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Mobile Robot Path Tracking Using Slip Estimation for Kinematics Information

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Abstract. This paper presents the advantages of kinematic model over the dynamics one to control the path of autonomous mobile robot in outdoor working environment since the kinematics model is easier to be sensed and calculated the inertial information. Certainly, global navigation satellite system receiver accompanied with conventional inertial measurement unit are used together, so-called INS, in order to compensate the limitation of each other. The slip angle is one of parameters that cannot be direct measured but with the measurement techniques using two antennas receiver, it can be estimated. Fuzzy logic control rule of determination is used for simply heuristic one in order to track the robot path. The results show the satisfactory of tracking path.

1 Introduction

The research in autonomous vehicle has been developed nowadays for the large amount of application especially road safety. The robot systems require a number of capabilities such as environment sensing, localization, offline and online planning, trajectory generation and robust control of path tracking. Trajectory tracking is mentioned about the vehicle is require to track a time parameterized reference path following the vehicle require to converge to and follow a path without any temporal specifications. The major challenge of the tracking process is the modeling as well as the measurement method selection. Some of them tried to model exactly as possible as dynamics aspects in force and torque calculation. There are some disadvantages concerning the parameters estimation and the system nonlinear behavior. From this reason, some researcher use kinematics model to approximate and estimate the physical of the vehicle ride and handling. There are some examples using kinematics. Wang et al [1] demonstrated the trajectory planning algorithm for four wheel steering vehicle based on kinematics Ungoren et al [2] presented the various approach of controlling the vehicle stability and four wheel steering using kinematics relationship of measured signal applied to bicycle model.

The number of studies on vehicle dynamics handling aspects has been increasing. Sideslip is one of the interesting criteria because it concerns the longitudinal and lateral movement and related to the cornering performance but it is difficult to determine directly since it related forces in any directions and cornering stiffness. So that there are many researches involving the slip estimation based on kinematics method like Chaichaowarat et al [3] proposed the algorithm to estimate the slip from the rear wheel drive.

Next requirement of such problems concerns sensor. Inertial Measurement Unit is commonly used to measure acceleration and rate of rotation as well as velocity but there is some limitation about position of mounting, noise, and etc. Thus, GNSS positioning information can also be used for other purposes such as navigation and monitoring of location based on time. In order to reduce the disadvantages of the two types of sensor, the sensor fusion is used and in this case it is called inertial navigation system (INS). Some works are in literature as Preda, et al. [4], introduced the methodologies to use common GPS receiver, it had potential and convenience to install in test vehicle with limitation only the line of slight from navigation satellites. The vehicle kinematics was estimated from GPS trajectory It is proved to be sufficient for vehicle kinematic measurements especially real-road environments. And our previous work, [5] R. Thitipathanapong et al. purposes the aggressive behaviour detection using GNSS. We also evaluated in this paper, the novel consumer grade multi-GNSS navigation receivers were investigated with the driving behaviour detection algorithm with multiple satellite navigation system were applied in this study. The consumer grade satellite navigation system could apply as input probe for vehicle monitoring system. In conclusion inertial sensor and satellite positioning systems have emerged as accurate device with high data rate providing position sensing data in outdoors and now widely integrated for automotive system. These make autonomous vehicles to obtain rapid position feedback in world coordinate during outdoor operation.

To enhance performance of the GNSS based estimation, the cost effective methods for predicting slip has been investigated. An Amount of them tried to apply the low cost GNSS receiver with the implement techniques and algorithm e.g. Bevly [6] presented the achievable performance of the combine GNSS/INS system using covariance analysis from Kalman filter. Further research from Bevly et al [7] introduced two antenna GNSS receiver in conjunction with INS to improve the estimate value of slip angle. Yoon et al [8] have also demonstrated the two antenna receiver for compensating low update rate and tried to overcome the unsynchronized updated between the two signals.

In our study, we are interested in developed the GNSS signal form the consumer grade receiver fused to the inertial measurement unit, then the fuzzy logic control shame is used in consideration with lateral and longitudinal acceleration and no side slip is assumed. It has already published in Boonporm et al., [9]. We found that the more speed does the vehicle have, the more tracking error has occurred so that sideslip angle has been reconsideration. In this paper we'd like to propose the tracking method in case of sideslip. The difficulty arises because we cannot directly measure this value but estimate from the sensor measurement information instead.

2 Kinematics slip model

The bicycle model is considered in order to identify the relationship among the various parameters like lateral, longitudinal as well as yaw dynamics. In Figure 1, X-Y earth fixed coordinate frame is defined in direction like east and north and x-y-z rotating frame at the vehicle's center of gravity. In plane kinematics, one of the rotation angle about z-axis, called yaw angle (ψ) is taken into account.

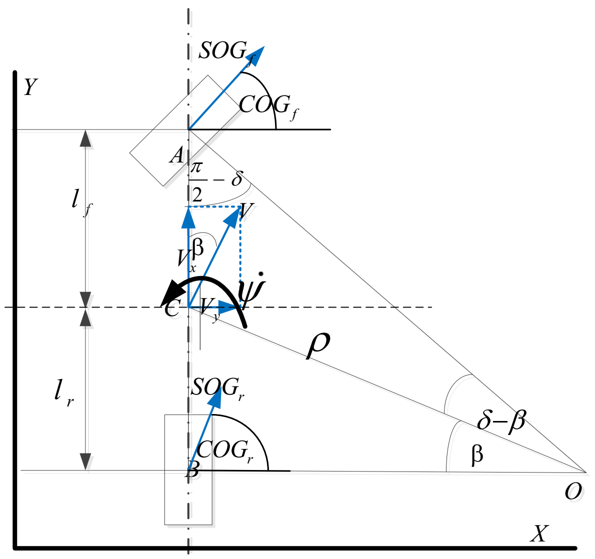

Figure 1. Bicycle model of lateral dynamics.

To define the relationship between the fix frame X-Y and the rotating frame x-y, the acceleration analysis is perform. Let $r = -R\hat{j}$, the acceleration of rigid body is defined as

$$\vec{a} = \dot{\psi}\hat{k}x(\dot{\psi}\hat{k}x(-R\hat{j})) + \ddot{\psi}\hat{k}x(-R\hat{j}) + 2\dot{\psi}\hat{k}x(-\dot{R}\hat{j}) + \ddot{x}\hat{i} + \ddot{y}\hat{j} \quad (1)$$

So that the lateral acceleration is

$$\vec{a}_y = \dot{\psi}^2 R + \ddot{y} \quad (2)$$

The term $\ddot{y}$ is interesting because it shows the vehicle slip so that side slip behavior cannot be negligible.

2.1 GNSS receiver model

In our study, we monitor the robot kinematic behavior in horizontal plane by means of acceleration determination and side slip. The Inertial Measurement Unit (IMU) should be applied to take direct data of acceleration and rotation speed. But from some disadvantages mentioned above, we are also applied the GNSS receiver with speed over ground (SOG) which is the velocity vector and course over ground (COG) at 10 Hz time step. COG denotes the direction of travel (or velocity vector) of the vehicle. Vehicle course is different from vehicle heading or yaw due to vehicle sideslip or lateral velocity.

$$COG = \psi + \beta \quad (3)$$

$$\beta = \tan^{-1}\frac{V_y}{V_x} = \sin^{-1}\frac{V_y}{\sqrt{V_x^2 + V_y^2}} = \sin^{-1}\frac{V_y}{V} \approx \frac{V_y}{V} \quad (4a)$$

or

$$\beta \approx \frac{\dot{y}}{SOG} \quad (4b)$$

There are amount of study concerning the vehicle body slip estimation [6]-[8] and their results proved that the two antenna GNSS receiver is recommended.

The disadvantages when using two-antenna receiver is the time synchronization. The problem of unsynchronized update of two GNSS receivers at front end and rear end when updating the measurements is addressed and solve following Yoon. Equations (5)-(6) are used with the front one as well as the rear end with equations (7)-(8) The idea of asynchronous update is proposed and applied by Yoon stated that the Kalman filter measurement update is executed only for the updated sensor and we also use the recommended measurement matrix with proving in the mentioned paper which are different between front end and rear one.

$$SOG_f \cos COG_f = V_x \cos\psi - (V_y + l_f\dot{\psi})\sin\psi \quad (5)$$

$$SOG_f \sin COG_f = V_x \sin\psi + (V_y + l_f\dot{\psi})\cos\psi \quad (6)$$

$$SOG_r \cos COG_r = V_x \cos\psi - (V_y - l_r\dot{\psi})\sin\psi \quad (7)$$

$$SOG_r s\text{in}\, COG_r = V_x \sin\psi + (V_y - l_f\dot{\psi})\cos\psi \quad (8)$$

Consequently, V_x and V_y can be expressed as functions of $(SOG_f, COG_f, SOG_r, COG_r)$ under assumption of the same standard deviation of GNSS velocity errors.

2.2 Inertial measurement unit

Governing equations for IMU measurements are

$$a_{x\_imu} = \dot{V}_x - V_y\dot{\psi} + w_x \quad (9)$$

$$a_{y\_imu} = \dot{V}_y + V_x\dot{\psi} + w_y \quad (10)$$

$$\psi_{imu} = \dot{\psi} + w_\psi \quad (11)$$

where w_x, w_y, w_ψ are Gaussian white noise in x,y and yaw rate respectively.

2.3 Data fusion

The GNSS will lost the signal in some case such as under the tree, or driving in urban area with high building, so that the fused data between both signal are helpful for correcting the data. Figure 2 show the algorithm of data fusion. It consist of two sources of them, the former is GNSS receiver that data is collected via serial port and the process the signal and at the same time the acceleration from accelerometer, the rotation rate from gyro and calculated heading from magnetometer are collected and processed. Both of them can fuse together using kalman filter technique.

3 Path tracking control

Path tracking in horizontal plane can be implemented as shown in Figure 2, starting with path planning depended on algorithm and constraint. We have got the desired trajectories in X-Y global coordinate direction and yaw rate with time parameterized ($X_{des}, Y_{des}, \psi_{des}$). After that the profile is calculated and compare with the information from sensor especially longitudinal, lateral acceleration and yaw rate as well as side slip. Then the control algorithm is implemented for the error between them. The control signal is generated for two motor, driving and steering.

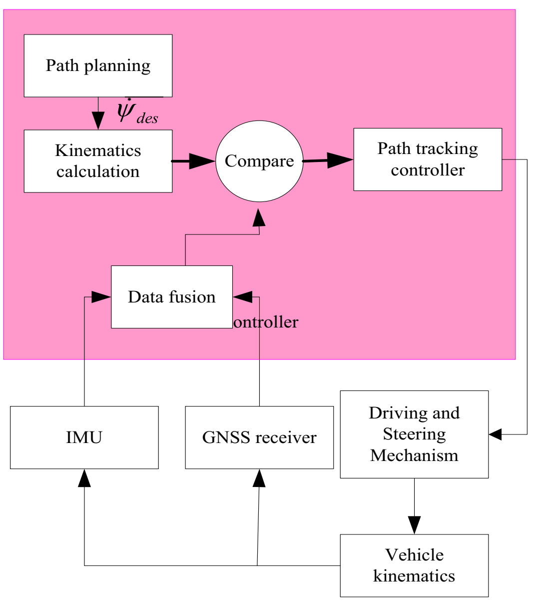

Figure 2. Tracking control algorithm.

3.1 Error model

Aim of control is tracking error that is defined as the shortest distance between the robot and the desired path for e_x, e_y and the yaw error with the difference between yaw rate and the desire one from path planning algorithm calculation.

$$\begin{bmatrix} e_x \\ e_y \\ e_\psi \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_{des} - X \\ Y_{des} - Y \\ \psi_{des} - \psi \end{bmatrix} \quad (12)$$

Refer to bicycle model in figure 1, the error dynamics respect to vehicle frame can be derived and simplified to

$$\begin{bmatrix} e_x \\ e_y \\ e_\psi \end{bmatrix} = \begin{bmatrix} 0 & \dot{\psi}_{des} & 0 \\ -\dot{\psi}_{des} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} e_x \\ e_y \\ e_\psi \end{bmatrix} + \begin{bmatrix} \cos e_\psi \\ \sin e_\psi \\ 0 \end{bmatrix} \dot{x}_{des} - \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} - \dot{\psi}_{des} \end{bmatrix} \quad (13)$$

3.2 Tracking control

In tracking environment, the issue of uncertainty in both model and surrounding are considered and make the model more complex and consequently control problem. One of the effective and ease to implement is the fuzzy logic control since it does not require an accurate mathematical model of the process. We have chosen the simply one, center of gravity method. When used in a control system, FLC is robust since it provides a fast rise time and a small amount of overshoot. However, some difficulties can occur when designing the FLC as stated in [9].

The input variables of acceleration norm as $a = \sqrt{a_{long}^2 + a_{lat}^2}$ which should be not exceed than the threshold in g-g diagram and yaw rate are considered as input. Speed and the command steering angle are classified as output. The results is acceptable but there is error in lateral direction when the vehicle drive faster.

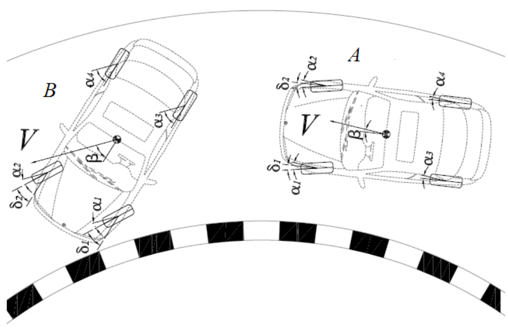

Figure 3. Vehicle driving as low-sideslilp (A) and large sideslip (B) during steady state cornering following Abdulrahim et al [10].

Consequently, the additional control with slip is implemented since we determine its behavior during cornering; the vehicles are subject to centripetal acceleration directed toward the center of rotation. As shown in Figure 3, vehicle A drives at a small sideslip and incurs acceleration that is mostly in the negative lateral direction. Vehicle B is oriented at a large angle relative to the velocity, which is here perpendicular to the turn radius. Functions will be presented to describe slip in term of path curvature and velocity.

The additional control rule is applied as mention in Figure 4. We consider the yaw rate error since the measured yaw rate is not the same as desire one because of side force leading to the lateral movement $\ddot{y}$ and $\dot{y}$ where slip is introduced in equation (4b).

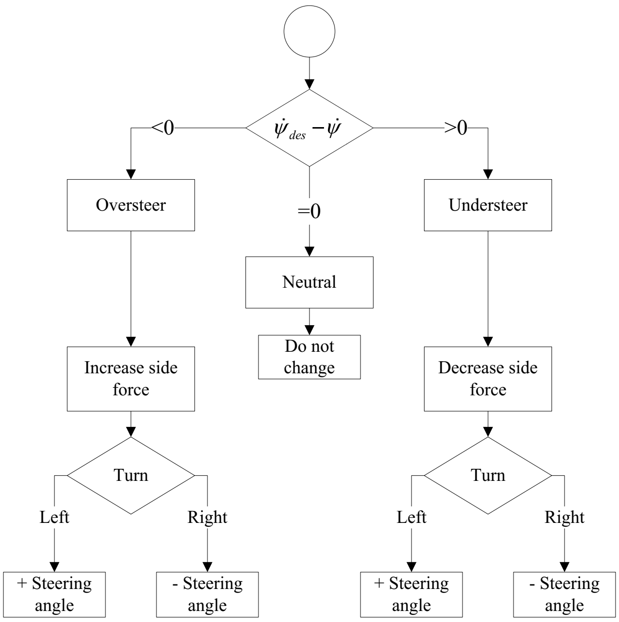

Figure 4. Flowchart of fuzzy determination.

4 Experimental results

The algorithm mentioned above is applied to the middle size vehicle like autonomous robot equipped with two main sensor as U-blox multi GNSS receiver with two antennas and inertial measurement unit both have 10 Hz sampling rate

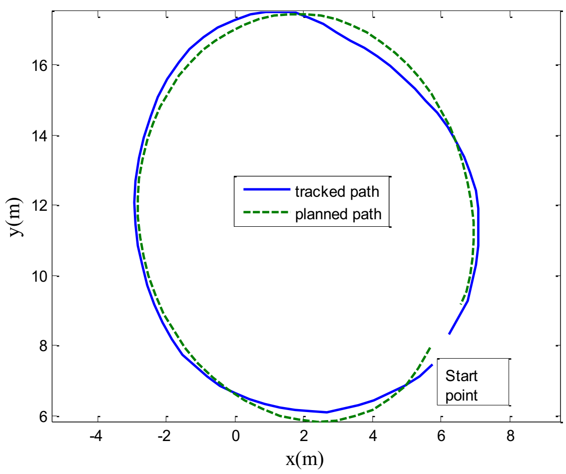

Figure 5. Compare the tracked path to the planed path.

One example of the results during cornering is driving with keeping the constant speed in the trajectory planning, in our sample experiment in Figure 5. we control its speed approximately 5 m/s The yaw rate occur during cornering in left or right turn In the same manner but only plus and minus sign depend on coordinate system. The result of the tracking is demonstrated in Figure 5. The desire path is shown in dash line and the sensor data readings are shown in solid line. The error of path tracking still occurs due to unbalanced of the steering link and some unbalance of the structure, as well as the sensor noise from GNSS receiver and IMU. There still have been error in lateral direction more than longitudinal direction even though the slip is compensated as demonstrated in Figure 6.

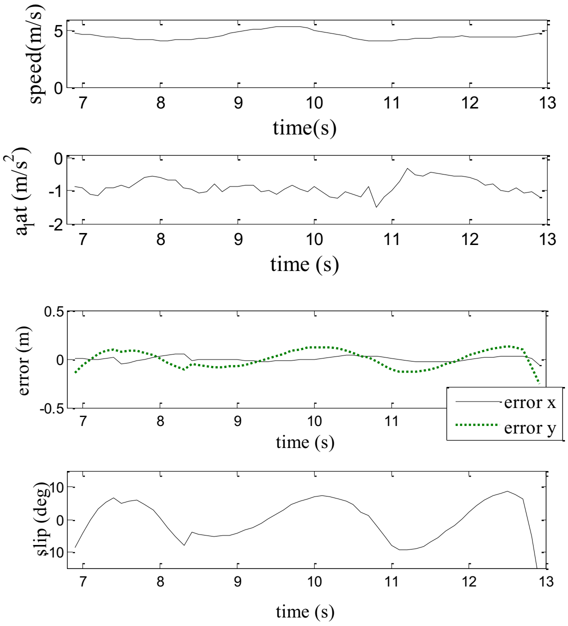

Figure 6. Speed, lateral acceleration, translational error and slip angle versus time from the tracked path´s sensor reading.

5 Conclusion

The kinematic model with slip behavior consideration is useful for path tracking problem without knowing its dynamics model and parameters which are difficult to evaluate. In order to measure the kinematics information, we use the information from GNSS receiver with two antenna fused with IMU to overcome some disadvantages. The results are satisfied but there are some position error still occurs but it is smaller. The extend measurement technique and hybrid control are in future consideration.

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