

PATH TRACKING OF AN AUTONOMOUS LHD ARTICULATED VEHICLE

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Abstract: This paper presents the path tracking and following for the Autonomous LHD (Load-Haul-Dump) articulated vehicle. A fuzzy logic control system for the articulated vehicle was developed to control longitudinal and lateral motion. The lateral control keeps the vehicle along the planned path and the longitudinal control makes the vehicle running at the required speed. Fuzzy logic control method is compared with classical methods to evaluate its performance and several simulation experiments were performed to develop the path following control system with 3-D motion animation. Different type of paths were tested and analyzed. *Copyright@2005 IFAC*

Keywords: Autonomous System, Intelligent Control, Articulated Vehicles, Path Tracking, and Fuzzy Logic Controller.

1. INTRODUCTION

Investigations on the motion analysis of wheeled vehicles presented in this paper have been mainly focused on stability and controller performance. Automatic navigation for autonomous operation of these vehicles has become the focus of several research works. The emphasis is on autonomy and replacement of human driver or telerobotic operator. This problem has been addressed first for the development of Automatic Guided Vehicles (AGV) in the automotive industry and later for the position control of wheeled mobile robots. The purpose of this paper is to develop an advanced, fuzzy logic based controller that would take into account complex nature of an articulated robot vehicle. The experimental results were performed on the articulated robot vehicle developed at Carleton University. This paper presents only simulation experiments performed to develop an advanced fuzzy logic controller (FLC).

The articulated vehicle is composed of two bodies

connected by a kingpin hitch. Each body has a single axle and the wheels are all non-steerable. Path following control of articulated vehicles is more challenging than controlling car-type robots due to the more complicated kinematics and dynamic design. The steering action is performed on the joint, changing the angle between the front and rear part using hydraulic actuators. The vehicle can steer in place i.e. the orientation of the vehicle changes varying the steering angle alone and the width spanned by the vehicle when turning is smaller than the car-like vehicle. The articulated vehicle is an underactuated drift-free nonlinear system with two inputs (propulsion and steering torques), which are controllable (Laumond, 1993).

In the articulated vehicle case, the error between the current and desired trajectories can be easily calculated in some situations. The main problem for the autonomous navigation of the articulated vehicle is to be able to follow the path while keeping a safe distance from the edges of the path. The problem of

the vehicle navigation can be modeled as a path to follow and the proper criterion can be formulated for reducing the tracking error of the vehicle. Given the measurements of the position and the orientation differences between the required and the actual values, a controller is expected to set the steering angle to the appropriate magnitude to bring the vehicle to its desired path. The rate of change of the heading for the front part of the robot is proportional to the steering angle, the speed of the machine, and the change rate of the steering angle.

There are several methods to choose the navigation reference point of the articulated vehicle (Sasiadek and Green, 1996; DeSantis, 1994, 1997; Altafini and Gutman, 1998; Altafini, 1999; Polotski, 2000; Hemami and Polotski, 1996; Petrov and Bigras, 2001; Sampei, *et al.*, 1995; Zhang, *et al.*, 1997).

DeSantis (1994, 1997) presented a path following controller. An articulated robot was modeled by taking into account not only its basic kinematics, but also dynamics. The dynamics equations take into account the inertial properties of the mass of the robot. Using this model, the error terms are presented as lateral, heading, and steering angle errors, which are multiplied by proper gains and added to the nominal turning rate to get the corrected turning rate for the robot. The navigation reference point is selected to be in the middle of the front axle of the vehicles. Analytically derived rules on how to determine the gains so that the controller becomes stable were shown in (DeSantis, 1997). The proposed controller includes a velocity controller.

The articulated vehicle model used in this paper is based on results obtained in (DeSantis, 1994, 1997). The performance of the controller is verified by simulation experiments with straight, circular, and mixed paths where the position and heading errors have been small. The controller would also perform well when the errors are large or the shape of the reference path is more complicated. The results with the two different controllers are shown in Fig.4 to Fig.12.

2. THE ARTICULATED VEHICLE MODELS

The desired articulated kinematic model was presented in (DeSantis, 1994)

$$\begin{aligned} \dot{x} &= \cos q v \\ \dot{y} &= \sin q v \\ \dot{f} &= -\frac{\sin f v}{l} - (1 + \cos f) w \\ \dot{q} &= w \end{aligned} \quad (1)$$

where $[x, y]$ is the coordinate frame located in the middle point of the front axle, v is the longitudinal velocity, w is the angular velocity, q is the orientation of the front body, and f is the angle between the front and rear bodies. Under the

slippage-free assumption and rear-wheels driving condition, the dynamics model may be rewritten as:

$$N \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{q} \end{bmatrix} = F + H [f_p \ f_s]^T \quad (2)$$

where $[f_p, f_s]$ is the propulsion, steering forces acted on the vehicle, and N, F, H are matrices with the system's parameters.

The model uses the current position $[x, y, q, f]$ as the initial condition and integrates it to determine the vehicle's new position after the inputs are changed for next time step.

3. PID CONTROLLER

The input to this PID path-following controller requires the knowledge of the longitudinal and angular velocities $[v \ w]$, and followed by a force block to select the propulsion and steering torques f_p and f_s . The path following task of the vehicle may be ensured by applying the propulsion and steering controls as: (DeSantis, 1997)

$$\begin{bmatrix} f_p \\ f_s \end{bmatrix} = -H^{-1} \left(F - N \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \right) \quad (3)$$

where $[f_p \ f_s]$ is the propulsion and steering torques acted on the driving wheels and the articulated joint. The vector $[u_1 \ u_2]$ is pseudoacceleration. It may be set as:

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = -K \begin{bmatrix} v - v_d \\ w - w_d \end{bmatrix} \quad (4)$$

with $K = [K_1 \ K_2]$ is the force component gain vector and $[v_d \ w_d]$ is the reference velocity vector.

Considering the characteristics of the articulated vehicle, velocities are set as: (DeSantis, 1997)

$$\begin{aligned} v &= v_d \\ w &= w_d - K_s [q_{os} \ f_{os} \ l_{os}]^T \end{aligned} \quad (5)$$

where $K_s = [K_{s1} \ K_{s2} \ K_{s3}]$ is the velocity component gain vector. q_{os}, f_{os}, l_{os} are the direction offset and lateral offset.

Under the assumption that q_{os}, l_{os} , and v_{os} / v_d are very small, the derivatives of the path tracking offsets can be written in form:

$$\begin{aligned} \dot{q}_{os} &= w - w_d \\ \dot{f}_{os} &= \dot{f} - \dot{f}_d \\ \dot{l}_{os} &= v_d q_{os} \end{aligned} \quad (6)$$

According to the Tikhonov's theorem on singular perturbed systems, if selected dynamic gain K is

sufficiently large, it can be set as:

$$v = v_d$$

$$w = w_d - K_s [q_{os} \ f_{os} \ l_{os}]^T$$

Then, it follows:

$$\dot{q}_{os} = -\frac{\sin f_d v_d}{l} - (1 + \cos f_d)(w_d - K_s [q_{os} \ f_{os} \ l_{os}]^T)$$

$$+ \frac{\sin f_d v_d}{l} + (1 + \cos f_d) w_d$$

$$\dot{f}_{os} = -K_s [q_{os} \ f_{os} \ l_{os}]^T$$

We can regroup the above equations as:

$$[q_{os} \ \dot{q}_{os} \ f_{os}]^T = [A - BK_s] [q_{os} \ f_{os} \ l_{os}]^T \quad (7)$$

$$\text{where } A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -\frac{v_d \cos f_d}{l} + w_d \sin f_d & 0 \\ v_d & 0 & 0 \end{bmatrix}$$

$$B = [1 \quad -(1 + \cos f_d) \quad 0]$$

The kinematic gain vector $K_s = [K_{s1}, K_{s2}, K_{s3}]$ can be computed using Lyapunov's indirect method so as to stabilize the matrix $A - BK_s$. Following the space state classical controller design procedure, K_s is assigned the eigenvalues of $A - BK_s$ located in the left-half complex plane.

For the selection of the dynamic gain vector K , by the Tikhonov's theorem, it's assigned as

$$K \gg \max(|p_1|, |p_2|, |p_3|) \quad (8)$$

where p_1, p_2, p_3 are the eigenvalues of the matrix $A - BK_s$.

The PID controller transfer function is given by:

$$D(s) = K_P \left(1 + \frac{1}{K_I s} + K_D s\right) \quad (9)$$

4. FUZZY CONTROLLER

The fuzzy logic rule base can be constructed in a symmetric fashion with rules such as:

1. IF e is NB Then u is PB
2. IF e is NM Then u is PM
3. IF e is NS Then u is PS
4. IF e is ZE Then u is ZE
5. IF e is PS Then u is NS
6. IF e is PM Then u is NM
7. IF e is PB Then u is NB

where NB, NM, NS, ZE, PS, PM, and PB are linguistic values representing "negative big", "negative medium", and so on.

According to the initial conditions and the dynamic gains given in the previous section, the widths of the premises and consequents of the rules for K_1 and K_2 are set as:

$$K_1 : [-12.5, 12.5] \Leftrightarrow [2, 8]$$

$$K_2 : [-8, 8] \Leftrightarrow [-80, 80]$$

The structure of the control system includes the conventional proportional control and the adaptive fuzzy logic control units. The output from the control units is converted to steering and propulsion torques.

5. SIMULATION EXPERIMENT

Figure 1 is the flowchart of the control system. First, the initialization involves creating the vehicle and path for animation and placing the vehicle on the path. Next, the vehicle's position on the path is determined and the values needed by the controller are calculated. With these values known, the controller then calculates the necessary propulsion and steering inputs to make the vehicle follow the path. These inputs are used in the dynamic model to update the vehicle's position and the animation is then updated to show the vehicle's new location. These steps are repeated until the end of the simulation is reached.

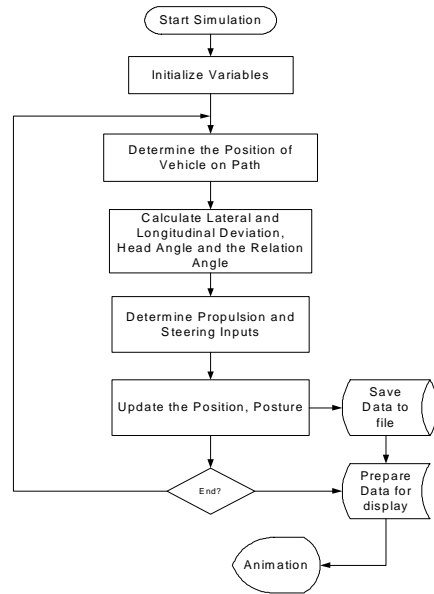


Fig. 1. Flowcharts for the MATLAB Simulink Program

The simulation experiment has been performed with six different paths, a straight line, a circle path, a mixed path that contains two straight segment, followed by a part of circle, a path with two sectors (similar to digit 8), and two other path with sudden tuning corners. The paths are defined in the $[x, y]$

global coordinates. The length and radius can be defined by the signal builder in Simulink. The mixed paths can be defined using a signal generation toolbox. All the paths initial parameters are put in the simulation initial m-files. With the vehicle following the path, the controller must know where the car is located and how it is oriented (Initial conditions). In practice, there are sensors on the front and rear of the vehicle that detect the current position and compare it with the desired position. In the simulation, the error estimation model finds the distance between the path and the vehicle. Subsequently, this value is sent to the controller as a reference input.

The inputs to the controller are the heading angle, or, the angle between the car and the path. The desired value can be calculated using the path parameters and constraints. The actual value can be calculated using the vehicle's velocity block and constraints. The next step in the program is to determine the steering and propulsion inputs to move the vehicle along the path. The controller must know the values for the linear and angular velocities errors. The movement is animated to provide a means of viewing the vehicle's motion. The first step of animation is to create the 3-D model. The vehicle's body position is defined using the patch command in MATLAB. It can be located and oriented anywhere on its path.

In the experiment, the vehicle's initial position is set at $[x_0 \ y_0]^T = [-4 \ 3]^T$ and the initial heading angle $q_0 = p/4$, and the initial angle between the two parts of the vehicle $f_0 = 0$.

The vehicle's geometry parameters are defined as:

$$l_1 = l_2 = 4 \text{ m}; a = 2 \text{ m} \quad b = 2 \text{ m}$$

$$m_1 = m_2 = 1000 \text{ kg}; j_1 = j_2 = 200 \text{ kg} \cdot \text{m}^2$$

In the case of a line maneuver, we set the linear velocity $v = 2.5 \text{ m/s}$. For the circle tracking, the vehicle has the same linear velocity and the radius is defined as $R = 40 \text{ m}$. Subsequently, the angular velocity is $w_d = 0.0625 \text{ rad/s}$. Also it is easy to get from the geometry that the angle between vehicle's two components $f_d = -0.2 \text{ rad}$ while the vehicle move on the circle trajectory. With the conditions and parameters listed above, the matrix A and B in Equation 7 can be calculated as:

$$\begin{aligned} & \text{(for circle following)} & & \text{(for line following)} \\ A &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & -0.6247 & 0 \\ 2.5 & 0 & 0 \end{bmatrix} & \text{or} & A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -0.6253 & 0 \\ 2.5 & 0 & 0 \end{bmatrix} \\ B &= [1 \ -1.98 \ 0]^T & & B = [1 \ -2.13 \ 0]^T \end{aligned}$$

Using the least-squares methods, for the kinematic part of the controller, the real parts of the eigenvalues of the matrix $A - BK_s$ are negative. It obtains:

$$K_s = [2.8 \ -0.13 \ 1] \quad (\text{for circle following})$$

$$K_s = [2.9 \ -0.17 \ 1] \quad (\text{for line following})$$

The matrix $A - BK_s$ becomes:

$$\begin{bmatrix} -0.28 & 0.13 & -1 \\ 5.544 & -0.8821 & 1.98 \\ 2.5 & 0 & 0 \end{bmatrix} \text{ or } \begin{bmatrix} -2.9 & 0.17 & -1 \\ 6.177 & -0.9874 & 2.13 \\ 2.5 & 0 & 0 \end{bmatrix}$$

(for circle following) (for line following)

K is set as $K = [5 \ 10]^T$. Figures 2 to 5 are the results from the straight line following case simulation. Both PID and Fuzzy Logic controllers perform initially the task satisfactorily. From Fig.2 and Fig.3,

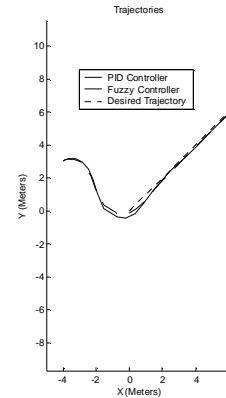


Fig. 2. Enlarged Drawing (Line Following)

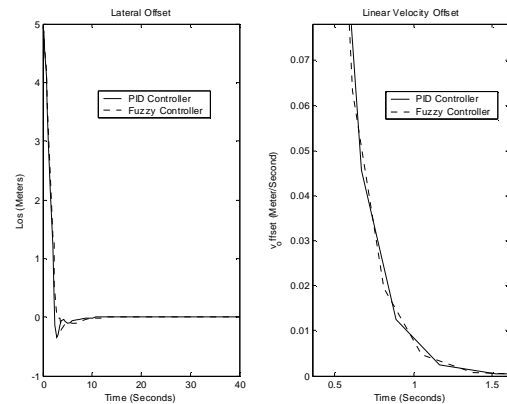


Fig. 3. Lateral and Linear Velocity Offset (Line Following)

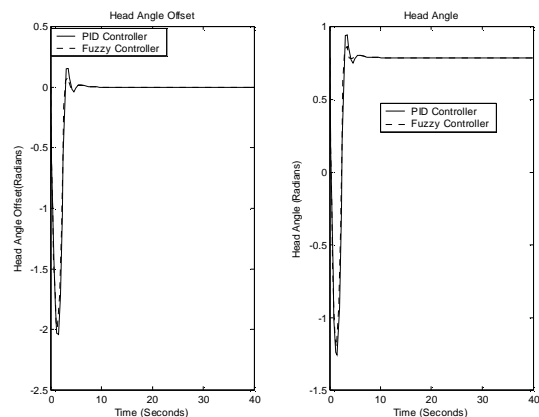


Fig. 4. Head Angle & Head Angle Offset (Line Following)

the Fuzzy Logic controller has a smaller lateral error than this with PID. According to the Figure 4 and Figure 5, the orientation errors of the vehicle's two bodies with the FLC are also smaller than this with PID and converge to zero more quickly.

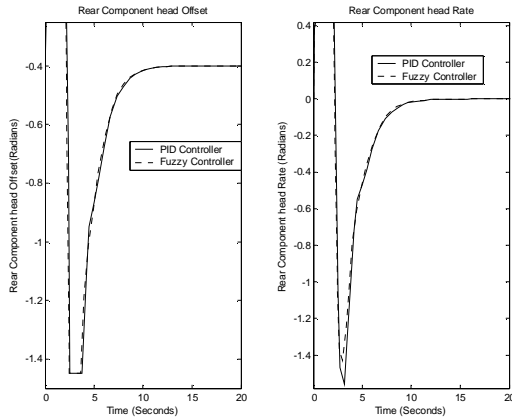


Fig. 5. Rear Component Head Angle and Offset (Line Following)

Figures 9 to 12 present results for an elliptical path following task. Similarly, the FLC controller yields more quickly converging and smaller errors than those with PID. For the rear body's orientation, both controllers give similar results. It can be noticed that the trajectory with the FLC controller is smoother than the one with the PID controller.

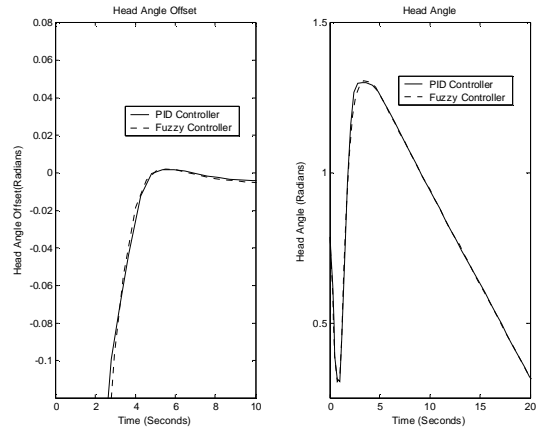


Fig. 8. Head Angle and Its Offset (Circle Following)

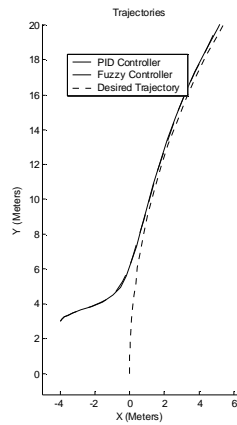


Fig. 6. Circle Following Performance (Enlarged Drawing)

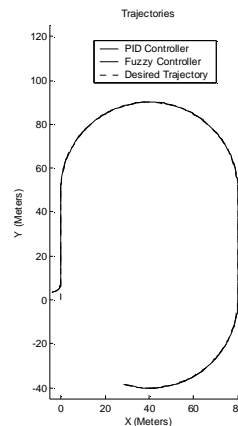


Fig. 9. Oval path Following Performance

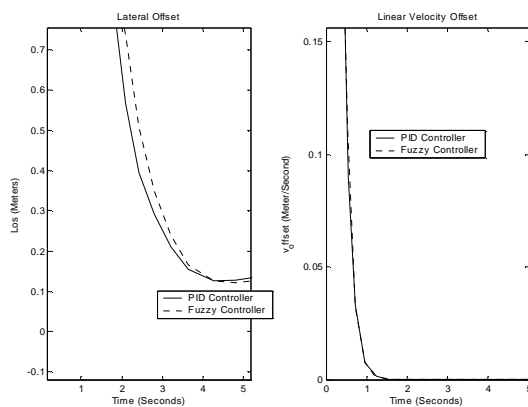


Fig.7. Lateral and Linear Velocity Offset (Circle Following)

Figures 6 to 8 are the simulation results from circle following task. For this path, the performances of the PID and FLC are similar. The errors for both controllers are small and eliminated quickly. The rear body's orientation error from FLC is smaller and the error curve is smoother than PID's error.

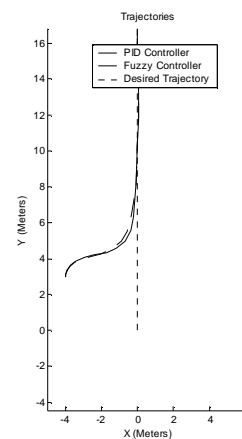


Fig. 10. Oval path Following Performance (Enlarged Drawing)

6. CONCLUSION

In this paper, the articulated vehicle is studied on dynamic level. The problems about the relations between the torques exerted on the vehicle and the accelerations, velocities, positions, and orientation angles are presented and solution suggested. Based on the cascade structure, a controller is designed to allow the articulated vehicle to follow the assigned paths adequately with a given velocity. The structure

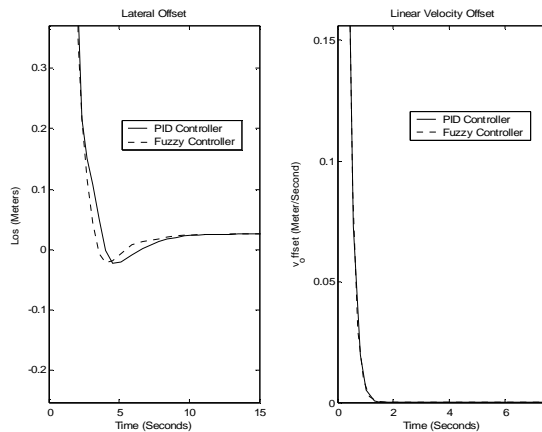


Fig. 11. Lateral and Linear Velocity Offset (Oval path)

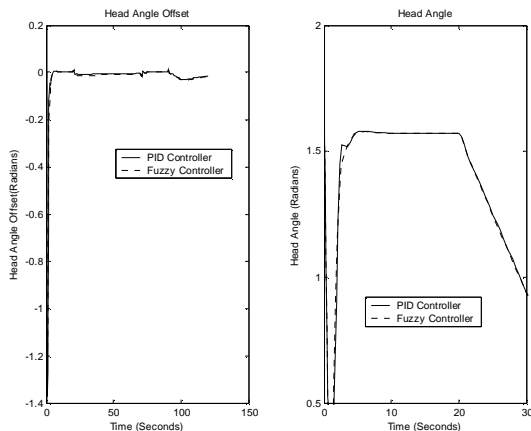


Fig. 12. Head Angle and Its Offset (Oval path)

of this controller is made up of a velocity component, which provides the longitudinal and angular velocities that are required for adequate path following, followed by a force component, which provides the propulsion and steering torques that are necessary to acquire these velocities.

This paper presents a Fuzzy Logic Controller (FLC) transforming a knowledge base into a nonlinear mapping, where the knowledge base consists of a collection of fuzzy IF-THEN rules. An adaptive fuzzy proportional controller has been developed to control the vehicle following the prescribed paths. The fuzzy logic unit can adjust the force gains adaptively according to the velocities errors in real-time.

The simulation results show that the performances of the controllers are satisfied and stable for the different assigned paths.

By analyzing the experimental results for different paths, one can find that the controller's performances for the paths, which curves have the continuing derivatives, are better than those with noncontinuous derivatives. The limitations or disadvantages result from the dynamic characteristics of the articulated vehicles, such as the structure limitation, constraints, inertia and others.

The two controllers, the conventional controller and the adaptive fuzzy controller, can control the vehicle to follow the different path well, but the controller with the fuzzy logic unit performs the path following task more accurately and more smooth. The lateral distance error and the errors of velocities in the fuzzy logic control process are smaller and converge more quickly.

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