Target Current Restriction Logic for Improvement on Steering Control of Assisted Parking System

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ABSTRACT: We have developed a new steering control system in order to reduce the driver's burden during parking manoeuvres. In this paper, first of all, the concept of this system and an outline of the steering control method are presented. Then, results of simulation and actual vehicle tests are described to verify the control logic which was applied to solve characteristic problems of the system.

KEY WORDS: (Standardized) Electronics and Control, Parking Assist System, (Free) Steering Control [E1]

1. Introduction

Parking is a manoeuvre that many drivers, whether beginners or seasoned drivers, find troublesome and difficult (1). This derives from various factors, for example, obstacles (walls, road shoulders, other vehicles, and so on) in the immediate vicinity of the vehicle, which require the driver to be able to judge the necessary steering operations to enable him/her to guide the vehicle along the target path toward the parking space while paying due attention to all nearby obstacles in order to ensure safety; in other words, the driver is required to accurately manoeuvre the vehicle based on his/her judgment. In addition, since parking is a manoeuvre that often involves backward movement, it is necessary for the driver to carry out the required movement in a rear-facing posture, where various blind spots come into play. For these reasons, the steering operations involved in moving backward during parking impose upon the driver a particularly heavy burden. Thus, there is a need for a parking assistance system that effectively reduces this burden, and that is constructed at low cost for benefits of many drivers.

Until now, a reverse parking assistance system with steering control was put on the market (2). This system was used multi external object sensors (parking stripes recognition from rear view image and parking space recognition using ultrasonic sensors).

In order to realize a simple system construction, various and continuous R&D efforts were made(3)(4). Based on the knowledge derived from the efforts, we have developed a new parking assistance system without using any external object sensors, and have launched it into the market(5).

This paper first explains the design concept of the steering operation used for this new system. Then, the system configuration is outlined and the steering angle control method applied to the system is described. In addition, in order to solve a problem characteristic to this system, i.e., a decrease in controllability arising from the back electromotive force generated in the motor used for steering control, a control method has been worked out for practical application. So, the effectiveness of this control method is also verified based on the results obtained from simulations and actual vehicle tests.

2. Outline of the System

2.1. Concept of the system

We have proposed about ideal ways of parking a vehicle in view of reducing the driver’s burden, by simplifying the parking manoeuvres based on the following concepts:
1) The vehicle should be able to park in a parking space by moving it backward in one try, without do-overs, and 2) The steering operation during the backward movement should be simple.

As shown in Fig. 1, this system is designed to bring this ideal way of parking into practice by allowing the vehicle to automatically operate the steering wheel and implement the necessary steering control over the following steering operations:

1) Steering control to move the vehicle to the appropriate start position for backward movement
2) Steering control to move the vehicle to the parking position accurately

Fig. 1 Concept of the new parking assistance system
1) Moving forward to the start position (B) that is appropriate for commencing the backward movement and guiding the vehicle into the parking space in one try, and
2) Moving backward precisely into the parking position (C), without do-overs.

Thus, this system assists the driver in executing the parking manoeuvre and reduces the driver’s burden (5).

2.2. System configuration

Figure 2 shows the basic system configuration. This system consists of the following components: an EPS motor which operates as an actuator when the system provides steering assistance, an EPS control unit (EPS-ECU) which controls the drive current in the EPS motor, a switch box with various switches which can be used by the driver to select the desired pattern out of many parking patterns and to initiate the selected type of assistance, a steering wheel angle sensor which detects the rotation status of the steering wheel, a wheel speed sensor which detects the travel distance covered by the vehicle based on the number of rotations made by the wheels, a parking assistance control unit (PA-ECU) which computes the intensity of the drive current used for controlling the rotation of the steering wheel based on the values provided by the sensors and communicates the computed values to the EPS-ECU, instructional devices (such as an indicator, buzzer and voice guidance speaker) which inform the driver of the operational status of the system as directed by the PA-ECU, and reference marks (not shown in the figures) provided at the top portion of the door linings on the left and right sides, which are used as a reference when making a stop at the start position for forward movement. In addition, the fact that the driver has operated the steering wheel is detected by the EPS steering torque sensor. Various other operations carried out by the driver are detected by the brake switch, shift sensor and throttle angle sensor. As mentioned above, the system is of a simple construction that does not use any external object sensors.

2.3. System operation procedure

Based on Figs. 3(a) to 3(c), the operation procedure of the system can be explained as an example of a parking pattern, in which left backward parking is selected and the vehicle is parked by backing up into the parking space to the left of the vehicle, as detailed below:

(a) The vehicle is advanced toward the vicinity of the parking space into which the driver is attempting to park the vehicle, and is stopped in such a way that the reference mark on the door lies on the extension line from the borderline of the parking space. This position is the start position for forward movement (A). Incidentally, the start position for forward movement was set at the borderline at the front in the direction of advance of the vehicle, as shown in Fig. 3(a), to enable the entire parking space to be positively confirmed. The driver operates the switch box while the vehicle is kept on halt, and then selects the parking pattern for left backward parking to allow the assistance program to run. Since the system controls the steering wheel, the driver only needs to keep his/her hands lightly on the steering wheel. Also, the system informs the driver of the commencement of the assistance by means of instructional devices (indicators and/or voice guidance).

(b) When the driver takes his/her foot off the brake and lets the vehicle move forward while checking the safety inside the parking space, along the passageway and in the vicinity of the vehicle, the steering wheel is controlled according to the distance covered by the vehicle in forward movement. First, the steering wheel is turned to the right, and as the vehicle continues to advance further, it is turned to the left. When the vehicle has advanced and reached the start position for backward movement (B), the steering wheel has turned to the steering wheel angle, which constitutes the reference angle for initiating backing up. Since the instructional device informs the driver that the vehicle has reached the start position for backward movement, the driver stops the vehicle there. In case the driver cannot stop the vehicle in time and the position at which the vehicle has stopped is beyond the start position for backward movement, the system keeps controlling the steering wheel so that the is kept constant, and the system memorizes the distance by which the vehicle has exceeded the start position.

(c) When the vehicle has stopped, the driver shifts into reverse to commence backward movement. The system assists the vehicle and allows it to roll backward from the spot at which it actually stopped just for the memorized distance. Thus, the vehicle reaches the designed start position for backward movement precisely.

Fig. 3 Parking procedure using the assistance system
meanwhile, the $\theta_b$ is kept constant. From this position, the vehicle can be backed up into the parking space in a single operation. Thus, the vehicle is provided with the conditions equivalent to the designed conditions under which it can be backed up from the originally designated start position for backward movement. When the vehicle has passed the start position for backward movement, the steering wheel is controlled according to the distance the vehicle has rolled backward as measured from the start position for backward movement. First, the steering wheel rotates leftward up to the maximum angle, turning the vehicle toward the parking space. When the vehicle has rolled backward further and turned to position itself parallel to the sides of the parking space, the steering wheel turns rightward to acquire a straight-ahead position. When the vehicle has backed up completely into the parking space, the driver is informed via the instructional devices that the vehicle has reached the parking position (C). The driver parks the vehicle at the intended position. Thus, the entire parking manoeuvre is completed.

2.4. Outline of the steering control

As shown in Fig. 4, this system controls the steering wheel angle based on a data map pre-memorized in the PA-ECU. One data map is provided for each of the possible parking patterns (for example, left backward parking, right backward parking, parallel parking, and so on), so the driver can select the parking pattern he/she needs. When the driver turns on the switch box to operate the system, the data map that corresponds to the parking pattern selected by the driver is read out. The data map is composed using the target steering wheel angle, $\theta_s$, according to the distance of the vehicle’s movement, $L$, and consists of a pair of sub-maps: one is used for the forward movement path, while the other is used for the backward movement path. In the sub-map for the forward movement path, a $\theta_f$ dataset is set according to the distance of the vehicle’s forward movement, $L$, whereas, in the sub-map for the backward movement path, another $\theta_b$ dataset is set according to the distance of the vehicle’s backward movement, $L$. When the driver advances the vehicle, $L$ is detected by the wheel speed sensor, and the $\theta_s$ value, which shows how much the steering wheel must be turned at each of the path points corresponding to a specific value of $L$, is read out sequentially from the data map. In order for the actual steering wheel angle, $\theta_m$, detected by the steering angle sensor, to catch up to the $\theta_s$, the steering angle controller computes a specific target current $I_{TE}$, which is used for the steering angle control, and then passes on the computed result to the EPS-ECU. In the EPS-ECU, when the system has been put into operation, its control mode is switched over from the EPS control mode operated based on the EPS target current, $I_{TE}$, to the steering control mode operated based on the $I_{TP}$, and the electric voltage, $V_M$, to be applied to the EPS motor to exert the $I_{TP}$ is computed by the current controller. The steering wheel angle is controlled by applying this voltage to the EPS motor to exert the drive current, $I_{M}$, in such a manner that the exerted current catches up to the $I_{TP}$. When the vehicle has reached to the start position for backward movement and the operation of shifting into reverse has been detected, the system switches to the data map for the backward movement path, and the steering angle control is implemented during the vehicle’s backward movement into the parking position, in the same manner as when the vehicle was controlled for the forward movement path. When the vehicle has moved to the parking position, the PA-ECU completes the steering control, and, in the EPS-ECU, the target current is switched over to the $I_{TE}$ and the EPS control is implemented. However, in order to prioritize the driver’s direct operation of the steering wheel even during steering control by PA-ECU, whenever the steering torque, $T_s$, has exceeded a pre-determined threshold value, the steering control is discontinued and the control mode is brought back to EPS control.

3. Restriction Control of the Target Current

In this system, in order to reduce the vehicle’s movement distance and make space-saving, effective parking possible, it is necessary for the vehicle to make as small a turn as possible. To make this happen, the steering wheel must be controlled to attain a high rotation speed, so that the maximum steering angle can be obtained as quickly as possible and the vehicle can be turned with the minimum turning radius at an early stage. In doing so, even if the target current, $I_{TP}$, has been increased in an attempt to enhance the rotation speed, due to the effects of the back electromotive force occurring in the EPS motor used for the steering control, the actual drive current, $I_{M}$, sometimes remains restricted and cannot catch up to the $I_{TP}$. In a case like this, if the state in which the $I_{M}$
cannot catch up to the \( I_{TP} \) continues for a while and the difference between those two values increases, the \( I_M \) is discontinued at the moment when it catches up to the \( I_{TP} \). This situation causes the rotation speed of the EPS motor to change suddenly. This sudden change is transmitted to the steering system, causing a twist torque \( T_T \), to arise due to the inertia moment of the steering wheel, and then the steering torque sensor detects this \( T_T \). As mentioned above, when the driver intervenes by directly operating the steering wheel, we designed the steering control to cease whenever the steering torque detected by the steering torque sensor has increased beyond the predetermined threshold value. Accordingly, when the \( T_T \) has increased beyond the aforementioned threshold value, even if the driver is not operating the steering wheel directly, steering control is discontinued. Thus, in order for the steering wheel to maintain a controlled high rotation speed and allow the vehicle to make a tight turn, it was necessary to solve this particular problem. In this chapter, as a solution to the aforementioned problem, we will outline a target current restriction control which we have newly invented and applied, as well as the effects thereof.

3.1. Outline of the restriction control

The situation in which the drive current, \( I_M \), does not catch up to the target current, \( I_{TP} \), and the difference between these two currents increases has been found to be the factor generating a twist torque \( T_T \) in the steering system due to the inertia moment of the steering wheel. Accordingly, we introduced a target current restriction control which we have newly invented and applied, as well as the effects thereof.

3.1.1. Steering angle controller

Basically, the steering angle controller is provided with a digital 1PD control (proportional and derivative toward PID control) and a velocity algorithm \(^{(5)}\), as shown in Fig. 5. The \( I_{TP} \) values are computed using the following equations:

\[
p(z) = \left( z^{-1} - 1 \right) \theta_p(z) \\
d(z) = (1 - z^{-1}) p(z) \\
\theta(z) = \theta_p(z) - \theta_g(z) \\
I_{TP}(z) = DI_{TP}(z) + z^{-1} \cdot I_{TP}(z) \\
I_{TP}(z) = K_p \cdot p(z) + K_d \cdot d(z) + K_i \cdot \theta(z) \\
DI_{TP}(z) = DI_{TP}(-1) + K_p \cdot \{2z^{-1} - 1 - z^{-2}\} \cdot \theta_g(z) + K_d \cdot \{\theta(z) - \theta_g(z)\} + z^{-1} \cdot I_{TP}(z) \\
DI_{TP}(z) = \{K_p \cdot \theta_g(z) + K_d \cdot \{2z^{-1} - 1 - z^{-2}\} \cdot \theta_g(z) + K_d \cdot \{\theta(z) - \theta_g(z)\} + z^{-1} \cdot I_{TP}(z)\}
\]

where, in order to prevent the EPS motor from getting damaged, the \( I_{TP} \) is given a saturation level (with the limit values at \( \pm I_{TP}\text{max} \)). \( K_p, K_d \) and \( K_i \) stand for proportional, derivative and integral gain, respectively.

3.1.2. Target current restriction logic

As shown in Fig. 6, when the absolute value of the difference, \( E \), between \( \text{DI}_{TP}(z) \) and \( I_M(z) \) exceeds the threshold value, \( EO \), the \( I_M \) is judged not to be catching up to the \( I_{TP} \). Then, the sign of \( \text{DI}_{TP}(z) \), i.e., the latest value of the change in \( I_{TP} \) computed, is compared with the sign of \( E \). When these two have the same sign, the direction of \( \text{DI}_{TP}(z) \) is suggested to be toward an increase in \( E \). Accordingly, the increasing of \( E \) is restricted by switching the \( \text{DI}_{TP}(z) \) value, i.e., the actual change in \( I_{TP} \), to zero (ON) and holding the \( I_{TP} \) at its previous value, \( I_{TP}(z) \). However, when they have different signs, the direction of change is toward a decrease in \( E \). When \( E \) is equal to or smaller than \( EO \), the \( I_M \) is catching up to the \( I_{TP} \), therefore, by switching the value of \( \text{DI}_{TP}(z) \) to \( \text{DI}_{TP}(z) \) (OFF), a basic steering angle control is implemented.

3.2. Verification of the effects

Regarding the effects of the aforementioned restriction control, we created a model for the system, made a prediction by means of simulations, and verified the prediction results by conducting an actual running test with a system-equipped vehicle.

3.2.1. Prediction of the effects by means of simulations

A steering system model for simulations is shown in Fig. 7. The relevant motion equations are as follow:

\[
J_m \cdot \frac{d^2 \theta_m}{dt^2} + K_{sm} \cdot (\theta_m - \theta_e) = 0 \\
(n_u \cdot J_m + \frac{1}{n_G} \cdot J_w) \cdot \frac{d^2 \theta_w}{dt^2} + (n_u \cdot C_m + \frac{1}{n_G} \cdot C_w) \cdot \frac{d \theta_w}{dt} + K_{sw} \cdot (\theta_m - \theta_e) = T_r \\
\theta_r = \frac{1}{n_u} \cdot \theta_m, \quad T_r = n_u \cdot T_m - \frac{1}{n_G} \cdot T_w
\]

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The front wheel angle means of the following equations:

\[ J_W \cdot \text{moment of inertia (Steering wheel)} \]

\[ J_M \cdot \text{moment of inertia (Motor)} \]

\[ J_F \cdot \text{moment of inertia (Front wheels)} \]

\[ C_M \cdot \text{damping coefficient (Motor & G-box)} \]

\[ C_W \cdot \text{damping coefficient (Front wheels)} \]

\[ K_{TS} \cdot \text{torsoal rigidity (Torque sensor)} \]

\[ n_G \cdot \text{steering gear ratio} \]

\[ n_M \cdot \text{EPS reduction gear ratio} \]

\[ \theta_i \cdot \text{pinion angle} \]

\[ \theta_M \cdot \text{pinion torque} \]

\[ T_M \cdot \text{motor torque} \]

\[ T_W \cdot \text{self-aligning torque} \]

\[ T_S \cdot \text{sensing torque (steering torque)} \]

**Fig. 7 Steering model**

**Fig. 8 EPS motor model**

**Fig. 9 Self-aligning torque model**

The parameter values used in the simulation are shown in Table 1. The self-aligning torque \( T_S \) are assumed as functions of the front wheel angle \( \theta_F \) shown in Fig. 9. The current controller is modeled as PI controller \( (K_{FC} \text{ and } K_{IC} \text{ stand for proportional and integral gain, respectively}) \).

The simulation results are shown in Figs. 10 and 11. Figure 10 shows the results obtained without restriction control, while Fig. 11 shows those with it. For each of the two rotation speeds, \( \frac{d\theta}{dt} \) (namely, 400 and 700 deg/s), when the target steering wheel angle, \( \theta_T \), varies from one constant value to another, the results shown in the figures are obtained for the output steering wheel angle, \( \theta_S \), the target current, \( I_{Tr} \), the drive current, \( I_{Sa} \), and the torque, \( T_S \), detected by the steering torque sensor. As shown in Fig. 10, in the case of 400 deg/s, since the \( I_{Sa} \) is catching up to the \( I_{Tr} \), the changes in \( I_{Sa} \) are gradual, and the twist torque, \( T_T \), which occurs due to the inertia of the moment of the steering wheel, is small.

**Table 1 Parameter values used in the simulation**

<table>
<thead>
<tr>
<th>Controller (Sample time 10ms)</th>
<th>Steering</th>
<th>Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_T ) 0.36 [A/deg]</td>
<td>( J_W ) 0.04 [kgm²]</td>
<td>( R_M ) 0.12 [Ω]</td>
</tr>
<tr>
<td>( K_D ) 0.025 [A/deg]</td>
<td>( J_M ) 1.9x10^4 [kgm²]</td>
<td>( k_T ) 0.052 [Nm/A]</td>
</tr>
<tr>
<td>( K_I ) 0.025 [A/deg]</td>
<td>( J_F ) 1.3 [kgm²]</td>
<td>( V_J ) 12 [V]</td>
</tr>
<tr>
<td>( I_{tor} ) 30 [A]</td>
<td>( C_M ) 3.8x10^4 [Nm/rad]</td>
<td></td>
</tr>
<tr>
<td>( E_O ) 1.5 [A]</td>
<td>( K_T ) 100 [Nm/rad]</td>
<td></td>
</tr>
<tr>
<td>( K_{FC} ) 0.36 [V/A]</td>
<td>( n_G ) 16 [-]</td>
<td></td>
</tr>
<tr>
<td>( K_{IC} ) 0.051 [V/A]</td>
<td>( n_M ) 18.5 [-]</td>
<td></td>
</tr>
</tbody>
</table>

Also, a circuit equivalent to the EPS motor is shown in Fig. 8. The drive current, \( I_{Sa} \), and the motor drive torque, \( T_M \), are obtained by means of the following equations:

\[ V_M = I_{M} \cdot \frac{dI_{M}}{dt} + R_M \cdot I_{M} + E_M \equiv R_M \cdot I_{M} + k_E \cdot \frac{d\theta_M}{dt} \]  \hspace{1cm} (12)

\[ I_{M} = \frac{1}{R_M} \left( V_M - k_E \cdot \frac{d\theta_M}{dt} \right) \]  \hspace{1cm} (13)

\[ T_M = k_E \cdot I_{M} \]  \hspace{1cm} (14)

where the battery voltage \( V_B \) governs the upper limit of \( V_M \). As can be seen in Eq. (13), when the rotation speed of the motor, \( \frac{d\theta}{dt} \), is increased in order to control the rotation speed of the steering wheel at a higher level, the \( I_{M} \) is restricted as a function of the increase.

Parameter values used in the simulations are expressed in Table 1. The self-aligning torque \( T_S \) are assumed as functions of the front wheel angle \( \theta_F \) shown in Fig. 9. The current controller is modeled as PI controller \( (K_{FC} \text{ and } K_{IC} \text{ stand for proportional and integral gain, respectively}) \).

The simulation results are shown in Figs. 10 and 11. Figure 10 shows the results obtained without restriction control, while Fig. 11 shows those with it. For each of the two rotation speeds, \( \frac{d\theta}{dt} \) (namely, 400 and 700 deg/s), when the target steering wheel angle, \( \theta_T \), varies from one constant value to another, the results shown in the figures are obtained for the output steering wheel angle, \( \theta_S \), the target current, \( I_{Tr} \), the drive current, \( I_{Sa} \), and the torque, \( T_S \), detected by the steering torque sensor. As shown in Fig. 10, in the case of 400 deg/s, since the \( I_{Sa} \) is catching up to the \( I_{Tr} \), the changes in \( I_{Sa} \) are gradual, and the twist torque, \( T_T \), which occurs due to the inertia of the moment of the steering wheel, is small.

**Fig. 11 Results of the simulation with control**

**Fig. 12 Results of the simulation without control**
However, in the case of 700 deg/s, due to the effects of the back electromotive force, the $I_T$ does not catch up to the $I_{TP}$ and the difference between them increases; thus, the $I_{TP}$ becomes saturated at the limit value, $I_{TP-max}$. Although the $I_{TP}$ decreases from the $I_{TP-max}$ when the $\theta_1$ has become constant and the difference between the $\theta_1$ and the $\theta_H$ has become smaller, the difference between the $I_{TP}$ and $I_M$ is still large, and the behaviors of these two values are different from each other; therefore, when the $I_M$ has started again to catch up to the $I_{TP}$, the $I_M$ changes suddenly in a discontinuous manner. Thus, the value $T_r$, which exceeds the threshold value for the torque, $T_{STth}$, at which the system is brought to a halt, is detected. In addition, since the $I_M$ is not catching up to the $I_{TP}$, the controllability of the $\theta_H$ decreases, apparently resulting in the occurrence of overshooting. However, as shown in Fig. 11, when restriction control is applied, even at 700 deg/s, behavior of the $I_{TP}$ is kept close to that of the $I_M$, and the difference between the $I_{TP}$ and the $I_M$ does not increase. So, those changes occurring in the $I_M$ when it has started to catch up to the $I_{TP}$ again become milder, and the generated twist torque, $T_r$, can be decreased to a value smaller than the $T_{STth}$. Also, apparently, the overshooting of the $\theta_H$, which occurred when no restriction control was applied, can be prevented from occurring.

3.2.2. Confirmation of the effects by means of vehicle tests

Since the effects of the restriction control were successfully predicted through simulations, as mentioned above, we next confirmed the actual effects through an actual running test using a system-equipped vehicle.

The test was conducted by applying the target steering wheel angle, $\theta_T$, the same parameter used for the simulation. The results are shown in Figs. 12 and 13. Figure 12 shows the test results without restriction control, while Fig. 13 shows the test results with it. As in the results obtained by the simulation prediction, it can be observed that, due to the application of the restriction control, the $T_r$ decreases to a value below the $T_{STth}$, and that the overshooting of the $\theta_H$ can be prevented.

Figure 14 shows the measurement results obtained for $T_r$, which occurred at each rotation speed, $d\theta_H/dt$, of the target steering wheel angle. The results obtained from the simulation are also shown.

It can be seen that, due to the effects of the restriction control, even if $d\theta_H/dt$ is increased, the $T_S$ still remains below the $T_{STh}$ and the steering control remains available without interruption.

4. Conclusion

Based on the ideal way of parking, we developed a parking assistance system which helps reduce the driver’s burden.

Although this system relies on a simple setup, which controls the steering wheel based on a data map stored in the memory of the ECU without using any external object sensors, it automatically implements steering control over the following steering operations:

1) Advancing the vehicle to the start position for backward movement that is suited for moving the vehicle into the parking space in one try, and
2) Precisely backing up the vehicle into the parking position.
without do-overs, thus achieving an ideal method of parking and putting it into practice.

Regarding the twist torque arising in the steering system due to the inertia moment of the steering wheel, which is an obstacle in controlling the rotation speed of the steering wheel at a higher level to allow the vehicle to turn with a small turning radius, we adopted the approach of applying a target current restriction control as a solution. According to the results obtained from the simulation using the modelled system as well as from actual running tests using a vehicle equipped with the system, we were able to maintain the generated twist torque at a lower level thanks to the effects of the restriction control, even when boosting the rotation speed of the steering wheel. Thus, we verified that the steering control can be prevented from interruption which occurs though the driver doesn’t operate the steering wheel.

References