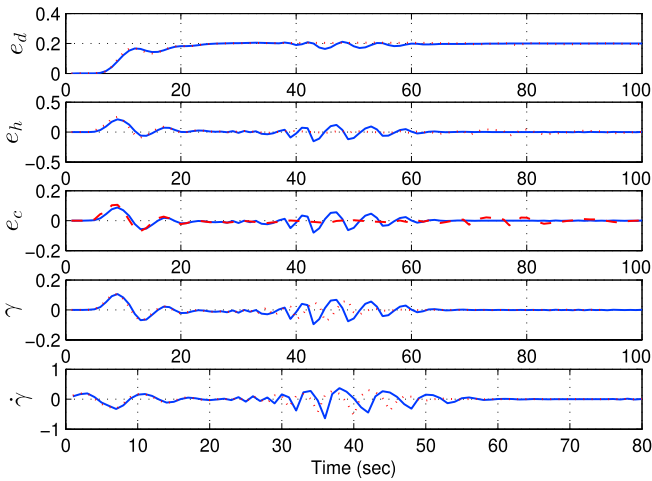


Fig. 8. Vehicle's error dynamics response and corresponding articulated angle γ and MPC's effort $\dot{\gamma}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(KP) defined by the vehicle's velocity v , the maximum allowable change in the steering angle $\Delta\beta$ suggested by the path planner, the safety distance d_{min} and the overall number of obstacles in a fixed size arena. The arenas that are going to be considered are: (a) an open area with dimensions (15×15) m, with 9-obstacles in fixed locations and (b) an open area with dimensions (35×35) m and with a random number, (0–400) or 0–200, and positioning of fixed size obstacles. In all the examined test cases, the obstacles are of a squared shape with sides of (1 m). The aim of the proposed on-line path planning scheme was to generate a collision free path, from the initial posture to the destination point. The previous selected KP are the ones that could be tuned and have a direct effect on the overall maneuverability of the AV. In all the simulated test cases, an important efficiency indicator will be the AV's length of route or translated distance (m), during the translation from the initial posture to the final one.

In the beginning of the sensitivity analysis, the case of having a fixed $\beta = 12^\circ$ and with varying d_{min} and v is being considered for the case of an open area with 9 fixed obstacles. In this case the AV starts from an initial point of $[0 \ 0 \ 10 \ 7.5]$ and with a final goal point at $[15 \ 15]$, while no demand on the orientation, when reaching the goal point has been set. The obtained simulated results are being depicted in Fig. 11, while for comparison reasons, it should be stated that the shortest distance in this problem is the straight, and

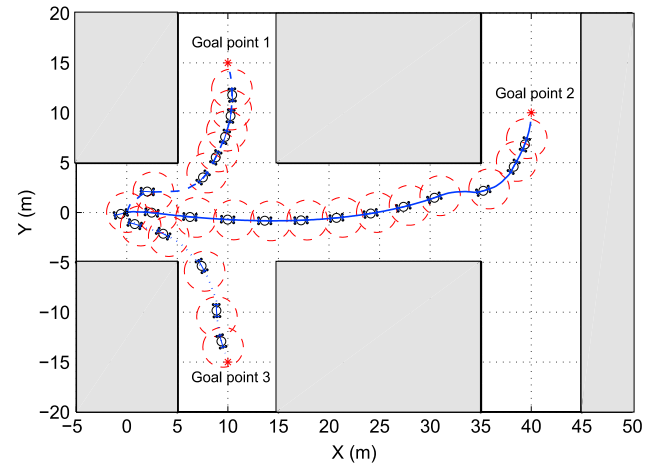


Fig. 9. The arena having same boundaries on both sides of the road.

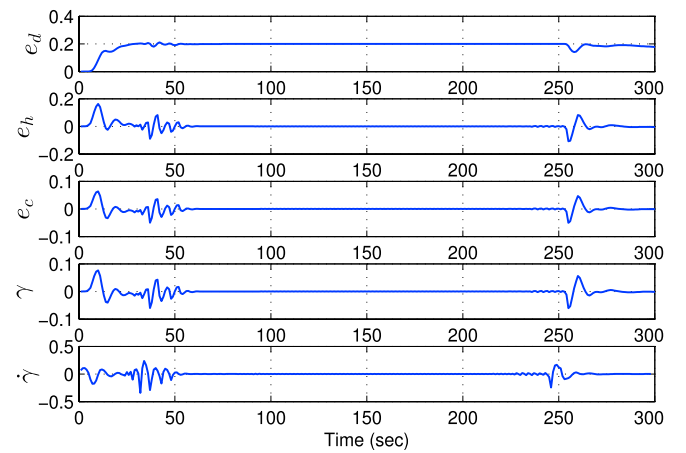


Fig. 10. The systems states error dynamics performance in meter, for the case of path generation and tracking to the second goal point.

free of obstacles, path of 21.2 m. During the described simulations, the variation of the KP has been set as $0.5 \leq v \leq 2$ m/s with a step change of 0.1 m/s and $0.5 \leq d_{min} \leq 2$ m with a step change of 0.1 m. In the presented results, when the traveling distance is equal to 0 m it indicates that the AV failed in reaching the desired end goal, with the selected KP configuration.

From the obtained results in Fig. 11 it is obvious that in general low-velocities and smaller safety distances can achieve an accurate and short-distanced path to reach the goal point, while in the examined scenario, from the 225 iterations, only 64 cases failed to reach the indicated target goal.

In Fig. 12, the case of fixing the velocity at $v = 1$ m/s and having the rest of KP varying as $10 \leq \beta \leq 25^\circ$, with a step change of 1° and $0.5 \leq d_{min} \leq 2$ m with a step change of 0.1 m is being presented. As it has been indicated from the obtained simulation results, at small safety distances, the allowable changing of the steering angle has the same effect during the movement towards the goal position. In these simulations, 68 cases out of total 225 iterations have failed in reaching the target goal. However, in contrast to the previous test case, it should be highlighted that in general the constraint on the steering angle is not so significant on the AV's steering responses under a constant velocity and small safety distances.

In Fig. 13, the final case for the first scenario has been considered, where d_{min} has been fixed at 1.2 m and the rest of the KP are considered varying as $10 \leq \beta \leq 25^\circ$, with a step change of 1° and $0.5 \leq v \leq 2$ m/s with a step change of 0.1 m/s. The obtained

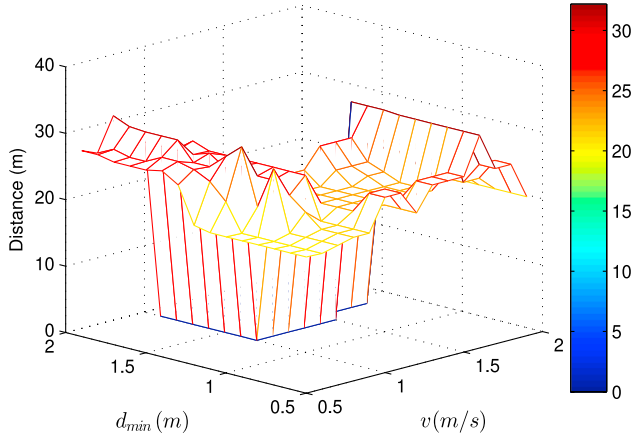


Fig. 11. Successful reaching of the final goal and overall distance traveled under constant allowable change of path planner's steering angle and varying speed and safety distance (open area with 9 fixed obstacles).

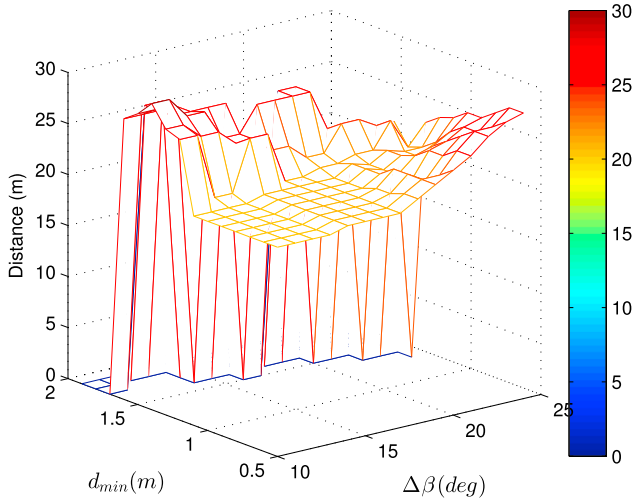


Fig. 12. Successful reaching of the final goal and overall distance traveled under constant speed and varying allowable change of the path planner's steering angle and speed (open area with 9 fixed obstacles).

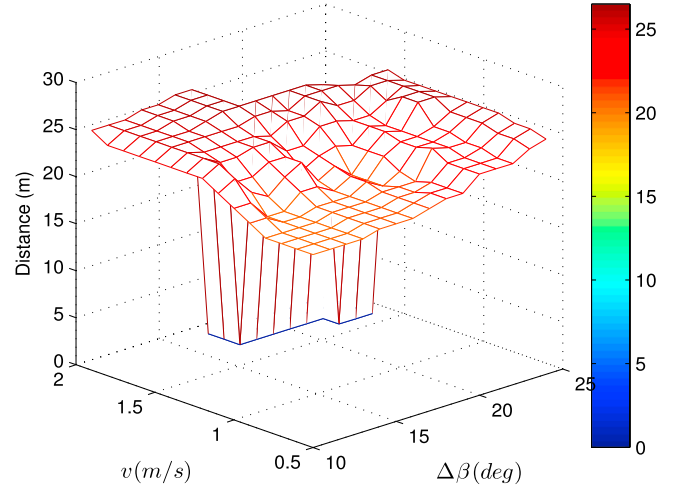


Fig. 13. Successful reaching of the final goal and overall distance traveled under constant safety distance and varying allowable change of the path planner's steering angle and safety distance (open area with 9 fixed obstacles).

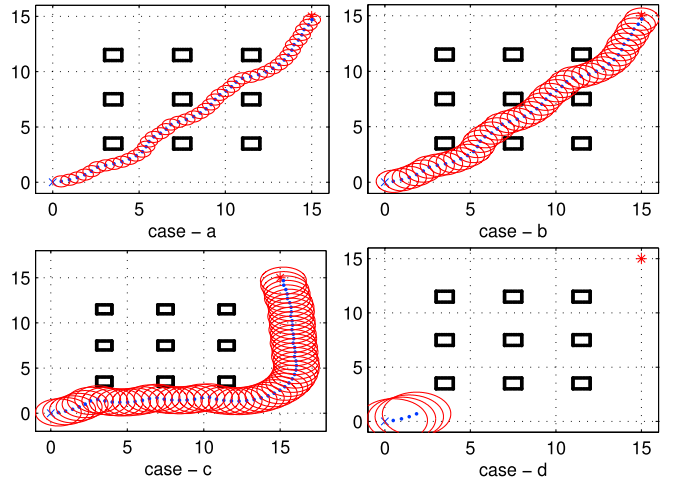


Fig. 14. Illustrative examples from the scenarios in the arena with fixed obstacles.

results indicate that the combination of a small rate for the steering angle with high velocities are sufficient proper for reaching the goal point at short distances. Overall, in these simulated test cases, there have been in total 27 failed cases out of the total 255.

As a general outcome, from the obtained sensitivity results, in order to increase the performance of the proposed on-line path planning and control scheme and allow the vehicle to reach the goal point successfully, it is better to travel at low velocities and at smaller safety distances, for avoiding the collision with obstacles, while normal (mean value) for the rate in the articulation angle are being suggested. As illustrative examples, from the presented analysis, in Fig. 14 the AV motion is being displayed under a fixed low-velocity of ($v = 0.5$ m/s), a fixed allowable change in the steering angle of ($\gamma = 12^\circ$) and in four cases with a different range of safety distance as: case-a ($d_{min} = 0.5$), case-b ($d_{min} = 1.0$), case-c ($d_{min} = 1.5$), and case-d ($d_{min} = 2.0$). From the obtained results it is obvious that in the cases-a and b the AV can reach the goal at the location [15 15] in a shortest traveling distance. In case-c, the AV reaches the goal point with a longer distance, while case-d could not reach the goal point.

In the sequel the sensitivity of the proposed scheme will be evaluated in the scenario of an open area being populated by moving and varying number of obstacles. As in the previous case, the cases of having varying β , d_{min} and v with respect to a varying

number of obstacles will be considered. In this case the vehicle again starts from an initial point of [0 0 10 7.5] and with a final goal point at [15 15], while no demand on the orientation, when reaching the goal point has been set.

For the first simulation, the case of having a varying speed and varying number of obstacles will be considered. The obtained results are being depicted in Fig. 15 with a corresponding variation of $0.5 \leq v \leq 2$ m/s and with a step change of 0.1 m/s, while the number of obstacles is between 0–400. From the simulated results it is obvious that the speed is of paramount importance, especially in the cases with a high number of obstacles. For speeds higher than 1.5 m/s the proposed algorithm cannot reach the end goal, while for lower speeds the performance of the path planning is satisfactory. In the presented results there have been in total 122 out of 400 iterations where the proposed on-line path planner did not achieve to reach the final goal. At this point it should be highlighted again that this simulations concern the on-line and closed loop (MPC) path planning, incorporating the full kinematic constraints of the AV.

In case that the safe distance is being considered with respect to the varying number of obstacles, the results are being depicted in Fig. 16. From the obtained results is obvious that smaller safety distances are creating more flexibility to the AV and prevents it from falling into local minimums, while large safety distances, in combination with an increased number of obstacles are causing the

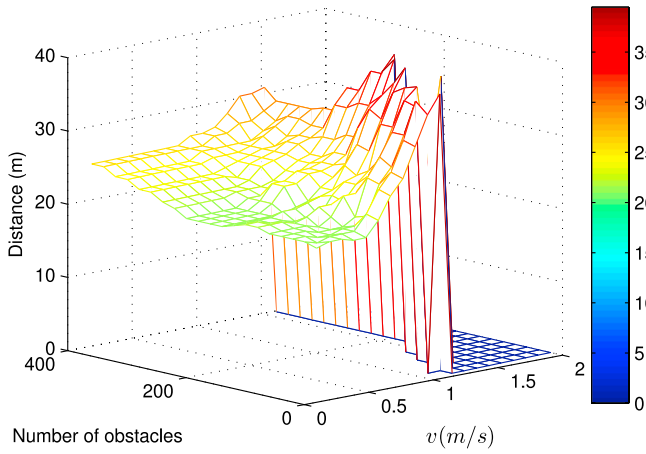


Fig. 15. Successful reaching of the final goal and overall distance traveled under varying speed and number of obstacles.

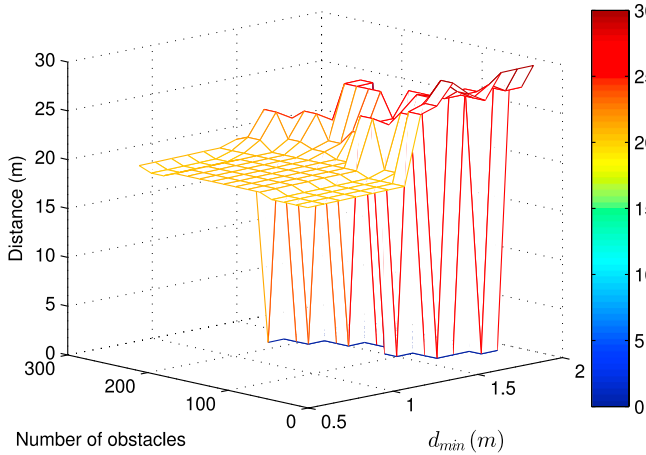


Fig. 16. Successful reaching of the final goal and overall distance traveled under varying safety distance and number of obstacles.

proposed scheme to fail. In the presented results there have been in total 56 out of 255 iterations where the proposed on-line path planner did not achieve to reach the final goal.

In the last case, the maximum allowable change in path planner's articulation angle is being considered with respect to the varying number of obstacles, while the results are being depicted in Fig. 17. From the obtained results it has been indicated that the proposed scheme operates with a very good performance, as long as the number of obstacles remain below 200 and the allowable change of the articulation is limited up to 20° . For a bigger number of obstacles, the space is populated in an extremely dense manner and thus the AV is arriving into local minimums, independently of the allowable change of the articulation angle. In the presented results there have been in total 22 out of 255 iterations where the proposed on-line path planner did not achieve to reach the final goal.

As an illustrative example from the presented analysis, in Fig. 18 the AV motion is being displayed with $v = 0.4$ m/s, $\beta = 12^\circ$ /s, and a safety distance of 1 m, in a geographically bounded area of 50×50 m and with 50, 100, 150 and 200 randomly positioned obstacles.

5. Conclusions

In this article the effect of kinematic parameters on a novel proposed on-line motion planning algorithm for an articulated

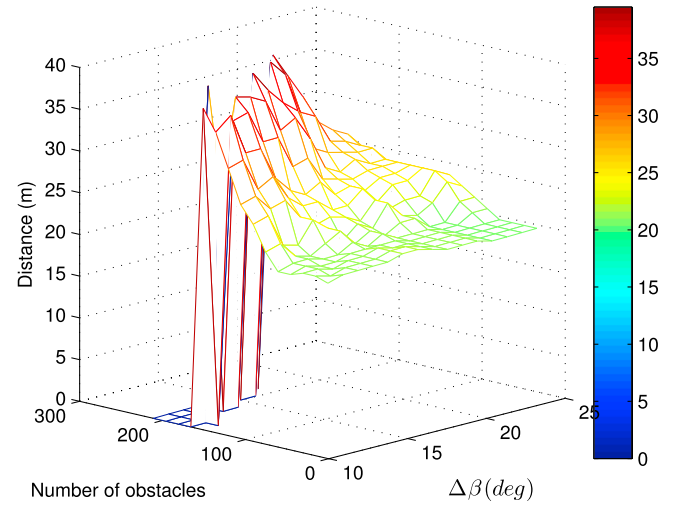


Fig. 17. Successful reaching of the final goal and overall distance traveled under varying allowable change in the path planner's suggested articulated angle and number of obstacles.

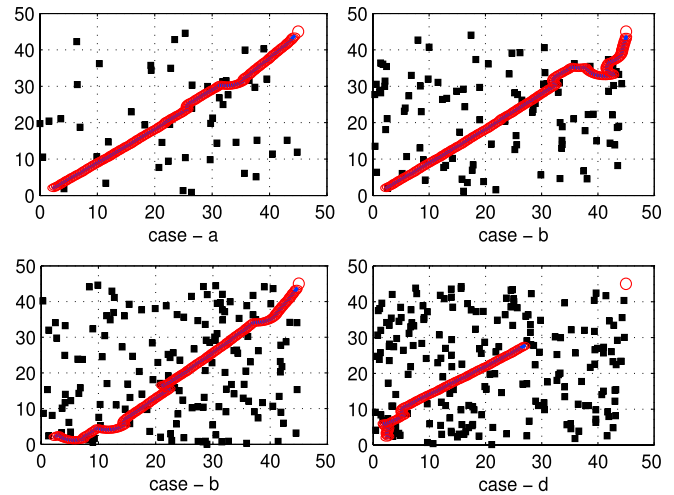


Fig. 18. Indicative On-line path planning in a geographically bounded arena of (50×50) m with the following selection of KP: $v = 0.4$ m/s, $\beta = 12^\circ$, and $d_{min} = 1$ m for the cases of: (a) 50, (b) 100, (c) 150, and (d) 200 obstacles.

vehicle based on Model Predictive Control (MPC) have been presented. The kinematic parameters that were considered have been the vehicle's velocity, the allowable change in the articulated angle from the path planner, the safety distance from the obstacles and the total number of obstacles in the operating arena. The proposed modified motion planning algorithm, for the articulated vehicle belonged to the family of Bug-Like algorithms and was able to take under consideration, the mechanical and physical constraints of the articulated vehicle, as well as its full kinematic model. The efficiency and the sensitivity of the proposed combined path planning and control scheme has been evaluated under numerous simulated test cases, while the dependencies to the selected kinematic parameters have been indicated.

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